Study of the intact stability of a Portuguese *Nau* from the early XVII century

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**ABSTRACT:** Discovered in 1993 at the mouth of the river Tagus, near Lisbon, the shipwreck known as *Pepper Wreck* was tentatively identified as the Portuguese ship *Nossa Senhora dos Mártires*, lost in this place on its return voyage from Cochin, in India, on September 14, 1606. Its archaeological excavation between 1996 and 2000 led to a tentative reconstruction of the ship’s hull form and rigging, based on the archaeological remains and in the Portuguese shipbuilding treatises. The data derived during this reconstruction is now used to study its intact floatability and stability. The floatation characteristics of the ship are determined applying modern naval architecture methods. The displacement and centre of gravity of the ship are estimated taking into account the weights of the hull planking, decks and structure, masts and rigging, guns and ammunition, crew, soldiers and passengers, and the cargo onboard. Finally the intact small and large angle stability of the ship are investigated and compared with modern stability criteria for large sailing vessels.

1 INTRODUCTION

The India Route was the longest commercial route of its time and the vessels that sailed it from Lisbon, Portugal, to Goa or Cochin in the Indian subcontinent, were the largest and strongest of their time. Figure 1 shows a contemporary drawing of a Portuguese ship of the *nau* type, and Figure 2 presents a sketch with the Indian route. The maritime route to India was opened by Vasco da Gama in 1497 and 1498 and during the following centuries the Portuguese ships sailed around the African continent and into the Indian Ocean, loaded with as many as eight hundred passengers and crew, and enormous quantities of precious and exotic merchandises.

Historians have studied extensively the period of the Portuguese expansion, but mainly from the humanistic

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*Figure 1.* Contemporary drawing of a *nau*.  
*Figure 2.* The India route, Castro (2001).
point of view. In fact there is nowadays a good knowledge of the intellectual environment in which these voyages were carried out, the artistic and architectural trends, the fashions in the dressing, etc. More technical issues have also been addressed, such as the difficulties encountered by sailors, the instruments and calculations available to estimate the ship’s position at sea, and the skills of fifteenth century map makers.

However there is presently very little knowledge about the technical characteristics of the vehicles of the Portuguese expansion, meaning the ships of the Age of Discoveries. These ships were built in a pre-industrial era when technical design and documentation procedures almost did not exist and, in fact, their construction relied mostly on practical knowledge and tradition. For these reasons, detailed descriptions of the ships are not available.

The methodology which can now be applied to investigate the technical characteristics of these ancient ships must be based on the analysis of archaeological remains and ancient shipbuilding treatises. This initial investigation work has been done by Castro (2003, 2005b) for a shipwreck discovered in 1993 at the mouth of the river Tagus, Portugal. The shipwreck was tentatively identified as the Portuguese ship *Nossa Senhora dos Mártires*, known to be of the nau type, and wrecked at this site on the 14th September 1606. Its archaeological excavation between 1996 and 2000 led to a tentative reconstruction of the ship’s hull form and rigging by Castro (2001). The information derived during this reconstruction is used here to study the intact floatability and stability of a Portuguese nau applying modern naval architecture methods.

The main aim of this paper is to carry out a study from the naval architect’s point of view of the stability of the *Nossa Senhora dos Mártires* based on the available information. The stability of the ship is studied using modern stability criteria applicable to large sailing vessels. This requires an estimation of the location of the ship’s centre of gravity. This is a particularly difficult task, taking into account that there is some uncertainty regarding the ship’s precise forms and dimensions, wood scantlings, amounts of cargo and passengers, provisions and artillery. After an estimate of all of these has been made, the modeling of the ship’s hull, sail plan, non-watertight openings and weight distribution can be made and the stability criteria applied. This study is considered as the first stage of a larger and more comprehensive naval architecture study of an early XVII century Portuguese nau.

2 RECONSTRUCTION OF THE NAU SUNK AT THE PEPPER WRECK SITE

The archaeological excavation of the Pepper Wreck site, located at the entrance of the Tagus river (shown in Figure 3), revealed part of the hull structure (see Figure 4), namely a portion of the bottom, including a section of the keel, an apron, eleven frames, and some of the planking extending over an area measuring $7 \times 12$ m, see Alves et al. (1998) and Castro (2005a). After analysis these authors concluded that this is the portion of the ship’s bottom immediately forward of the midship frames.

