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Article

The Hull of A Galleon: An Archaic Construction or A Masterpiece of Ship Design

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Abstract: The Galleon was considered a masterpiece of shipbuilding in the sixteenth century, but from a modern point of view, the shape of her hull looks archaic and primitive. However, how accurate is this perception? Is the hull form of Galleon primitive? What were the reasons for its unique design features? This article investigates these questions by directly analysing the hull's features from the point of view of modern ship's theory, as well as from a historical perspective.

A careful evaluation of specific design criteria of a typical Galleon, together with analysing a 3D model of its hull on modern software, with further insight for the seakeeping behaviour of Galleon with a comparison to more modern full-rigged ship (Barque of 19 CE), showed that these features were not random, but instead had a good rationale behind it, and served specific and carefully decided functions, required at the time.

Keywords: history of shipbuilding; Galleon hull; Barque hull; seakeeping analysis; CFD analysis; 3D model

1. Introduction

The Galleon was considered a masterpiece of shipbuilding in the sixteenth century. Still, from a modern point of view, the hull shape of a sixteenth-century Galleon looks archaic and primitive - especially considering that the forms of sailing ships have improved significantly since that time. As Peter Kirsch [1] describes it: '*… (Galleons) may seem podgy and clumsy to our eyes, in comparison with the flush-decked warships of the eighteenth and nineteenth centuries*'. A common understanding is that this happened due to a lack of knowledge of ancient shipwrights: '…*naval architecture was a nascent science in sixteenth-century England, coming into its own as an accepted practice only by the middle of the seventeenth century…*' [2]. Only when the science of shipbuilding was developed in 18-19th centuries, shipbuilders gained the ability to create fast and efficient sailing ships.

How accurate is this? How primitive was the Galleon's hull form? What were the reasons behind different features of the Galleon's hull? Was it due to lack of knowledge or something else? Many more puzzling questions remain:

- Why did galleons have a raised and narrow Quarterdeck, and such a low and wide Forecastle, when later sailing ships of 18-19th centuries had a flat deck of the same width without castles?
- Why did Galleons have a round midsection, when it is not economical (a rectangular cross-section allows much more capacity with the same ship's dimensions)?
- Why were the sides so tumblehome and the open decks so narrow?
- Why did galleons have a full form/bluff bow, when a sharp, V-shaped bow had much better resistance?
- What was her extended beak head/snout intended for? Decoration? Latrine? Support for bowsprit?

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- In general, what were the main requirements, which drove the design of a Galleon's hull? Where did they come from, and how were they fulfilled?

There are not many written sources from that time in existence today, and those that we do have access to, do not fully explain the above points. While professional historians know the answers to at least some of these questions, it will be helpful to look at this from a different point of view. Hence, the objective of this article is to consider and directly evaluate the various features of a typical 16th-century Galleon's hull from the point of view of modern science, which allows to explore the reasons of those features used at that time.

Firstly, a brief overview of forerunners, which powered the Age of Explorations, will help to understand better why and how the Galleon was developed. Then the specific features of Galleon's hull were evaluated from modern ship theory's point of view. To further investigate the validity of the assumptions, the 3D model of a Galleon's hull was created, and a seakeeping analysis was done using a modern software (MAXSURF from Bentley Systems, Inc.). The results were compared with a more modern hull type (in this case, the 19th-century Barque), which allows to arrange an evaluation of the relative Galleon-vs-Barque hull's characteristics. This helps to understand better the Galleon's development and reasons how the new and more advance ship's hulls appeared in the 18th - 19th centuries.

Main Objectives

The main goal in this article is to demonstrate that a Galleon was and is a masterpiece of shipbuilding, even by today's standards. Her hull forms were well developed to satisfy all requirements and technologies of 16th century.

Any further improvements of the sailing ship's hull form, which happens in the 18-19th centuries, could be done only after new technologies became available, and new requirements became dominant.

2. Age of Discovery and first seagoing ships - Caravel and Carrack

The *Age of Discovery*, or the *Age of Exploration* (a period in European history approximately from the beginning of the 15th century until the end of the 18th century), was started with the Portuguese discoveries of the Atlantic archipelagos of Madeira and the Azores, the coast of Africa, and the discovery of the sea route to India in 1498. Then, it was Spain's trans-Atlantic Voyages of Christopher Columbus between 1492 and 1502, and the first circumnavigation of the globe by Ferdinand Magellan in 1519–22.

These explorations were made possible when the special ships of unlimited seagoing capability were developed, which could reliably traverse the broad reaches of the oceans and were able to bring back the treasures from new worlds. And such ship could be created only when new techniques and technologies become available- first in carpentry (hull fabrication) and metallurgy (tools and gunnery), fabric and rope manufacturing (rigging and sails), chemistry (gun powder), mapping and navigations. This, in turn, stimulated the rapid development of new ships and shipbuilding methods.

However, we need to understand that travel across oceans was very risky and scary business in early 16th CE, both for sailors and for shipwrights.

2.1. Caravel

The Caravel (*ERROR! REFERENCE SOURCE NOT FOUND.*) was developed sometime in the 1440s, under the sponsorship of King Henry the Navigator of Portugal and was based on earlier Portuguese fishing boats. It was a *'...small, slender-hulled vessel, light enough to stay near shore and move in light airs, and that was also able to sail close to the wind…'* [3]. The Caravel had a tonnage of 50 to 160 tons, an average length of between 12m and 18m, and a high length-to-beam ratio of around 3.5 - 4.1. Its narrow, ellipsoidal frame had 1 to 3 masts, with lateen triangular sails (originally) allowing beating, and it was armed with a few light guns [4]. These were speedy and manoeuvrable, reasonably seaworthy, and weatherly, but with a somewhat low cargo capacity.

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Figure 1. Portugal Caravel with Lateen sails. PHGCOM, CC BY-SA 3.0.

2.2. Carrack/Nau

For trading, the Caravel conceded to the **Carrack (Nau),** which was bigger and more economically efficient (*ERROR! REFERENCE SOURCE NOT FOUND.*). A Carrack was developed in Portugal in the 14-15th century, evolving from the single-masted Cog.

Figure 2. Carrack_Madre_de_Deus. https://upload.wikimedia.org/wikipedia/commons/5/5d/Carrack_Madre_de_Deus.jpg.

A typical carrack was an ocean-going, oared and sailing ship, three- or four-masted, square-rigged on the foremast and mainmast, and lateen-rigged on the mizzenmast (which made her a first full-rigged ship) [3]. They were large enough (from 100 to over 1000 tons) to carry cargo and the provisions needed for very long voyages. Carracks had a rounded frame (unlike the ellipsoidal structure of the caravel), stern with rudder, bowsprit at the stem, large and high stern-castle and forecastle. Over the forecastle, the Carrack had a distinctive triangular projecting bow – so called 'carrack bow' [5].

Later (at the beginning of the 16th century), it was discovered that the raised forecastle seriously hampers sailing. The great bulk of it, catching the wind ahead of the mast, has

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the effect of pushing the bow to leeward, making it difficult to sail close to the wind. Therefore, the height of the forecastle was reduced.

Carracks were commodious merchant vessels, which were not designed to withstand a heavy pounding from enemy fire. They could be armed with artillery (few anti-personnel guns) and filled with troops in time of war, but in general, they were not able to fight successfully against enemy ships.

3. Galleon – a masterpiece of sixteenth century's shipbuilding

3.1. General description

Multiple voyages of ships to India and the Americas became a leading source of tremendous wealth, which initiated a lot of conflicts at sea - pirates, privateers, corsairs, everybody would like to get a share of those treasures. Experiences, accumulated during first open ocean expeditions, created a demand for more powerful and better armed ships, able to carry and, most importantly, to protect the treasures on the way from New World back to the homeland. So, in the 16th-century shipowners started to demand larger, more '…*nimble and defensible ships…'* [6], for wartime privateering during the multiple wars and the long-distance routes once peace returned.

In the 1540s a new type of ship was introduced - the Galleon. It was a purpose-built warship with large cargo-carrying capacity, which was more substantial, more heavily armed, and cheaper to build (five Galleons could cost around the same as three Carracks) [7]. The exact origin of the term *Galleon* is unknown, but *'…by about 1570, the word 'Galleon' was commonly used by all nations, to refer to the kind of ship that we associate with the word today, but the precise meaning varied from country to country…*' [6].

Galleon was a faster, more manoeuvrable vessel then Carrack; she had a high level of stability in the water, more robust hull with more guns than a Carrack could carry, and she also had a large enough cargo hold to bring treasures [7]. For over a century, these great ships dominated the waters of three oceans.

3.2. Distinctive features of the Galleon

All countries were built various types of Galleons, which have a substantial difference in construction. However, for the goals of this article, we will consider (just for illustration of basic principles) the typical features of the 'race-built galleon' infrastructure as described by Baker/Hawkins c.1570 [8] .

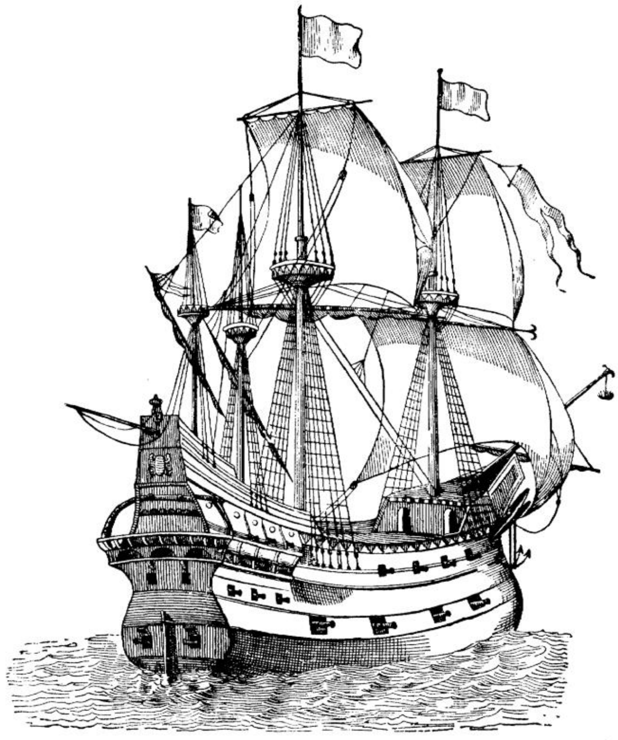

Figure 3. 15th century galleon.

