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Sailing warships in early modern Europe: Technological evolution, naval strategy, and archaeological insights

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Abstract

This study examines the historical development of sailing warships from the sixteenth to the nineteenth century, focusing on their technological innovations and strategic significance. It explores major naval engagements, shipbuilding techniques, and the organization of naval crews, highlighting the implementation of new tactical practices at sea. Particular attention is given to the gradual transition from sail-powered fleets to steam-powered vessels and its impact on the decline of traditional sailing warships.

By integrating archaeological findings and historical sources, this research provides new insights into shipwrecks and naval architecture, emphasizing the interrelation of technology, strategy, and political power during the early modern period. Contemporary scholarly literature indexed by DOI is incorporated to support the analysis.

Overall, the study offers a comprehensive understanding of naval history, presenting sailing warships as essential instruments of military, political, and economic influence. It establishes a foundation for further research on maritime technology, naval tactics, and the broader geopolitical role of warships.

Keywords: Sailing Warships; Naval Warfare; Shipbuilding; Maritime Archaeology; Age of Sail; Steam Navigation

1. Introduction

The period spanning the late 15th to the 18th centuries witnessed a profound transformation in European maritime power, driven by technological innovations, evolving naval strategies, and expanding imperial ambitions. Sailing warships, from early carracks to sophisticated ships of the line, became central instruments of state power, commerce protection, and territorial expansion. Their design and armament reflected not only advances in shipbuilding and artillery but also the shifting doctrines of naval warfare, which increasingly emphasized line tactics, coordinated maneuvers, and firepower concentration (Rodger, 2004).

The technological evolution of warships during this era was marked by incremental but critical developments. Hull designs improved for greater seaworthiness and cargo capacity, rigging systems evolved to enhance maneuverability, and broadside artillery became the standard for offensive capability. Such innovations facilitated extended voyages, reinforced the projection of naval dominance, and enabled European powers to secure vital maritime trade routes (Baugh, 2010).

Concurrently, naval strategy underwent a parallel transformation. Commanders adapted to the challenges of long-range engagements, coordinated fleet formations, and the integration of intelligence and reconnaissance. The emergence of formalized naval tactics, such as the line of battle, reflected a growing understanding of the interplay between ship

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design, armament, and operational doctrine (Sondhaus, 2001). These strategic considerations were instrumental not only in large-scale conflicts, such as the Anglo-Dutch Wars, but also in smaller engagements where maneuverability and tactical acumen often outweighed numerical superiority.

Figure 1 Pioneering 15th-Century Warship.

Archaeological investigations of shipwrecks and material culture provide invaluable insights into these historical dynamics. Excavations of early modern warships reveal construction techniques, armament configurations, and provisioning strategies that are often absent from contemporary textual sources. Such findings illuminate the practical realities of naval life, the logistical complexities of maintaining fleets, and the nuanced adaptations made by shipwrights and commanders in response to evolving technological and strategic imperatives (Gerritsen, 2012).

By examining the interrelationship between technological innovation, naval strategy, and archaeological evidence, this study aims to provide a holistic understanding of sailing warships in early modern Europe. It highlights how maritime power was both a product of material capability and strategic ingenuity, and how the archaeological record continues to reshape our understanding of naval history.

2. The Age of Sail: Origins, Development, and Design Innovations

The Age of Sail in Europe, spanning from the late 15th to the early 18th centuries, marked a decisive transformation in naval history, where exploration, commerce, and warfare converged to drive technological and strategic innovation. Early sailing vessels such as the carrack and the caravel emerged from a synthesis of Mediterranean and Northern European shipbuilding traditions, balancing cargo capacity with the mounting of defensive and offensive armaments (Pryor, 1988; Zazzaro, 2021).

Carracks, used predominantly by Iberian powers, featured high fore and aft castles that facilitated artillery deployment but affected stability, while their robust hulls enabled transoceanic voyages and played a central role in the expansion of global exploration. Caravels, smaller and more maneuverable, excelled in reconnaissance, coastal navigation, and rapid-response operations, with lateen sails that allowed superior windward performance in Atlantic and Mediterranean waters. The proliferation of naval artillery fundamentally altered ship design, as gun decks were integrated to optimize broadside firepower, affecting weight distribution, stability, and sailing performance (Rodger, 2004; Capponi, 2025).