Following this work, a reconstruction of the hull was proposed by Castro (2003) derived from an analysis of the timbers dimensions and carpenters’ marks, helped by a collection of Iberian texts on shipbuilding from the late 16th and early 17th centuries. A number of these texts suggest explanations for both the dimensions and the shipwrights’ marks found on the Pepper Wreck site.

The first text considered was Fernando Oliveira’s *Liuro da Fabrica das Naus*, dating from 1580. The second was an anonymous list of the timbers necessary to build a three-decked, 600-ton nau for the India route included in the *Livro Náutico*, a codex of Lisbon’s National Library, dating from the 1590s. The third was the manuscript titled *Livro Primeiro da Arquitectura Naval*, by João Baptista Lavanha, written sometime around 1610, which includes two contracts for the building of India nau by two well-known shipwrights, Valentim Loureiro and Gonçalo Roiz, dating from
1598. The fourth was Manoel Fernandez' Livro de Traças de Carpintaria, dated to 1616.

When checked against the measurements found on the Pepper Wreck, the model proposed by Fernando Oliveira seemed to fit fairly well, if this was a nau of 18 rumos of keel (27.72 m). The unit in Portuguese shipyards of the late 16th and early 17th centuries was the rumo (1.54 m).

Once Oliveira's model was chosen for the bottom of the vessel, the preserved portions of the frames could be placed over the body plan of the lines drawing and faired. The remaining hull was then reconstructed from the list of proportions supplied by Oliveira. The reconstructed lines plan is presented in Figure 5 and the main particulars in Table 1.

### 3 CALCULATION OF THE CENTRE OF GRAVITY

The displacement of the ship has been subdivided in a number of components: hull, masts and yards, sails, rigging (shrouds, etc), anchors and ship's boats, artillery, ballast, cargo, crew, soldiers, passengers and supplies.

The hull of the ship, shown in Figure 6, has been estimated to weight 398 t according with the hull structure description given by Castro (2001). An extensive list of components, comprising the hull planking, decks and structure, was identified together with their individual weights and positions of the centre of gravity. The various types of wood were also considered. The hull's centre of gravity has been estimated to be located 18.0 m forward of the aft perpendicular and 5.9 m above the baseline.

The weight of the masts and yards has been estimated by Castro (2005b) at around 26 t by calculating the volumes of wood involved in each component and considering the specific weight of the wood to be 0.52 t/m³. Taking into account the dimensions given in Figure 7, the centre of gravity of the mast and yards can be estimated to be located 20.25 m forward of the aft perpendicular and 19.45 m above the baseline.

The weight of the sails, shown in Figure 8, was calculated by taking the total area of the sails (1789 m²) and multiplying it by 1.5 Kg/m². Furthermore, two sets
of sails were considered to be carried onboard, resulting in a total weight of 5.4 t.

Taking into account the reconstruction of the sail plan shown in Figure 8, the centre of gravity of the sails can be estimated to be located 22.5 m forward of the aft perpendicular and 24.0 m above the baseline. The areas and centres of mass of the various sails are shown in Table 2.

The rigging of the ship was estimated to weight 5 t, as a rough estimate. The location of its centre of gravity is obviously very difficult to find, so it was assumed that it is located at the same location that the centre of gravity of the sails.

The anchors carried by a ship of this type are, according with the documents presented by Domingues (2004), 4 anchors weighing 17 quintais each and 4 anchors weighing 16 quintais each, with a total weight of 7.8 t. The corresponding anchors lines weighted approximately 10.2 t. Both these weights were usually carried inside the forecastle and were assumed to be located at 36.5 m from the aft perpendicular and 9.5 m above the baseline. The ship also carried two small boats called batel and esquife weighing around 10 t. These were assumed to be located at the centre of the main deck, between the two castles, 24.0 m from the aft perpendicular and 8.5 m above the baseline.