- Three masts, of which foremast and mainmast, were both noticeably taller than mizzenmasts (in larger galleons, a fourth mast could be added, called the Bonaventure mizzen), complemented with small sprit topmast on the end of the bowsprit.
- A foremast and mainmast hold 2-3 square sails each, with mizzenmasts carrying sloped lateen sails; additionally - square spritsails on bowsprit; [3]
- Armed with 20-70 guns of various sizes on 1-2 gundecks, and equipped with watertight gun ports [9];
- The carvel-built hull was longer and narrower than that of a Carrack (having length-to-beam ratio of 2.5-3.1 [1], later even up to 3.5-4.1 [9] [3] [2]), but still had a large cargo hold for transportation of goods;
- Highly raised stern castle with a quarter's gallery, but instead of two or three decks in solid layers from main mast to stern, the Galleon had each deck shorter than the one below, so that the ship's sides rose aft gradually.
- A pintle-and-gudgeon rudder, which allow to build a bigger, deeper, and stronger rudder (having enhanced aspect ratio -the ratio of the depth to width of a rudder), with better course keeping and manoeuvring ability
- Narrowed hull near the stern, sharp and flat at the deep draft, then flared (V-shaped) at waterline level; and a square tuck stern (instead of a round tuck on carracks),
- Broad and a rounded midship section with narrowed decks - tumblehome boards,
- Full-body and wide bow with a low forecastle, which was set back from the prow/beakhead,
- Triangular Carrack's prow was replaced with a long prominent beaked head of skeleton/cage construction, projecting forward from the bow below the level of the forecastle, typical for Galleons.

In this article, we will discuss the most interesting points from above - the features of the hull of Galleon.

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4. Modern ship theory and a Galleon's hull

First, to understand how the Galleon's hull features were developed and how they affect the ship's seagoing ability, we need to agree that those features were not results of luck of knowledge of low educated people. Ancient seafarers were perfectly able to analyse the ship's behaviours and its dependence on different hull's features. They used such observations to suggest and implement modification of ships. However, shipwrights of the time usually were very reluctant in changing anything significantly in an already successful design of their ancestors. In such situations, any changes in ship's hull were initiated by seamen (not by shipwrights), were slow and in minor quantities, and implemented only after testing on real ships. It took years and even decades, but eventually, it led to new improvements, and was effectively the same process of optimisation of design - like one we follow today!

Then, there is a need to understand that before any ship's modifications (as we remember from history) became possible, the foundational technologies had to be developed. So, the Galleon was developed only in the 16th century, because not all relevant technologies and techniques have existed before. And newer, more advanced ships of 18-19 centuries cannot be built in 16 century- for the same reason. This factor is quite commonly forgotten when discussing the features of a ship.

With that in mind, if we know that a particular design (e.g., ship hull) was in use for decades (and sometimes for centuries!), we can confidently say that this design was ideally suited for **available technology, regional conditions, sailing practice and required functionality** of that period. This is the same reason why, in some countries, even today, the locals are building and using indigenous time-honoured wooden boats for their daily needs.

As a result, we first need to understand what the sailors and shipbuilders at that time wanted from their ships in 15th - 16th centuries, and to check how they were able to implement these requirements from a technological point of view.

4.1. Raised stern-castle (with V-shaped hull below)

The common understanding of a Galleons' stern structures could be seen in A. Konstam [9]: '…With their elegant lines, it could even be said that they were graceful vessels, and if their high stern structures did little else, it made them appear imposing, like floating bastions filled with the finest-trained musketeers of the day…'.

The primary (and most mentioned) use of high sterncastle was a raised battle platform – because the main tactic of naval battles of that time (from ancient time up to arguably 16th century) was boarding [10] [7]. The guns of that time were used mostly as antipersonnel weapons, and the high stern castle (and forecastle too) of a Galleon provided high-ground advantages for archers/musketeers/gunners during naval battles and been exceptionally efficient when boarded or during a mutiny on board. Also, the raised stern castle/poop was usually the driest and most ventilated compartment of a ship, providing a comfortable position for the officers' cabins, and it was typically a high place for the helmsman (close to the rudder and good observation) and for the captain (dominant point of view above deck) [3]

Using the modern understanding of ship hydrodynamics, a few more points could be added to above:

- The 15th - 16th centuries were a time of the first attempts to cross the open ocean, and those voyages were perilous and risky. Therefore, the biggest concern of sailors was the ability of a ship to survive heavy storms during this voyage – their seagoing ability.

Since ancient times, when Phoenicians and Greeks first started to build narrow and long ships with high board, they have faced a problem of survivability of such ships during storms (keeping in mind that no oars nether sails were strong enough to be used for that). Seafarers noted that those ships were better surviving the storm if they free drifted with bow turned to incoming waves – the so-called **'head-to-sea' passive mode of**

survivability [11]. And the vessel with its stern highly raised above the deck had an easier time doing this. Thus, special ships were developed with the raised stern structure, adopting this mode of survivability (**Error! Reference source not found.**) [10].

Figure 4. Persian ship during greek-persian wars https://commons.wikimedia.org/wiki/File:Persian_ship_during_greek-persian_wars.webp.

From the modern point of view, the raising of a stern higher above deck results in moving the lateral and frontal centre of windage CW (centre of application of wind forces on a ship without sails) aft from the centre of buoyancy CB and centre of lateral resistance CLR of the submerged part of a hull. This created turning moments from wind and drift forces, which can turn the ship. Such vessels, as soon as all sails were lowered during the storm, automatically started to weather-wane freely (turning bow to incoming wind/wave) and could stay in this position during entire storms. Those minimised the load applied on the hull during a storm and improved ship's survivability.

The Galleon has inherited this raised stern feature entirely. She has highly raised superstructures of a stern-castle, but her bow is low and has full body lines and is wider than the stern. Therefore, CLR and CB are moved forward, but CW (without sails) in lateral and frontal projections is pushed back towards the stern. So, we could assume that under the wind pressure, this will create a turning moment between Drifting and Windage forces, and the ship (without sails) will automatically start to weather-wane (lying to) and stay steady in this position with little effort from the helmsman (Of course the masts and riggings also affect this, and later its influents become dominant, but during the discussed period we believe that weather-warning of the hull still was important).

- The highly raised stern castle supposed to move the centre of gravity (CG) aft. To compensate for this and to keep the ship on an even keel, CG of the entire hull needed to be shifted forward. It was achieved by reducing (if comparing with Carracks of same dimensions) of weights of sterncastle by reducing of width and length of several gradually stepped poop decks, while at the same time moving CG of holds with cargo forward (by V-shaped stern and widened fore part of hull with holds). This arrangement (of course together with masts and riggings) moved the overall CG of Galleon to the same vertical line with Centre of Buoyancy CB and brings the ship to even keel (as it was in reality).
- The same stepped decks of a stern-castle with several transversal bulkheads across the deck also limited the spread of sea water on decks [3].
- V-shaped stern with flat rudder, and full-body wide bow together compliments to directional stability, when free drifting backward with some speed during the storm.
- The height of the forecastle was significantly reduced (early Carracks have it nearly same as sterncastle) to improve sailing - the high forecastle, catching the wind ahead of the mast, could have the effect of pushing the bow to leeward, making it difficult to sail close to the wind.

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Now it can surely be said that the high and narrow stern structures were a lot more than just imposing!

However, in later years, when rigging was improved, when a higher quality of ropes, sails and new sailing techniques allowed ships to survive during a storm using special storm sails - the reliance on the hull for its weathervane feature decreased. The military role of stern-castles also become less important due to the development of firearms, when boarding as the principal naval tactic was replaced with the destruction of ships by gun-fire. Thus, highly raised stern-castles were gradually reduced and then eliminated on ships in the 18th - 19th century.

4.2. Wide circular midship section, with tumblehome boards and narrow decks

Many available original drawings of midsections of ships from 16-18th century show the midship sections sized to fit a circle (see, for example, extract from *Souvenirs de Marine,1882* [12] (**Error! Reference source not found.**) or illustrations from William Sutherland's *The Shipbuilders Assistant*, of 1711 [13]). It can be assumed that this was done for good reasons:

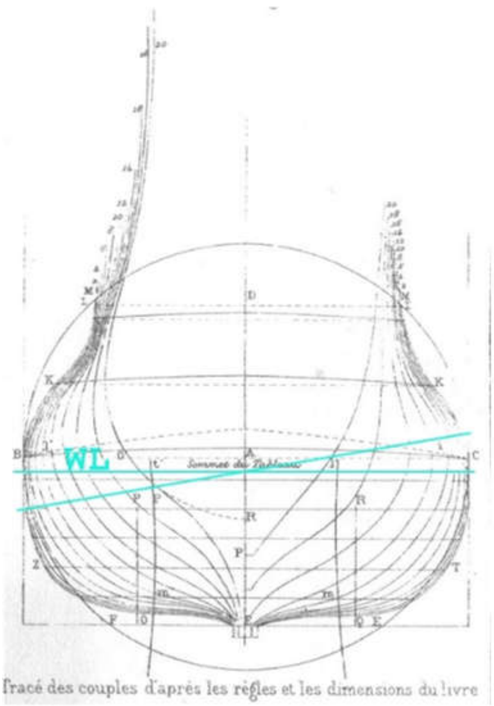

Figure 5. Man-of-war 'La couronne', France, 1632, Souvenirs de Marine [12] from the public doma.in

Figure 6. John Benson- Spanish galleon at sea. https://commons.wikimedia.org/wiki/File:John_Benson_spanish-galleon.png.