As combat shifted from boarding to artillery engagements, reinforced hulls and standardized gun placements became essential, prompting innovations in internal bracing and framing to withstand increasingly powerful cannon recoil. Hull

improvements, including the beakhead bow and refined stern structures, enhanced hydrodynamics, speed, and maneuverability, reflecting a growing understanding of the interplay between form and function. Rigging systems advanced in parallel, combining square and lateen sails to exploit diverse wind conditions while maintaining tactical flexibility in line-of-battle formations (Baugh, 2010; Sondhaus, 2001).

The integration of multiple gun decks, particularly in ships of the line, allowed devastating broadsides, reshaping naval strategy in the 17th century (Rodger, 2004; Symonds, 2025). The English, Dutch, and French navies led these developments, adapting design to local conditions, strategic imperatives, and resource availability, fueling rapid innovation. Shipyards became centers of experimentation, with Royal Dockyards such as Deptford and Chatham implementing standardized construction and quality control to ensure fleet durability (Maarleveld & Guérout, 2021; Ford, 2022).

Material selection was crucial: oak for hulls provided strength, while pine and fir for masts balanced durability and weight. Naval architects evolved from master shipwrights to trained designers, exemplified by figures like Phineas Pett, who combined empirical knowledge with emerging scientific principles (Guérout, 2023). The line-of-battle tactic imposed new design constraints, requiring vessels to maintain offensive capability and formation cohesion, shaping hull proportions, sail plans, and gun layouts. Advances in ballast distribution and keel construction enhanced stability, while long-range voyage requirements influenced storage for provisions, water, and ammunition (Blickle, 2025).

Shipboard life was shaped by these design considerations, as narrow decks, limited ventilation, and crowded gun ports affected crew efficiency, health, and morale. The Dutch Golden Age illustrates the fusion of commerce and naval innovation, with fluyts and warships combining cargo efficiency and defensive capability, protecting trade while asserting maritime dominance. Standardization of ship classes enabled predictable fleet performance and streamlined logistics. Advances in artillery, including cast iron and bronze cannon, standardized shot sizes, and improved carriages, increased range, accuracy, and rate of fire, enabling sustained broadsides and coordinated fleet maneuvers (Ciarlo, 2023; Tevali, 2025).

Environmental conditions in the Mediterranean and Atlantic required further design adaptations, from hull shape to sail configuration. Archaeological excavations of shipwrecks provide critical evidence of construction techniques, armament layouts, repairs, and provisioning strategies, while recovered artifacts illuminate crew life, hierarchy, and daily operations (Ginalis, 2022; McCarthy, 2021). Comparisons with surviving naval treatises allow tracing design evolution and tactical doctrine, highlighting the interplay between theory and practice (Capponi, 2025).

The synthesis of technological, strategic, and archaeological insights underscores that sailing warships were dynamic systems shaped by environmental, economic, and human factors. European naval power during the Age of Sail emerged from continuous innovation, where material capability and strategic thinking were inseparable (Baugh, 2010; Flatman, 2022; Del Cairo Hurtado et al., 2025). Ultimately, the Age of Sail represents a period of extraordinary technological sophistication, strategic adaptation, and empirical knowledge, with archaeology continually enriching our understanding of early modern European naval forces.

3. Strategy and Naval Battles

The strategic deployment of sailing warships was a decisive factor in shaping naval warfare from the sixteenth to the early nineteenth century. The growing militarization of maritime trade routes and the emergence of powerful state navies transformed naval engagements into instruments of geopolitical influence (Janžekovič, 2020; Solórzano Telechea, 2026). Large-scale battles demonstrated the importance of fleet coordination, disciplined formations, and technological superiority.

One of the most emblematic cases is the Battle of Trafalgar (1805), where the British fleet under Admiral Horatio Nelson defeated the combined French and Spanish fleets. The tactical innovation known as “breaking the line” allowed the British fleet to penetrate enemy formations and concentrate firepower effectively. This battle highlighted the strategic advantages of maneuverability, disciplined gunnery, and superior naval training (Capponi, 2025; Symonds, 2025).

In addition to large-scale engagements, smaller naval conflicts in the Mediterranean and Aegean seas played a crucial role in maintaining maritime control. Regional naval encounters often involved patrols, escort missions, and anti-piracy operations, reflecting the importance of naval power for securing trade networks and territorial sovereignty (Özdaş & Kızıldağ, 2026; Tevali, 2025). These operations required flexible tactics and command structures capable of adapting to rapidly changing maritime environments.

Recent archaeological research has significantly enriched the understanding of naval strategy and shipboard operations. Studies of shipwrecks and submerged battlefields reveal artillery positioning, deck arrangements, and structural modifications designed to maximize combat efficiency (Ginalis, 2022; Guérout, 2023). Such evidence allows historians to reconstruct real battle conditions and compare them with historical records.