The artillery carried in this ship is not known, but Domingues (2004) presents several documents detailing the artillery carried by the nau type of ship, which is given in Table 3. The artillery was subdivided into 21 heavy weapons and 16 light weapons, with a total estimated weight of 34.9 t. Ships of the galleon type were generally better armed, but Nossa Senhora dos Mártires was a merchant ship.

The ammunitions for these weapons can be estimated to weight 3 t and the gunpowder carried onboard weights approximately 0.5 t. The 21 large guns, one of which is shown in Figure 9, were located in the main deck, 20.0 m forward and 6.90 m above the keel, while the lighter guns were carried in the main and upper decks, 20.0 m forward and 9.5 m above the baseline.

The amounts of ballast carried in these ships are not known, but Blot (1994) indicates that a XVIII century ship with 64 guns carried 270 t of ballast.
Taking into account the dimensions of this ship and the dimensions of the *Nossa Senhora dos Martires*, the ballast could be estimated, with a considerable incertitude, to amount to 154 t. Castro (2001) indicates that taking into account the ballast found in the Molasses Reef and Highborn Cay wrecks, the ballast for this ship could be in the region of 200 t. In this study, a value of 175 t has been considered. The ballast was carried directly above the keel, inside the lower hold, at an estimated location 20.0 m forward of the aft perpendicular and 0.75 m above the baseline.

The cargo aboard this nau consisted mainly of pepper, weighting between 3000 and 5000 quintais, as indicated by Castro (2005). Costa (1997) also indicates some cargo weights for ships returning from India and 4500 quintais (265 t) appears to be a plausible weight. This cargo was mainly pepper and was carried in the hold. Its centre of gravity has been estimated to be 21.0 m forward of the aft perpendicular and 2.0 m above the baseline.

Castro (2001) estimates that this ship could be carrying a crew of 150 men and 230 soldiers. Furthermore, 75 passengers could also be onboard. Each man of the crew or soldier could weight 60 Kg and carry a baggage weighting 20 Kg. The passengers could carry 100 Kg each and weighted the same as the crew members. The total weight of the crew, soldiers and passengers (plus their baggage) may have reached 42.4 t. The passengers made the voyage in the poop deck, quarter deck and some of their cargo in the main deck. The centre of gravity of them and their cargo can be estimated to be located 8.0 m forward and 9.3 m above the baseline. The crew and their cargo were located in the lower deck, 17.0 m forward and 4.6 m above the baseline. The soldiers made the voyage in the main deck (gun deck), with a centre of gravity 17.0 m forward and 6.9 m above the baseline.

The supplies carried onboard for six months of navigation comprised mainly water, wine and biscuits. Each person on board consumed 1.8 l of water a day, resulting in a total of 146 t of water. Regarding the wine, the average consumption was 0.5 l a day, resulting in a weight of 40 t. The biscuit was consumed at a rate of 1.3 Kg per person each day, requiring a total of 106 t. These three items (292 t) where supplemented by many other less significant items, in an estimated total of 350 t. The water and wine (186 t) were carried in the lower deck, 21.0 m forward of the aft perpendicular and 4.8 m above the baseline. The biscuit was carried in the gun deck, 20.0 m forward of the aft perpendicular and 7.1 m above the baseline.

These are average values obtained taking into consideration the distribution scheme outlined in Falcão (1607) and remembering that, obviously, people would move considerably during the voyage. Table 4 summarizes the estimated loading condition when departing from India.