- Most of the time, the sailing ships moved in inclined/heeled positions (**Error! Reference source not found.**) due to wind force [14]. Therefore, it is important for a ship to keep the same performance at any practical angles of heel. Seafarers have noted that ships with rounding (or close to round) midsection and reducing the width of upper decks (tumblehome boards) demonstrate better seagoing capability. It was implemented first in the Carrack, then in Galleon's design. From a modern point of view, this allows keeping the waterline area (and therefore, to a certain extent, the hull resistance) unchanged at any angle of heel. This also reduces yawing when moving due to the relative vertical sectional symmetry of the inclined hull. For the same reasons, the sporting yachts today still using round midsections.
- Wide waterline provides an excellent initial transversal stability for this ship. However, early sailing ships did not need big, wide decks - they did not hold any cargo on deck or placed any turrets, machines, or superstructures there. Stability concerns also did not allow for the use of big guns at the higher deck's elevation.
- Tumblehome boards reduce area of upper decks, therefore reduce its weight (compare with vertical boards). Reduction of upper weights contribute to stability, at the same time those also saves on the materials (wood), and that reduces the total cost of construction (compare with Carrack) [13].

We know that from 1560 till 1590 English shipwrights (Peter Pett, Mathew Baker, and others) have experimented with Galleon's size and proportion and have discovered that increasing of the length-to-beam ratio over 3.0 was not efficient [2]. However later in 17th century, this ratio was increased to 4.0 [2], and for sailing ships of 19th century up to 6-7 [15], because of the development of new building and sailing technologies.

So, when shipbuilders learned how to build longer and narrower sailing ships, they noted that effect of changes in widths/WL area on resistance and manoeuvrability for such vessels became less substantial – this round midsection with tumblehome boards become less critical and have been replaced with more modern midsections on the ships of the 19th-20th century, designed for more economical criteria.

4.3. Full body round bow with extended beakhead

Our ancestors were aware of the effect of water resistance on the hull – to understand this, it is enough to look at a bow of Galley, designed for speed under rowing (*ERROR! REFERENCE SOURCE NOT FOUND.*).

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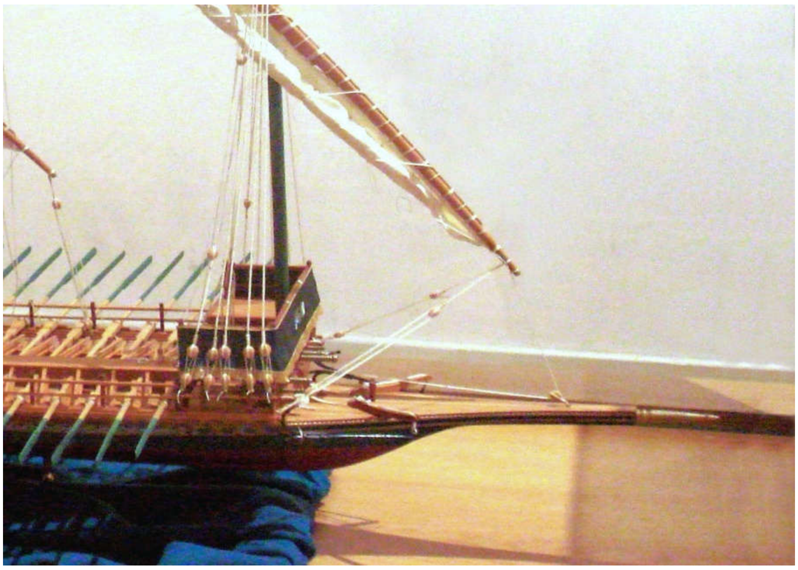

Figure 7. Ottoman Imperial Galley.

The water resistance was crucial to them (each oarsman on her can feel it!) - therefore she was made long, slim, and sharp-nosed. In modern terms she has a small *slope angle* (the angle formed by the centreline of the vessel and the tangent to the design waterline at the forward perpendicular) and as a result, her *Form resistance* was low. However, the capacity and the storm survivability of a Galley was less of a concern since the areas of war Galley's operation were mostly coastal. And all attempt to develop the Galleass- (ocean-going ship from galleys) was not very successful [6] [2].

For an early Galleon (same as for her predecessors), with her unlimited navigation in open oceans, the survivability in harsh condition of open seas was a priority when designing a hull. These ships also needed to have the cargo capacity, to be healthy and well-armed, and they needed to be comfortable for their officers and essential passengers.

Speed was a less critical factor for these ships- even in 19th century the average travel speed (speed from port A to port B) during long ocean voyages was more dependent on wind direction and force. The effect of the shape of the hull on this travel speed was insignificant and, at that period most probably was not a priority. Indeed, for the galleons, which quite often used trade winds as assistance, and made just a single journey to and from the New World each year - the hull resistance was the lesser concern.

From the forms of Galleon (see *ERROR! REFERENCE SOURCE NOT FOUND.*) we can assume that the fullness of bow contributed significantly to the ability of ship to scend ("to climb") on waves. Besides, the waves attack the ship's bow already partially broken by well-developed beakhead, the skeleton shape of which is correctly managed to do that. Those together reduced *'green water'* on deck (prevented wave rolling over the deck of the ship) and therefore, improve the seagoing ability of Galleon. At the same time, the bow of Galleon develops significant *Form drag/resistance* when move, which obviously was considered as acceptable compromise.

Figure 8. Bow of typical Galleon (model).

With that in mind, we can assume that initially the Galleon was designed more for survivability, rather than for speed. But we need to admit that for contemporary ships even an early Galleons were reasonably fast (fasted then Carrack of same size).

However, in later years, when warship's maximum speed became crucial for battles, when merchants have started to compete for faster delivery (Great tea racing, etc.), when ships and rigging became more robust, and ocean travel become routine -the survivability was less of concern, and the new requirements for better ship's hull forms were developed with more significant concern for lower resistance.

During the last half of the eighteenth century, the first serious application of mathematical theory to the design of ships was developed. The Euler, Bernouilli and Borda had experimented with fluid resistance and floating bodies which made possible an improvement in hull forms. Books such as Af Chapman's *Architectura Navalis Mercatoria* (1768) [16], Mungo Murray's *Treatise on Shipbuilding and Navigation* (1754) [17], and the Jorge Juan's *Examen Maritimo Teorico Practica* (1771) [18] were proof that science was beginning to influence shipbuilders. The gap between theory and practice, between the discoveries of mathematicians and the rule-of-thumb traditionalism of shipbuilders, become narrower.

Those allow to develop new technology in hull construction and to design a new type of ships, which leads to creation in 19 century much more advanced hulls of sailing ships.

5. Comparative analysis of the typical hulls of a Galleon and a sailing ship of 19 century

5.1. Selection of ships and methods

The main goal of calculations in current chapter is to verify the assumptions from previous chapter by direct calculations and comparison of some features of hull of Galleon vs hull of more modern sailing ship.

A lack of reliable information about the ships of 16th century was a limitation in calculating accurate response characteristics of a Galleon. More than that, the accuracy of evaluation of seakeeping performance, in general, is known to depend on the tools and methods of computations, on the selected environment (wave spectra), parameters and coefficients. Therefore, instead of calculation of actual parameters, it was decided to compare *relative* characteristics of hull's forms of two different ships being subjected to same arbitrary conditions (environment, spectrum, mathematical methods and coefficients, assumptions, etc.), identical for both ships and adopted for comparison only. This way, it will also be possible to obtain a better visualisation of the results of the calculation.

There are not many surviving Galleon hulls, and most of the available Line plans are more or less accurate reconstructions. So, for this study, the hull of a Swedish galleon *Vasa* was selected as the only surviving intact hull which was available for measuring. *Vasa* (or *Wasa*) is a Swedish warship built between 1626 and 1628 (**Error! Reference source not found.**). The ship capsized and sank on 10 August 1628. It has been salvaged with a largely intact hull in 1961, and from 1988 it was housed in the *Vasa* Museum in the Royal National City Park in Stockholm [19] [20]

Vasa is not the best example of shipbuilding, since she capsized after sailing into its maiden voyage under a slight gust of wind due to a lack of stability. It happened because the builders used standard shapes of the hull for increased sizes and loads required by the client. However, in our case, we are not concerned about loads. Therefore, it is believed that those drawings of Vasa could be used for comparison of hull's features only if her CG will be corrected and second deck gun ports ignored (as added to its design after construction was started) [19].

Figure 9. Model of *VASA* from http://modelkitsships.name/2017/11/vasa-1628.

General characteristics of Galleon *Vasa* (https://www.abc.se/~m10354/publ/vasa.htm):

Displacement: 1210 tonnes
Sparred length: 69.5 m (228 ft)
The length between perpendiculars: 47.5 m (155.8 ft) including beakhead
Beam: 11.6 m (38 ft)
Height: 52.5 m (172 ft)
Height of the aftercastle: 19.8 m (65 ft)
Draft: 4.8 m (16 ft)
Propulsion: Sails, 1,275 m^2 (13,720 ft^2)
Crew: 145 sailors, 300 soldiers
Armament: 64 cannons (were 48 of 24-pounders)
Capacity (inside volume) 700-900 m^3

An additional complication is that the available Line Plans of *Vasa* (**ERROR! REFERENCE SOURCE NOT FOUND.**) are not of high quality and therefore had to be slightly adjusted/faired. As a result, used here model is not an exact representation of *Vasa*, but rather an expression of some typical galleons of that period, based on available Line Plans of *Vasa*. However, all key features of the hull and all the hull's coefficients have remained unchanged.

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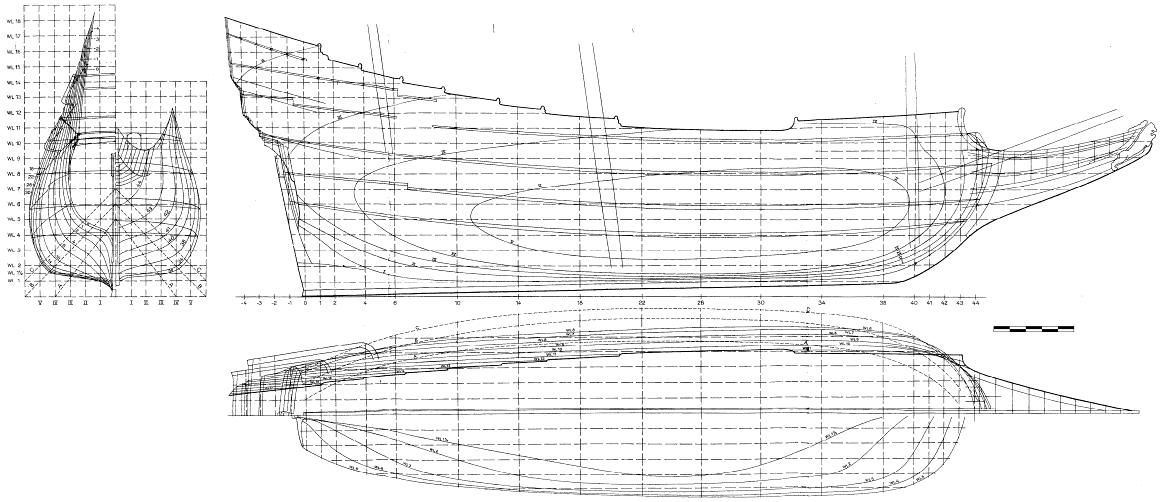

Figure 10. Lines Planes of galleon Vasa, 1628. https://forum.game-labs.net/topic/4220-wasa-1628-swedish-warship-with-plans.