Naval warfare during the sailing era also depended on effective logistics, communication, and fleet organization. The development of signal flags and standardized command systems allowed fleets to coordinate complex maneuvers during engagements, enhancing operational cohesion and fleet effectiveness (Adams, 2020; Ford, 2022).

Furthermore, naval battles were closely linked to diplomatic and economic interests. Control of sea routes enabled states to dominate trade and colonial networks, reinforcing maritime supremacy as a central component of national security and imperial expansion (Symonds, 2025; Blickle, 2025).

Modern scholarship continues to analyze these battles using interdisciplinary approaches combining historical documentation, maritime archaeology, and naval architecture. This integrated perspective provides a comprehensive understanding of how sailing warships shaped military strategy and influenced the balance of power in early modern Europe (McCarthy, 2021; Zazzaro, 2021).

4. Archaeological Evidence

Maritime archaeology has become an essential discipline for understanding the technological development of sailing warships. Shipwrecks, submerged harbors, and historic shipyards provide direct evidence of naval construction techniques, operational practices, and the material culture of fleets. Systematic underwater excavation, combined with advanced digital reconstruction, allows researchers to examine structural elements often absent from written historical records (Ciarlo, 2023; Flatman, 2022; Guérout, 2023).

Among the most significant discoveries in recent years are the Yenikapı Shipwrecks in Istanbul, which include vessels from multiple historical periods. The Yenikapi 7 wreck, in particular, offers detailed insights into hull construction, ballast distribution, and cargo storage systems. Analysis of these elements demonstrates how naval architects optimized stability, maneuverability, and combat readiness through careful structural design (International Journal of Nautical Archaeology, 2025; Özdaş & Kızıldağ, 2026).

Additional archaeological evidence from Mediterranean shipwreck sites, including Venetian and Ottoman vessels, highlights the diversity of regional shipbuilding traditions and the transfer of maritime knowledge between European and Mediterranean powers. Comparative study of keel design, framing systems, and fastening techniques reveals adaptations to local conditions and specific military requirements (Ginalis, 2022; Guérout, 2023).

Ballast materials constitute another key area of research. Stones, sand, and other ballast configurations were crucial for maintaining stability during long voyages and in combat situations. Analyses indicate that ballast arrangements were dynamically adjusted according to cargo weight, weather conditions, and tactical considerations, reflecting sophisticated understanding of naval engineering (Blickle, 2025; Capponi, 2025).

Traditional shipyards provide further evidence of the continuity of maritime knowledge. Centers in the Aegean and other Mediterranean regions preserved techniques that had been developed over centuries. These shipyards functioned as living laboratories, allowing historians and archaeologists to observe craftsmanship, test historical reconstructions, and compare contemporary techniques with archaeological findings (Ford, 2022; Maarleveld & Guérout, 2021).

Modern technologies have revolutionized maritime archaeological research. Three-dimensional scanning, digital modeling, and material analyses enable the reconstruction of complex hull geometries and simulate vessel performance under historical sailing conditions (Ciarlo, 2023; Tevali, 2025). Such methods allow precise study of ship dynamics, structural resilience, and the operational realities of naval warfare.

The integration of archaeological data with historical documentation provides a comprehensive understanding of naval technology. By combining physical evidence from shipwrecks, ports, and shipyards with archival records, scholars reconstruct not only the physical structure of sailing warships but also the operational context, including crew organization, tactical deployment, and trade logistics (Tevali, 2025; Özdaş & Kızıldağ, 2026).

This interdisciplinary approach demonstrates that maritime archaeology is not merely descriptive; it informs broader interpretations of naval strategy, technological innovation, and political influence. Insights gained from material

remains illuminate how naval powers adapted to evolving maritime environments, integrated new technologies, and maintained dominance at sea during the early modern period (Baugh, 2010; Sondhaus, 2001; Blickle, 2025).

5. Transition to Steam-Powered Navigation

The nineteenth century marked a fundamental transformation in naval technology with the introduction of steam-powered vessels. This transition was closely linked to the broader industrial and technological developments of the Industrial Revolution, which introduced new manufacturing techniques, materials, and mechanical innovations (Ciarlo, 2023; Flatman, 2022).

Steam propulsion offered several advantages over traditional sailing ships. Unlike sail-powered vessels, steamships could operate independently of wind conditions, providing greater reliability and tactical flexibility. This capability significantly enhanced naval maneuverability and allowed fleets to maintain consistent speed during extended voyages or military operations (Baugh, 2010; Sondhaus, 2001).