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight (t)</th>
<th>Xg (m)</th>
<th>Zg (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hull</td>
<td>398.0</td>
<td>18.0</td>
<td>5.90</td>
</tr>
<tr>
<td>Masts and yards</td>
<td>26.0</td>
<td>20.25</td>
<td>19.45</td>
</tr>
<tr>
<td>Sails</td>
<td>5.4</td>
<td>22.5</td>
<td>24.0</td>
</tr>
<tr>
<td>Rigging</td>
<td>5.0</td>
<td>22.5</td>
<td>24.0</td>
</tr>
<tr>
<td>Anchors</td>
<td>18.0</td>
<td>36.5</td>
<td>9.50</td>
</tr>
<tr>
<td>Boat</td>
<td>10.0</td>
<td>24.0</td>
<td>8.50</td>
</tr>
<tr>
<td>Light artillery</td>
<td>12.9</td>
<td>20.0</td>
<td>9.50</td>
</tr>
<tr>
<td>Heavy artillery</td>
<td>25.5</td>
<td>20.0</td>
<td>6.90</td>
</tr>
<tr>
<td>Ballast</td>
<td>175.0</td>
<td>21.0</td>
<td>0.75</td>
</tr>
<tr>
<td>Cargo</td>
<td>265.0</td>
<td>21.0</td>
<td>2.00</td>
</tr>
<tr>
<td>Crew</td>
<td>14.4</td>
<td>17.0</td>
<td>4.60</td>
</tr>
<tr>
<td>Soldiers</td>
<td>21.0</td>
<td>17.0</td>
<td>6.90</td>
</tr>
<tr>
<td>Passengers</td>
<td>7.0</td>
<td>8.00</td>
<td>9.30</td>
</tr>
<tr>
<td>Water/Wine</td>
<td>186.0</td>
<td>21.0</td>
<td>4.75</td>
</tr>
<tr>
<td>Biscuit</td>
<td>106.0</td>
<td>20.0</td>
<td>7.10</td>
</tr>
<tr>
<td>Other supplies</td>
<td>58.0</td>
<td>20.0</td>
<td>7.10</td>
</tr>
<tr>
<td>Total</td>
<td>1333.0</td>
<td>20.0</td>
<td>4.98</td>
</tr>
</tbody>
</table>

Figure 10 shows graphically the weight distribution expressed in percentage of the total displacement. The largest weight is the hull, with approximately 30% of the total displacement, followed by the cargo (pepper) with 20%, the water and wine with 14% and ballast with 13%. These four weights amount to 77% of the ship’s displacement.

### 4 STABILITY ANALYSIS

Figure 11 shows an isometric view of the ship’s hull, as modeled for hydrostatic calculations. The planking thickness (11 cm) was taken into consideration when defining the hull sections. The large forecastle and the three-decked aft superstructure are clearly visible but were not considered watertight.
Hydrostatic calculations show that the ship, for the loading condition shown in Table 4, would float on an even keel with 5.0 m draught, shown in Figure 12, which is 0.9 m below the gun deck level amidships. For this draught and load condition, the ship’s metacentric height would then be 1.14 m.

Figure 13 shows the ship’s hydrostatic properties. It may be seen that both the centre of buoyancy and centre of floatation are located slightly forward of midship (midship is located 19 m forward of aft perpendicular).

Figure 14 shows the ship’s cross curves of stability, calculated for the centre of gravity located at the baseline.

5 COMPARISON WITH CURRENT INTACT STABILITY REGULATIONS

The Portuguese shipbuilders of the late XVI century knew nearly nothing about ship stability, except that, for example, locating large weights high in the ship would degrade the ship’s stability.

Therefore, it is interesting to investigate if a Portuguese nau would comply with modern intact ship stability criteria. There are a number of such criteria available, which are mainly used in the stability evaluation of the so-called “tall ships”. The International Maritime Organization generally advises the use of the classic cargo ship stability criterion and the weather criterion, both contained in IMO-Assembly (1990).
However, it recognizes that both are not suitable for ships fitted with extensive sail areas. For this purpose, the US Coast Guard establishes a criterion contained in the Code of Federal Regulations (1983).

According with this criterion, the ship shall have numerals $X$, $Y$ and $Z$ larger than given values. The $X$ numeral expresses a measure of protection against water on deck. Numeral $Y$ expresses the resistance against downflooding the interior of the ship and numeral $Z$ indicates the capacity of the ship to resist a knockdown (leading to capsize). The numerals are given by:

$$\frac{1000 \Delta H Z^a}{A h} > X$$

$$\frac{1000 \Delta H Z^b}{A h} > Y$$

$$\frac{1000 \Delta H Z^c}{A h} > Z$$

where:
- $\Delta = \text{displacement (t)}$,
- $A = \text{projected lateral area of the hull and sails (m}^2\text{)}$,
- $h = \text{vertical distance between centre of pressure of the projected lateral area and center of the underwater lateral area (m)}$.