There are many diverse types of Galleons of other countries/different builders are known, but for the purpose of this article the only main/ most distinctive and common features of Galleon's hull are essential- therefore we believe that conclusions, obtained from Swedish *Vasa,* could be extrapolated (with a certain level of accuracy) to any Galleon.

As a second hull for comparison, a more modern ship - The German Barque *Albert Neumann (1869)* - was selected because of availability of its Lines Plans (***ERROR! REFERENCE SOURCE NOT FOUND.***) in library and because the hull of this Barque represents one of the typical hulls of merchant and fast naval ships (*FIGURE 12.*) of 19th century [21]. Such hulls become standard and were in use up to middle of 20 century.

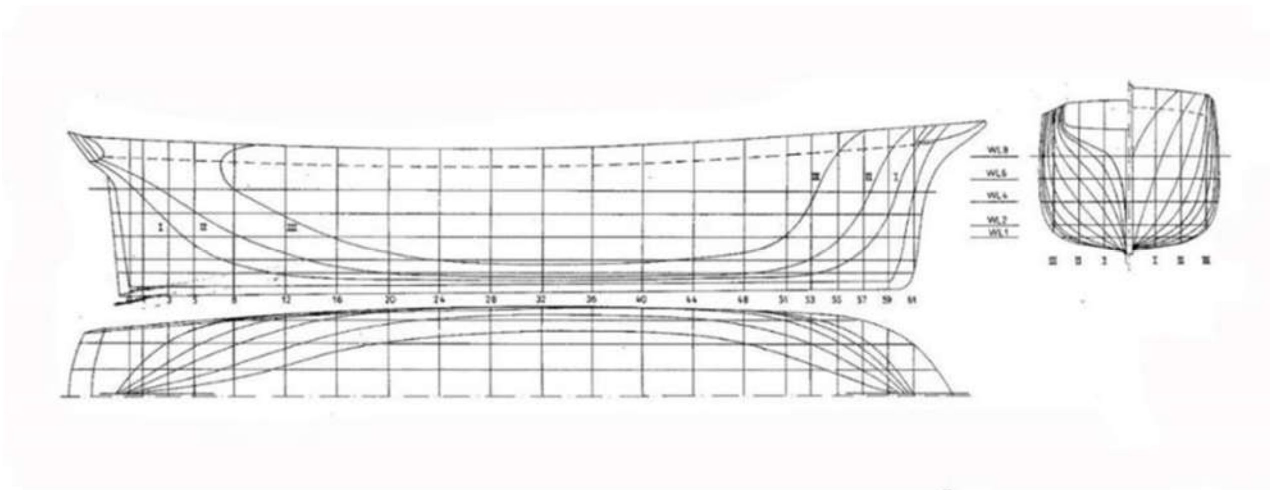

Figure 11. German Barque *Albert Neumann*, commissioned in Warnemünde/Rostock in 1869). Free image from http://www.shipmodell.com/index_files/0PLAN1E.html.

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Figure 12. Model of HMS_*Hyacinth*, (https://www.rmg.co.uk/collections/objects/rmgc-object-65972) free image from National Maritime Museum, Greenwich, London.

An original Barque was significantly bigger in size than selected Galleon. To allow accurate comparison, the 3D model of a real-size Barque was created and then it was parametrically adjusted (automatically scaled down using MAXSURF software) to the sizes of Galleon (see ERROR! REFERENCE SOURCE NOT FOUND.). The equal displacement (with Galleon) was selected as a parameter for adjustment - this allows to hold constant all coefficients (and shapes of a hull) of the original vessel without distortion. This way, it will be possible to compare the results of calculations for both ship's hulls 'apple-to-apple' - with a sufficient level of accuracy.

Table 1. Parametric adjustment of Barque's hull.

	Original Barque	**Modelled Barque**
Displacement tonnes	3291	1260
Draught m	6.6	4.8
WL Length m	63.5	46.18
Beam max extents on WL m	12.4	9.04
Wetted Area m^2	1192.31	618.44
Waterplane Area m^2	626.38	331.93
Prismatic coefficient (C_p)	0.679	0.679
Block coefficient (C_b)	0.614	0.614
Max Sect. area coefficient (C_m)	0.904	0.904
Waterplane area coefficient (C_{wp})	0.795	0.795

We would like to emphasize that we are not compare two ships in this paragraph- but rather compare only shape of their hulls. The goal of calculations here is to evaluate the influence of shapes (only!) of two hulls on performance.

The position of centre of gravity CG is unknown and depends only on loading – which is out of scope of this paragraph. Therefore, the assumptions about position of CG (same for both hulls) were used here.

The drafts and total displacements of both models were calculated up to design waterline from drawings, which provide us with realistic data for both models.

The height of metacentre KM is a function of hull's shape and was calculated from Lines Plans also.

To keep the models on even keel, the longitudinally and transversally CG of both models were allocated on the same vertical line with CB, also calculated from Lines Plans.

The position of vertical CG for both models could not be obtained from any historical source and (for the sake of comparison only) were assumed for both hulls at 1/2 of vessel depth at midship (in the middle of "theoretical" hold between upper deck and bottom), which could be realistic for Galleon (with full holds and all heavy guns on and below the upper deck), as well as for Barque with loaded holds.

The distribution of those arbitrary loads along the ships were taken in account by using of radiuses of gyration- defined by the standard (and same for both hulls) methods.

For a discussion about the hull's forms (only) those assumptions were considered as acceptable.

Both hulls were modelled in MAXSURF software (*FIGURE 12.*), using the same method of modelling and computation. The results are presented numerically (***ERROR! REFERENCE SOURCE NOT FOUND.***) as well as graphically for better visualisation of the differences.

Table 2. Comparison of two models.

	Model of Galleon	Model of Barque
Displacement t	1261	1260
Draft at LCF m	4.8	4.8
WL Length m	43.384	46.18
Beam max on WL m	11.55	9.036
Wetted Area m^2	633.1	618.44
Waterplane Area m^2	416.2	331.9
Prismatic coeff. (Cp)	0.727	0.680
Block coeff. (Cb)	0.514	0.614
Max Sect. area coeff. (Cm)	0.790	0.904
Waterplane area coeff. (Cwp)	0.832	0.795
KB m	3.14	2.74
KG m	5.5	3.56
GMt m	0.69	0.672
GML m	36.84	35.50
KMt m	6.19	4.232
KML m	42.34	39.06

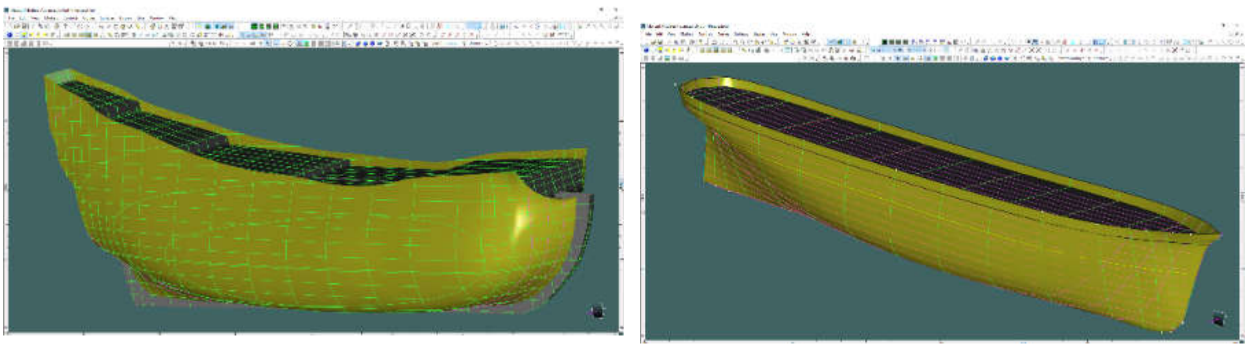

Figure 13. Image of 3D models of Galleon and Barque.

The parameters, which we would like to compare, are as follows:

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1. WL area on calm waters at different angles of inclination.
2. Water resistance of hull on calm weather as a characteristic of hull's form.
3. Locations of CW, CLR and CB as representation of weather waning effect.
4. A characteristic of ship's motions – Natural period of oscillation and Response Amplitude Operators (RAO) for Heave and Pitch on Poop deck and Forecastle deck on head seas/ RAO for rolling at CG of vessels on beam seas.
5. Deck wetness parameter on forecastle/bow deck (at 0 speed) and Motion Sickness Incidence (MSI) parameters on poopdeck/quarters and forecastle deck as an indication of the seagoing ability of the ship.

5.2. Initial Hydrostatics

As it can be seen in ERROR! REFERENCE SOURCE NOT FOUND. (& APPENDIX 1 TABLE 1), the compared ship's models have the same displacement (1260 tonnes) and draft (4.8m), close length (43.38m vs 46.18m), but a different beam of ship (11.55m vs 9.04m). Those happens due to different shape coefficients of the hulls.

Length-to-beam ratio was also different: for the Galleon it is= 3.76, and for the Barque=5.11; this makes the Barque much better "runner".

The height of transversal metacentre KM_t =6.19m for the model of Galleon is bigger than the KM_t=4.23m for the model of Barque. This is a result of a broader and shorter hull of the Galleon.

Both calculated GMs are positive and close in value. However, investigations about loadings of ships and their stability are beyond the scope of this article.