During the early stages of this technological transition, many navies employed hybrid ships that combined sails with steam engines. These vessels retained conventional rigging systems while integrating steam propulsion as an auxiliary power source. Hybrid ships represented an intermediate technological phase, enabling navies to gradually adapt to mechanical systems without abandoning the knowledge and experience gained through centuries of sailing warfare (Ford, 2022; Symonds, 2025).

The introduction of steam engines necessitated substantial changes in ship design. Naval engineers had to accommodate boilers, engines, and coal storage within the hull, which altered internal structures, weight distribution, and stability. Consequently, shipbuilders experimented with new materials and construction techniques, including the increasing use of iron hulls and reinforced frameworks (Ciarlo, 2023; Capponi, 2025).

These technological innovations also transformed naval labor and training. Sailors who had previously relied predominantly on seamanship and wind navigation now required technical skills related to machinery maintenance and engineering operations. The emergence of specialized roles, such as marine engineers and mechanics, reflected the growing complexity of naval technology during this period (Baugh, 2010; Sondhaus, 2001).

Furthermore, the transition to steam propulsion influenced naval strategy and global maritime networks. Faster and more reliable vessels allowed states to maintain a continuous naval presence in distant territories, strengthening imperial and commercial connections. Steamships also facilitated rapid troop transport and logistical support, enhancing operational mobility (Blickle, 2025; Symonds, 2025).

Despite these advancements, sailing technology did not disappear immediately. For several decades, sailing ships and steamships coexisted, and many naval vessels continued to rely on sails as auxiliary propulsion. This transitional period illustrates how technological innovation often occurs gradually rather than through abrupt replacement (Baugh, 2010; Sondhaus, 2001).

Modern scholarship emphasizes that the development of steam-powered navies was not merely a technical innovation but represented a profound transformation of maritime culture, naval organization, and global power structures. The legacy of sailing warships continued to influence ship design, naval tactics, and maritime traditions well into the modern era (Blickle, 2025; Flatman, 2022).

Concluding with a comparison with the contemporary navigation procedures based on GPS, Satellites, and important information streamed via the internet, we understand that the jump in the technology of sailing and navigation that was accomplished in the last century has been affected and inspired by the digital technology exploitation, in all the aspects of technological development and especially in education that is the driving force of the digital transformation of every aspect of economic development. We have to be inspired and adopt methodologies, technologies, and procedures from the various forms of digital technologies exploitation in the education domain. These technologies, such as mobile devices (25), a variety of ICT applications (26), AI STEM & ROBOTICS (27-30), facilitate and enhance educational procedures such as the training for navigation and sailing abilities. Additionally, the use of ICTs in conjunction with theories and models of metacognition, executive functions, and self-empowering methods [31-34], accelerates and improves educational practices and outcomes, particularly in the naval domain.

6. Conclusions

The historical analysis of sailing warships highlights the close relationship between technology, naval strategy, and political power from the sixteenth to the nineteenth century. Technological innovations in shipbuilding, the organization and training of naval crews, and the development of advanced tactical formations significantly influenced the effectiveness of warships in naval engagements. These factors enabled maritime powers to expand their influence and maintain control over strategic sea routes.

Archaeological discoveries provide tangible evidence regarding ship construction, the arrangement of gun decks, and the application of technological solutions that improved the operational capacity of sailing warships. The analysis of shipwrecks and traditional shipbuilding sites contributes to a deeper understanding of how naval tactics and strategies were implemented in real maritime conditions. Such findings establish an important connection between historical documentation and material evidence.

The transition to steam-powered navigation during the nineteenth century marked a crucial turning point in naval history. Steamships introduced new technical and operational capabilities, significantly improving speed, maneuverability, and firepower. At the same time, hybrid vessels combining sails and steam engines preserved aspects of traditional sailing experience while gradually integrating new mechanical technologies. This transitional phase illustrates how innovation in naval engineering evolved through the adaptation of earlier maritime knowledge.

Overall, this study demonstrates that sailing warships were not merely means of transport or instruments of warfare, but also powerful tools of strategic, political, and economic influence. The combined examination of historical sources and archaeological evidence provides a comprehensive perspective on the evolution of naval power and the development of maritime history in Europe and the Mediterranean. Furthermore, this research establishes a foundation for future studies on naval technology, maritime strategy, and the broader geopolitical significance of warships in shaping international relations.

Compliance with ethical standards

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Disclosure of conflict of interest

The Authors proclaim no conflict of interest.

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