HZa, HZb and HZc are calculated using:

$$HZ_a = \frac{GZ_c}{\cos^2 \theta_v}$$

$$HZ_b (or \quad HZ_c) = \frac{I}{((\theta_v / 2) + 14.3 \sin 2\theta_v)}$$

where:
- $\theta_v = \text{angle of deck immersion (°)}$,
- $GZ_c = \text{righting arm (m) at the angle of deck immersion}$,
- $\theta_v = \text{angle of downflooding (°) or 60°, whichever smaller, when calculating HZ_b}$; 90° when calculating $HZ_c$,
- $I = \text{righting energy (m.rad) up to downflooding angle or 60°, whichever smaller, when calculating HZ_b}$; righting energy up to 90° or the angle of extinction, whichever larger, but not more than 120°, when calculating $HZ_c$.

For a ship intended for navigation in exposed areas, the angle of extinction must be larger than 90° and the numerals must exceed the following values:

$$X = 16.4 \text{ t/m}^2$$

$$Y = 18.6 \text{ t/m}^2$$

$$Z = 20.8 \text{ t/m}^2$$

Figure 14. Cross curves of stability of the Pepper Wreck Nau.

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The calculations were made for the full sail plan and assuming that all sails act on the fore-and-aft plane and have the areas shown in Table 2. The ship has been assumed watertight up to the main deck level, that is, the gun holes could be secured watertight. Downflooding can occur only through the deck hatch, located at the centre plane, near the mainmast, originating that the angle of downflooding is larger than 60°. The angle of deck edge immersion is approximately 26°.

Figure 15 shows the righting arm and energy curves for the ship in the loading condition specified in Table 4.

The angle of extinction is of 111° and clearly surpasses the minimum required angle of extinction of 90°. Taking in consideration Figure 15 and the formulæ above, the ship numerals are:

\[
X = 16.5 \text{t/m}^2 > 16.4 \text{t/m}^2 \\
Y = 20.8 \text{t/m}^2 > 18.6 \text{t/m}^2 \\
Z = 34.9 \text{t/m}^2 > 20.8 \text{t/m}^2
\]

It may be concluded that the ship is capable of complying with the criterion, narrowly for the first numeral and with a significant margin for the two other numerals. This is explained by the reasonably large breadth of the ship and is valid in conjunction with the assumptions regarding watertightness and loading condition explained above. In practice, the watertightness was generally far from satisfactory and the overloading and overcrowding common practice. In fact, for instance, D’Intino (1998) indicates that the real distribution of cargo, supplies and people onboard seldom followed the theoretical scheme of Falcão (1607).

Regarding the cause for the wreck of this ship, it is known that the ship hit the north coast at the entrance of river Tagus, while attempting to enter this river in very heavy following or quartering seas and, possibly, against the strong tidal current. The ship was probably overwhelmed by the sea and pushed to the rocks bordering the north shore of the narrow river entrance. Further studies of the ship’s characteristics are expected to cast some light to the possible cause(s) for these unfortunate events.

6 CONCLUSIONS

The paper presents a study of the weight distribution, loading condition, floatation and stability characteristics of an early XVII century Portuguese nau, the Nossa Senhora dos Mártires, wrecked at the mouth of river Tagus in 1606.

It was found that the weight of the ship hull is around 400 t, which is approximately 30% of the total displacement. This weight was determined by summation of the hull’s component weights. The reconstruction of the general arrangement and rigging, together with data from contemporary texts on the loading of this type of ships, allowed an approximate evaluation of the other weights aboard, obtaining finally a displacement of 1333 t. The same methodology was used to determine the location of the centre of gravity.

For this estimated loading condition, which corresponds to the departure from India, the ship would have an approximately even keel draught of 5.0 m. The corresponding metacentric height is 1.14 m. The ship’s hydrostatics and cross curves of stability are also presented.

For the same loading condition, the righting arm and energy curves are presented and the US Coast Guard intact stability criterion for large sailing vessels is applied to this ship. Under the assumption of watertightness up to the main deck and of the gun holes, the ship complies with the criterion.

The general conclusion of the study is that this ship had stability characteristics appropriate for open sea operation, at least when well maintained and correctly operated. Unfortunately, these two requirements were seldom found in practice.

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