5.3. Inclined properties

As expected, the inclined waterplane area A_{wl} of the Galleon is nearly constant at heel from 0 to 20 degree, but for the Barque, the A_{wl} is increased on these angles (see ERROR! REFERENCE SOURCE NOT FOUND. and ERROR! REFERENCE SOURCE NOT FOUND.).

Table 3.

Heel to Starboard, degree.	0	5	10	15	20
Waterplane Area, m^2 - Galleon	416.2	416.1	415.9	415.7	415.6
Waterplane Area, m^2- Barque	331.9	333.1	336.3	341.2	348.6

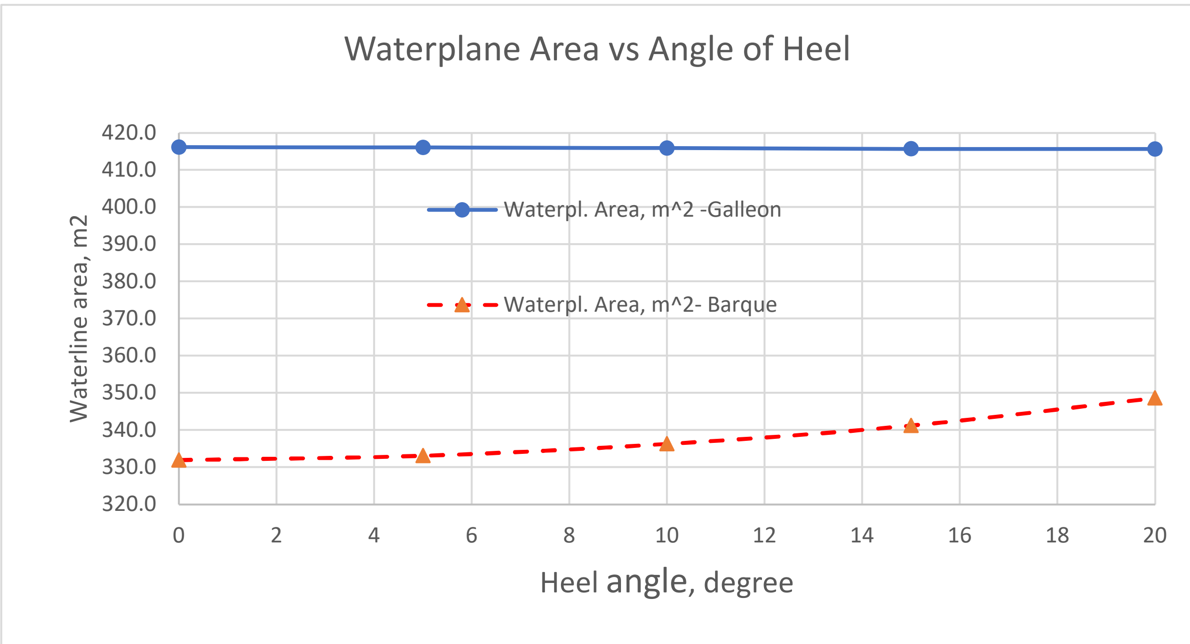

Figure 14. Waterplane area vs angle of heel.

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The same can be observed in

, which shows WL of both models at a 20-degree heel.

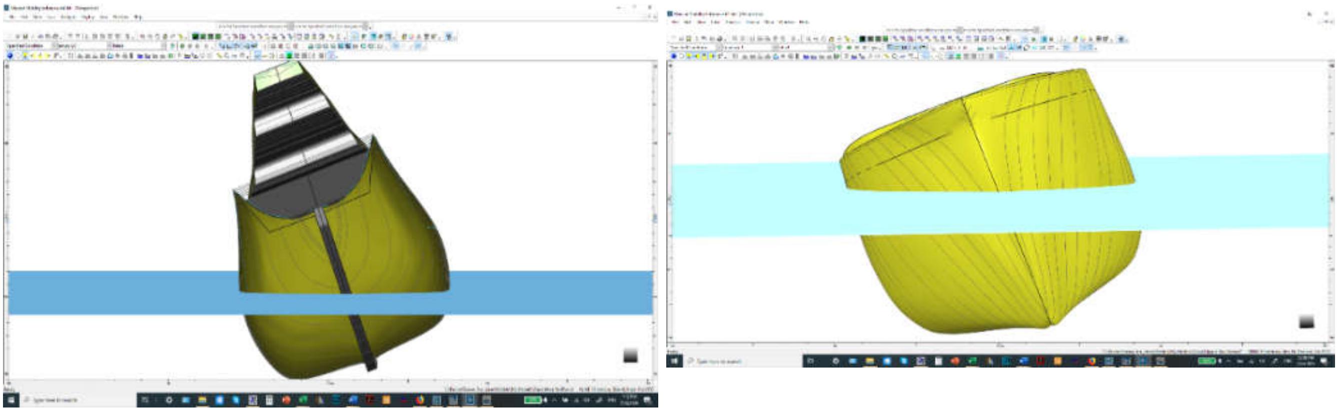

Figure 15. Inclined (20 degree) hulls view for Galleon (left) and Clipper (right).

5.4. Calm Water Resistance

As expected, the overall resistance of a Galleon was significantly higher than the resistance of a Barque (*Error! Reference source not found.*) (it should be noted here, that this is not only because of blunt full-body bow- there are a number of another factors involved, such as friction, viscous pressure, air resistance, etc.). For comparison, two methods of calculation have been selected: *Compton* for fast displacement hulls, and *van Oortmerssen* for full form hulls. Both are not exactly accurate with used models, but we are not interested in absolute results. Both models were tested with identical parameters, and this approach is sufficient to demonstrate the clear advantage in lower resistance of a Barque's hull. Unfortunately, it was not possible to calculate the inclined hull's resistance on MAXURF software to understand how this feature (inclination) affected the ship's performance.

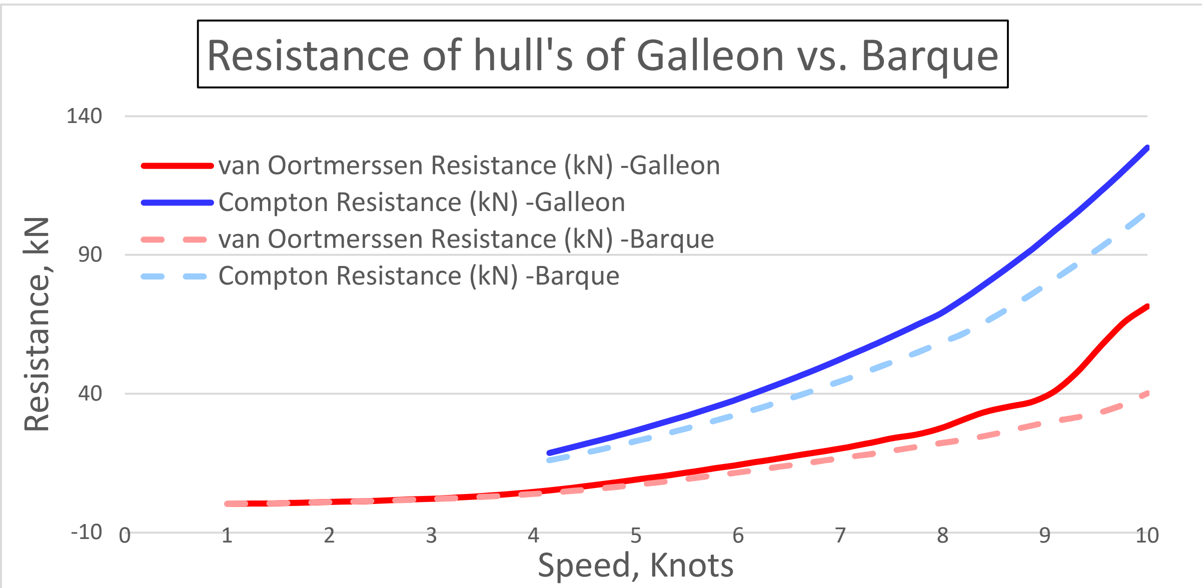

Figure 16. Comparison of hull's resistance of Galleon vs Barque.

5.5. Windage

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Centre of wind force application CW (here LCW=18.31m) of the Galleon (see) is located aft from the centre of lateral resistance (LCR=20.28m) for 1.97m, and for 3.64m from LCB=21.92m. This confirms the assumption that under wind pressure, the hull will be subject to turning moment and would start to weathervane.

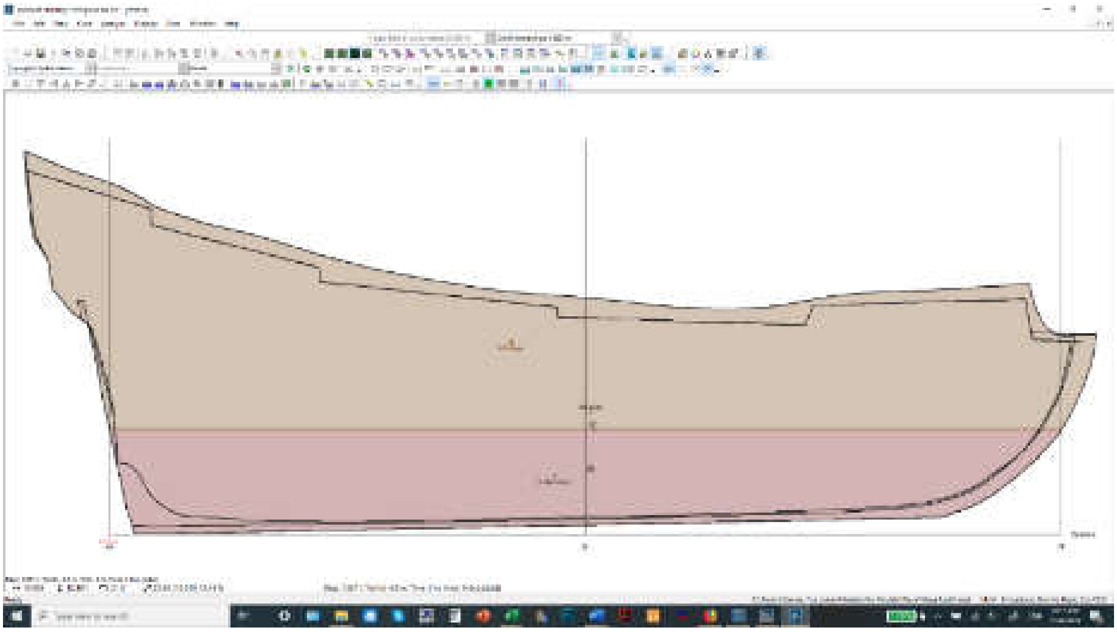

Figure 17. Lateral windage/ Drag areas of Galleon .

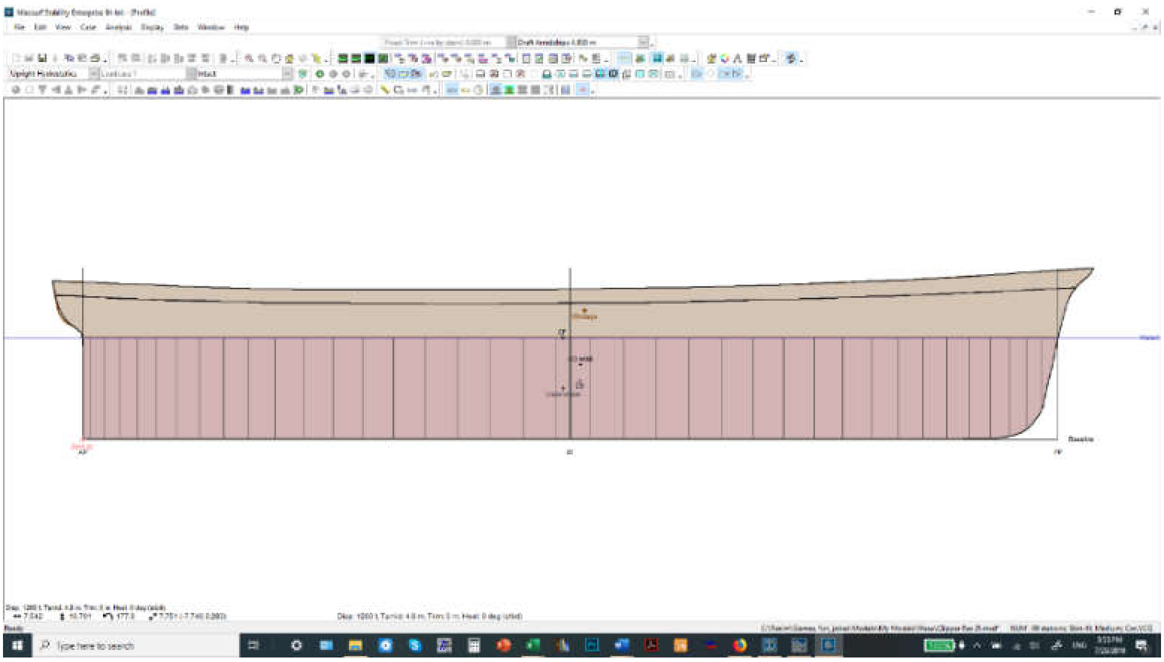

Figure 18. Lateral windage/ Drag areas of Barque.

For Barque longitudinal CW (LCW=23.776m) is located slightly forward of mid-section (see **Error! Reference source not found.**), and forward of the centre of lateral resistance CLR. This effect is because the bow is raised for better seakeeping (if comparing with a flat-deck bow). It is clear evidence that highly raised sterncastle with weather-waning effect of the hull was no longer a requirement.

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5.6. Natural period of oscillations

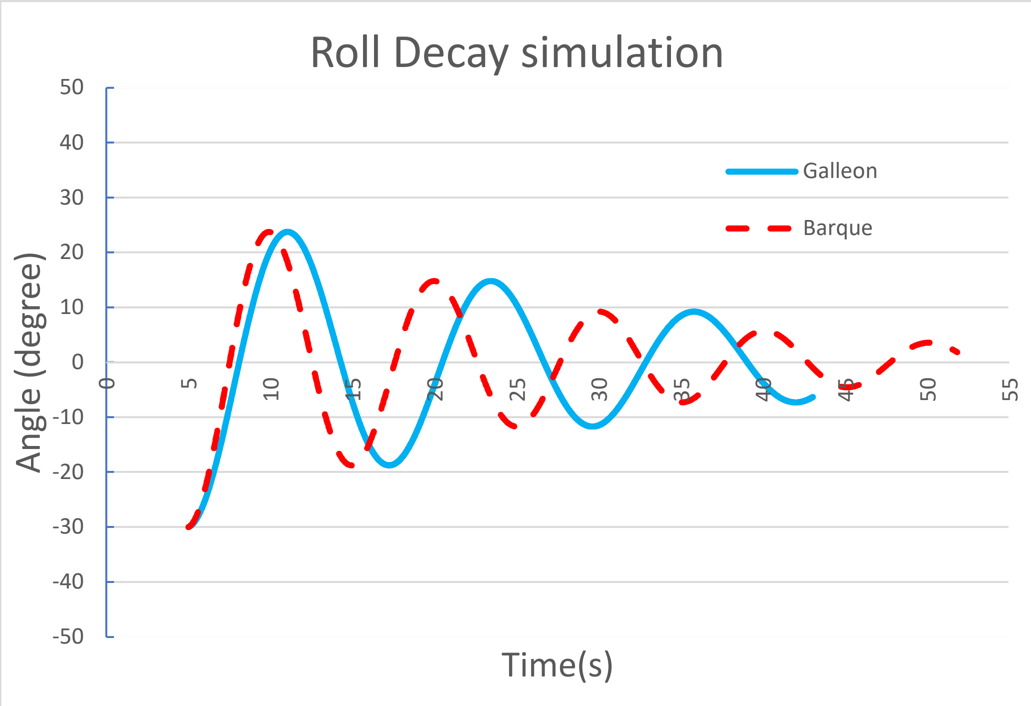

Figure 19. Roll decay simulation diagram Galleon vs Barque.

Roll Decay Simulation is defining the period of natural oscillations (rolling) of ship on calm water. In the studied case, the diagrams shown on the *FIGURE* are results of simulation of roll decay on MAXSURF (at the limitations described above). And the calculated average natural periods of rolling were:

Galleon Tφ,av=12.7 sec (peaks)

Barque Tφ,av=10.05 sec (peaks)

So, considering that draft and GMt of both models are nearly equal, we can see from *FIGURE* that Damping coefficients for both vessels are very close. Still, the natural period of the described hull of Galleon is higher than of a Barque.

Therefore, *cet.par*. (lat. *ceteris paribus*- "when all other things being equal"), accelerations on a Galleon could be lower (for verification, see below in *SECT. 0*), making the Galleon more comfortable for the crew (as mentioned in 0, those describes the influence of hull form only, without effects from loading.)

5.7. Motion characteristics

For all response calculations, the Panel method has been used - a zero speed 3D first-order diffraction/radiation hydrodynamics solver in the frequency domain. It performs linear analysis of the interaction of surface waves with floating structures. The panel method is valid for an extensive range of geometries but is restricted to zero forward speed. Considering that the goal of this paragraph is to compare two hulls under identical arbitrary conditions, the hulls' response has been calculated for the following conditions (for both ships):

- JONSWAP spectrum with characteristic significant wave height 5m (zero crossing period 7.847s, peak enhancement factor 3.3) was chosen for the calculations.
- Wave heading 180 degrees (head seas) and 90 degrees (beam seas).
- Frequency range was limited to most effective - from 0.2rad/sec to 3rad/sec.
- Vessel sailing speed of 0 knots was assumed, to simulate free drifting during a storm.

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- 3 Locations on each vessel were selected for comparison - at CG of a ship, on the Poopdeck and Bow/Forecastle deck (defined as actual deck points at centreline).

This way the behaviour of both models during a storm survivability mode can be simulated and compared "apple-to-apple". The resulted identification of parameters in different motions, as well as the ratio of Galleon/Barque are shown in *TABLE 2* (see *APPENDIX 2*)

5.7.1. Response Amplitude Operators (RAO)

The *ERROR! REFERENCE SOURCE NOT FOUND.* shows RAOs for location at CG of a model for the Galleon and the Barque, for beam seas (90 degrees).

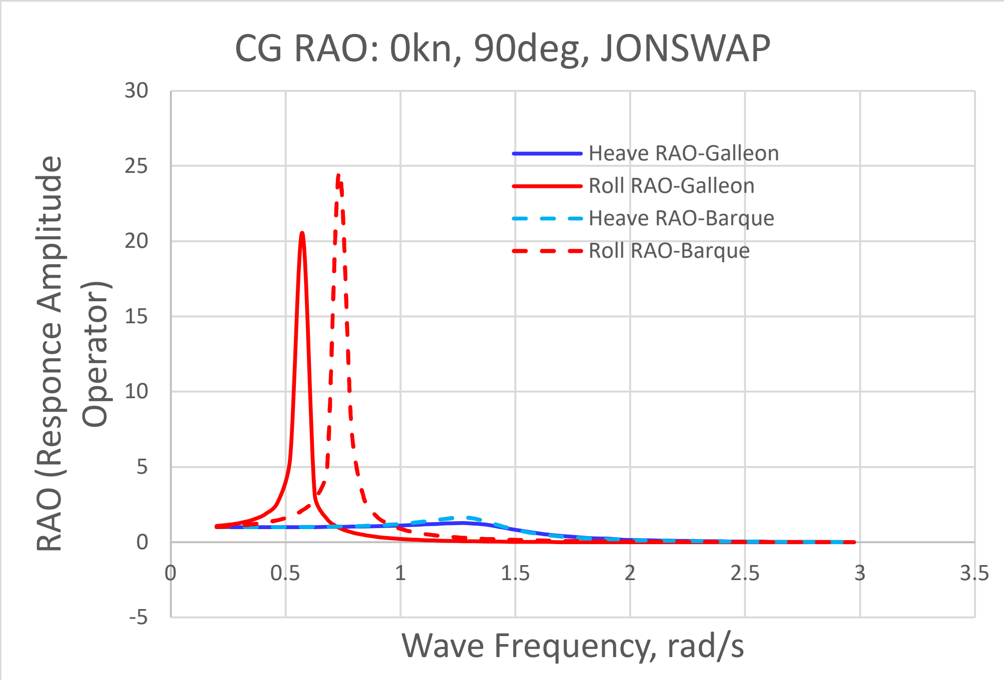

Figure 20. RAO for location at CG of ships, for Beam Seas (90 degree) seas.

The *ERROR! REFERENCE SOURCE NOT FOUND.* shows a comparison of RAOs for location at CG of a model for the Galleon and the Barque, for head seas (180 degrees).

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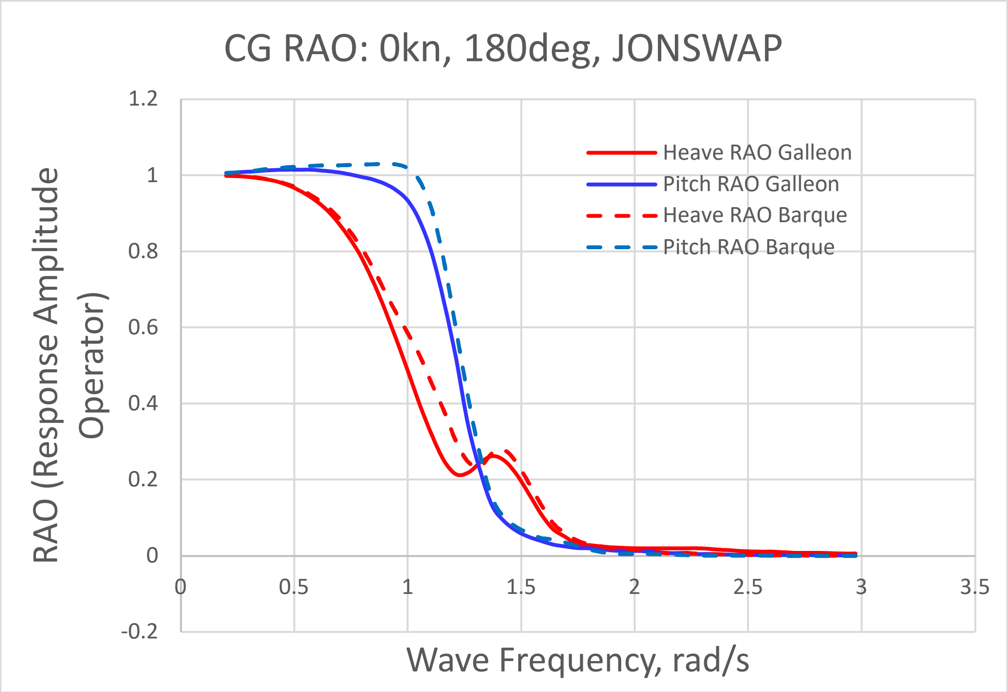

Figure 21. RAO for location at CG of ships, for Head seas (180degree).

The *ERROR! REFERENCE SOURCE NOT FOUND.* shows RAOs for location at Poopdeck point on the Galleon and the Barque, for head seas (180 degrees).

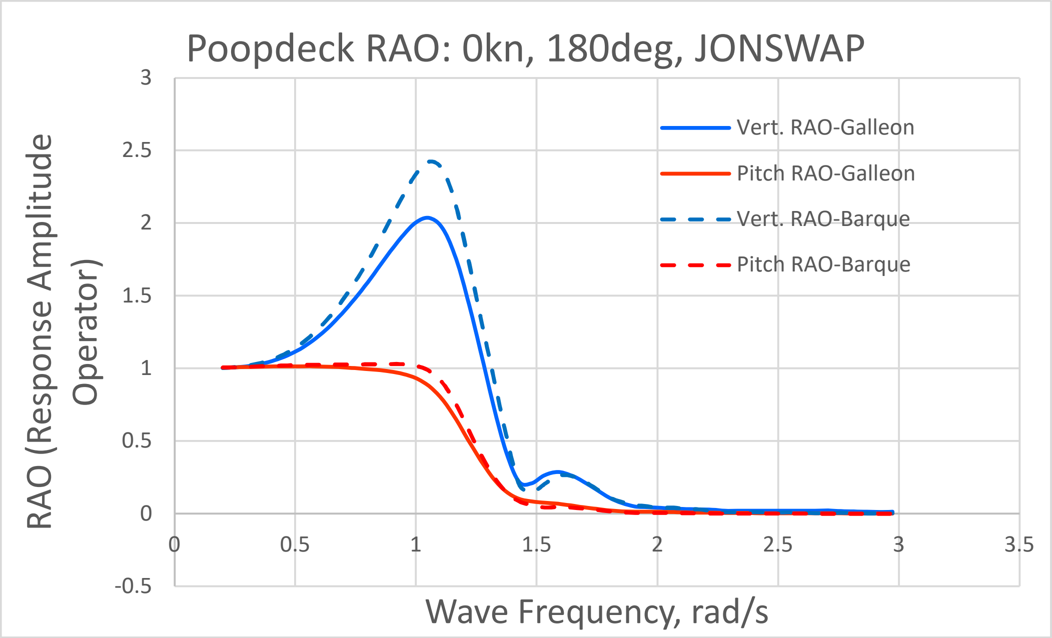

Figure 22. RAO for location at Poopdeck of ships, for Head seas (180degree).

Diagram below (*ERROR! REFERENCE SOURCE NOT FOUND.*) shows RAO for location at Bow/Forecastle deck point on the Galleon and the Barque, for head seas (180 degrees).

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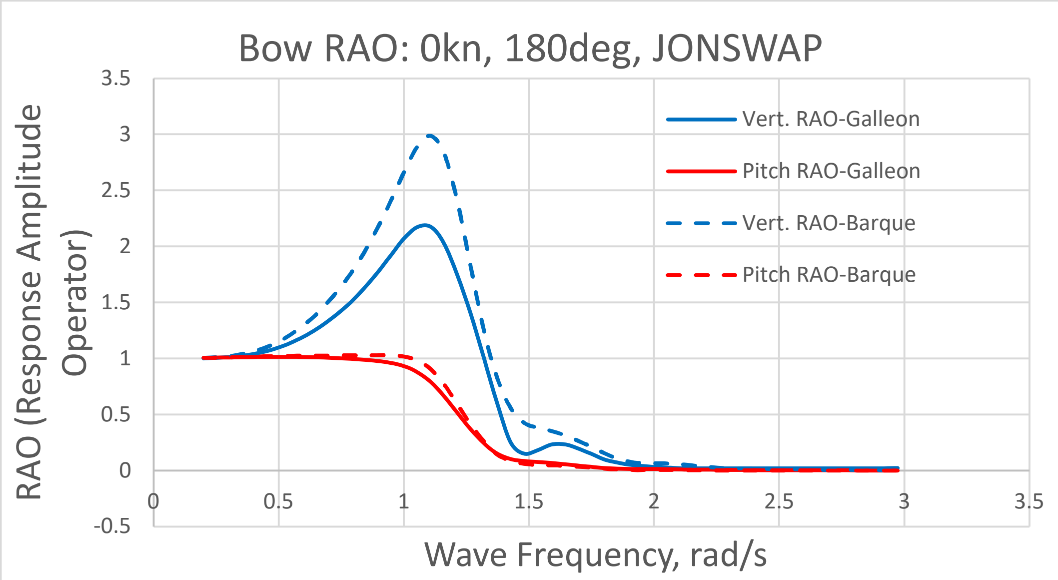

Figure 23. RAO for location at Bow /Forecastle deck point of ships, for head seas (180 degree).

The comparison of above diagrams indicates that hull of Galleon (*cet. par.*) at 0 sailing speeds could have lower responses than Barque, for head (180^0) and beam (90^0) seas.

5.7.2. Deck wetness parameter

Deck wetness can be estimated by comparing the relative vertical bow motion with freeboard of bow.

For forecastle deck of Galleon, the relative vertical bow motion=1.89m and freeboard at forecastle deck =6.07m (see *Table 2 & Appendix 2*). Therefore:

For bow deck of Galleon 1.89m/ 6.07m = 0.31

For bow deck of Barque 2.96m/3.3m= 0.89 (see Table 2 & Appendix 2).

The hull of Galleon, due to a higher deck and lower response, could have a better Deck wetness parameter and therefore, improved survivability.

5.7.3. Motion Sickness Incidence (MSI)

MSI is a measure of an individual's ability to complete a specific task (without seasickness) while on board of moving ship. MAXSURF MOTIONS calculate the MSI accelerations (see *Table 2 & Appendix 2*), according to the *McCauley et al. 1976* formulation, which includes an exposure time (120 min).

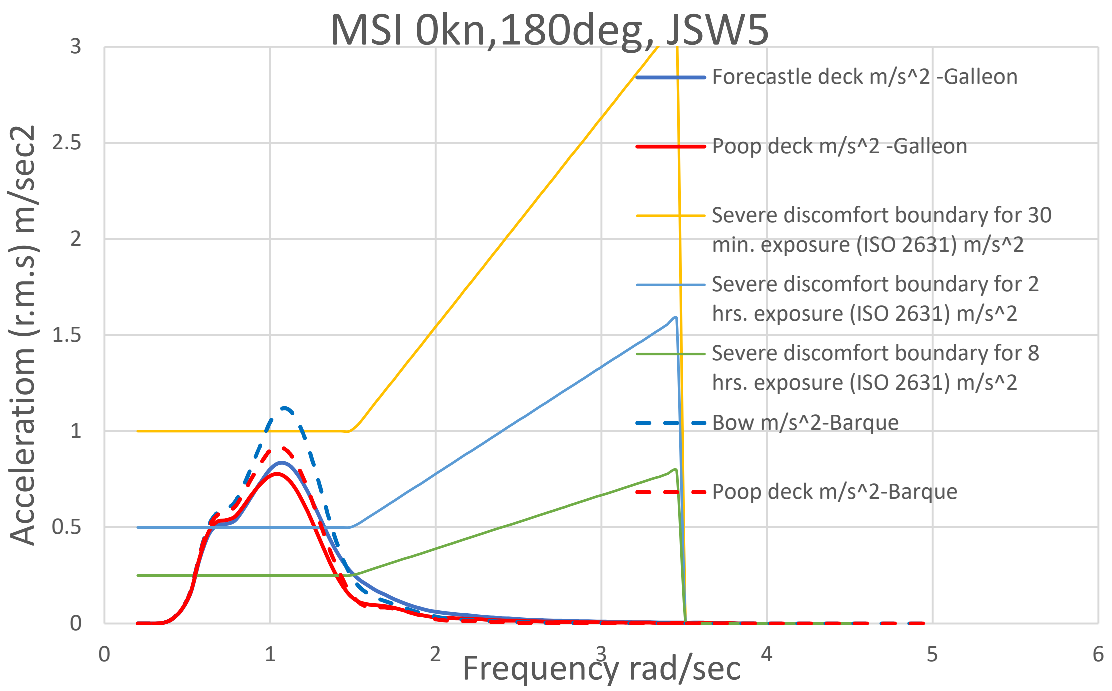

Figure 24. Motion Sickness Incidence diagram.

It is apparent in ERROR! REFERENCE SOURCE NOT FOUND. that the hull of Galleon could have (*cet.par.*) a better (lower) parameters and will be slightly more comfortable conditions on board than the hull of Barque of same dimensions.

6. Observation and Discussion

The conclusions here are based on modern understanding – it is not believed that ancestors knew all these features as described and purposefully accounted for them. However, ancient seafarers and shipwrights observed and evaluated the behaviour of a ship because of changes in hull forms. As a result of accumulating such observations and 'trial-and-error' methods of optimisations, they have developed the hull of a Galleon in the 16th century that was perfectly suited for all their current needs. The critical conditions at the time that led to a Galleon's development were:

- Available shipbuilding technology of that period.
- Existing sailing technology (sails, masts, riggings, etc.) and sailing practice.
- Required unlimited area of exploitation (and therefore distinctive storm survivability of a ship, and sea endurance/autonomy of ships).
- Practical efficiency in terms of cargo-carrying and enemy-fighting ability.
- Tactics of naval battles of that time

Across all analyses, it was found that the Galleon's hull was designed, or otherwise inherited that design from her predecessors, with significant emphasis chiefly on seagoing ability. After all, early in the 16th century, sailing across oceans was a hazardous business, and it appears that some other features were considered of less importance. Thus, using our modern knowledge and tools, we can affirm that the shape of the Galleon's hull has satisfied the below characteristics:

- Due to a highly raised sterncastle, the hull of a Galleon (without sails) under wind pressure was subject to turning moment/weathervane bow to incoming seas - a feature which improved its survivability during heavy storms.

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- The hull of Galleon in general could provide lower motion responses (RAOs) than the Barque of same dimensions, and therefore could have improved motion characteristics and better seagoing ability.
- The full and round bow of the Galleon provides the improved ability to ascend on waves, notwithstanding that it increases resistance.
- The well-developed beakhead allows breaking incoming waves, improving seagoing ability.
- Due to a high decks and low responses, the Galleon had a better deck wetness parameter and therefore, was safer at sea.
- The rounded midsection and tumblehome sides kept waterplane area of a Galleon constant on angles of inclination of at least up to 20^0 heels, which could positively affect performance of the ship.
- The wide WL of the Galleon provides her with a bigger height of initial transversal metacentre and therefore increase initial stability. At the same time, the narrowed and shortened upper decks/poop decks/quarter decks reduced its weights and reducing the cost of hull.

By 18th - 19th century, the requirements were changed: development of new technologies allow to build bigger, longer, and more substantial ships. The crossing the ocean became a routine trip, and ships were designed with economic and trading efficiency in mind, with much less concern for survivability and comfort. This was where the ships with more modern hulls (like discussed Barque) excelled. Such ships were a culmination of sail shipbuilding, accumulated all developments in hull shapes during past centuries. Such modern hulls gradually replaced the old traditional hulls in the 18-19th centuries. And their hulls later were smoothly transformed into hull we are still using today.

7. Conclusion

The result of Galleon's design was so optimal that all European states adopted her as the main fleet unit - both within the merchant navy as well as military. Even today, if we apply the same requirements and restrictions which were valid in the 16th century: i.e. improved ability to climb the wave (ascend); prevention of 'green water' on decks with less concern about speed; required capacity within the limited length; ability to weathervane without using sails (hull only); highly raised battle platforms; permanent symmetrical waterline when inclined; plus all the limitation of available techniques and technologies of that period - we probably will design the ship quite similar to the Galleon.

Galleon was really a masterpiece of shipbuilding technology of the 16th century. She met all requirements and available technologies of those days and continued to be in use till the end of the 18th century (for about 250 years!), when she was replaced with better ships.

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Appendix 1

Table 1 Hydrostatics table

	Model of Galleon	Model of Barque
Displacement tonnes	1261	1260
Draft m	4.8	4.8
Trim m	0	0
WL Length m	43.38	46.18
Beam max extents on WL m	11.55	9.04
Wetted Area m^2	633.08	618.44
Waterplane Area m^2	416.18	331.93
Prismatic coefficient (C_p)	0.745*	0.679
Block coefficient (C_b)	0.566*	0.614
Max Sectional area coefficient (C_m)	0.839*	0.904
Waterplane area coefficient (C_{wp})	0.856*	0.795
LCB from zero pt. m	21.92	23.55
TCB m	0	0
VCB m	3.15	2.74
LCF m	22.04	22.72
TCF m	0	0
VCF m	4.8	4.8
KB m	3.15	2.74
KG m	5.5	3.54
BM_t m	3.05	1.49
BM_l m	39.2	36.322
GM_t m	0.69	0.672
GM_l m	36.85	35.50
KM_t m	6.19	4.23

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KM_l m	42.347	39.061
Immersion (TPC) tonnes/cm	4.27	3.40
MTC tonne.m	11.6	9.14
Righting Moment tonne.m	15.2	14.8
Lateral projected Windage area m^2	328.1	120.3
Lateral projected Windage VCA (world) m	8.75	6.09
Lateral projected Underwater area m^2	178.8	217.9
Lateral projected Underwater VCA (world) m	2.65	2.42

*-without keel beam (software typically includes keel beam in the calculation of areas, which, in case of Galleon, leads to underestimated values)

Appendix 2

TABLE 2 MOTION CHARACTERISTICS SUMMARY- 0 kn; Head, 180 deg; JONSWAP (9.958 s, 5 m)

Ship motions (summary)	**Galleon**	**Barque**		
	Significant values		Units	Ratio G/C
Surge motion	1.98	1.91	m	1.04
Sway motion	0.00	0.00	m	
Heave motion	2.04	2.11	m	0.97
Roll motion	0.00	0.00	deg	
Pitch motion	7.43	7.87	deg	0.94
Yaw motion	0.00	0.00	deg	
Surge velocity	1.33	1.28	m/s	1.04
Sway velocity	1.37	1.43	m/s	0.96
Heave velocity	1.37	1.43	m/s	0.96
Roll velocity	0.00	0.00	rad/s	
Pitch velocity	0.11	0.12	rad/s	0.93

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Yaw velocity	0.00	0.00	rad/s	
Surge acceleration	0.94	0.90	m/s^2	1.04
Sway acceleration	0.00	0.00	m/s^2	
Heave acceleration	0.98	1.05	m/s^2	0.94
Roll acceleration	0.00	0.00	rad/s/s	
Pitch acceleration	0.10	0.11	rad/s/s	0.91
Yaw acceleration	0.00	0.00	rad/s/s	
Forecastle deck: Abs. vert. motion	3.37	4.06	m	0.83
Forecastle deck: Rel. vert. motion	1.89	2.96	m	0.64
Forecastle deck: Abs. vert. velocity	2.69	3.37	m/s	0.80
Forecastle deck: Rel. vert. velocity	2.17	3.14	m/s	0.69
Forecastle deck: Abs. vert. accel	2.43	3.14	m/s^2	0.78
Forecastle deck: Rel. vert. accel	2.95	3.74	m/s^2	0.79
Forecastle deck: Long. (due to pitch) motion	2.61	2.44	m	1.07
Forecastle deck: Long. (due to pitch) velocity	1.84	1.72	m/s	1.07
Forecastle deck: Long. (due to pitch) accel	1.41	1.31	m/s^2	1.08
Forecastle deck: SM	8.15	11.82		0.69
Poop deck: Abs. vert. motion	3.40	3.74	m	0.91
Poop deck: Rel. vert. motion	1.63	2.07	m	0.79
Poop deck: Abs. vert. velocity	2.64	2.98	m/s	0.88
Poop deck: Rel. vert. velocity	1.75	2.12	m/s	0.82
Poop deck: Abs. vert. accel	2.28	2.66	m/s^2	0.86
Poop deck: Rel. vert. accel	2.38	2.66	m/s^2	0.90
Poop deck: Long. (due to pitch) motion	3.18	2.27	m	1.40
Poop deck: Long. (due to pitch) velocity	2.32	1.57	m/s	1.47
Poop deck: Long. (due to pitch) accel	1.86	1.17	m/s^2	1.59
Poop deck: SM	7.33	9.19		0.79

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Appendix 3

Table 3 List of Abbreviations:

Awl	waterplane area, m2
CLR	centre of lateral resistance, m
CB	centre of buoyancy, m
CF	centre of flotation, m
CG	centre of gravity, m
CW	centre of windage area, m
Cb	Block coefficient
Cm	Max Section area coefficient
Cp	Prismatic coefficient
Cwp	Waterplane area coefficient
e.g.	*exempli gratia*- Lat. for example
GM	metacentric height, m
GML	metacentric height longitudinal, m
GMt	metacentric height transversal, m
KB	height of Centre of buoyancy, m
KG	height of Centre of gravity, m
KML	height of Metacentre longitudinal, m
KMt	height of Metacentre transversal, m
LCB	longitudinal coordinate of centre of buoyancy, m
LCF	longitudinal coordinate of centre of flotation, m
LCF	longitudinal centre of flotation, m
LCR	longitudinal coordinate of centre of water resistance (lateral), m
LCW	longitudinal coordinate of wind force application, m
MSI	Motion Sickness Incidence
RAO	Response Amplitude Operators
cet.par.	Ceteris paribus (lat.) - where all other variables are kept equal
SM	Subjective Magnitude
Tφ,av	period of natural oscillations (rolling) of ship on calm water, sec
VCG	vertical centre of gravity, m
WL	waterline

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