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RESEARCH ARTICLE

Selected issues of optimising parameters on square riggers to maximise speed

Szymański Rafał,[1]* and Specht Cezary[2]

[1]Commander of the Sailing Ship Dar Młodzieży, Gdynia Maritime University, Gdynia, Poland
[2]Department of Geodesy and Oceanography, Gdynia Maritime University, Gdynia, Poland.
*Corresponding author: Szymański Rafał; Email: rszymanski@onet.com.pl

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Abstract
Due to the exceptional complexity of the propulsion system (sails), square-riggers form a special group of sailing vessels. In modern pleasure and sport sailing, simple Bermuda (triangular) sailing rigging prevails, which is widely discussed in the literature, both in terms of theory and numerous experiments. The literature on the theory on square-riggers is, in turn, limited mainly to the description of good sailing practice developed over the centuries. Its important element was maximising vessel speed, but this discussion has not been documented by scientific research. This paper presents the significant parameters influencing the speed of a square-rigged sailing vessel and selects those which are the most important from the point of view of its maximisation. The paper also proposes methods and measurement systems which optimise selected parameters affecting the achievement of higher speeds. The paper describes the types of speeds of typical sailing vessels, provides a historical synthesis of sailing ships with respect to their speed, and presents a selection and description of the parameters affecting the speed of modern square-rigged vessels. The paper ends with a proposed method and measurement system for experimental research aiming at rigging optimisation in a square-rigged sailing vessel from the point of view of maximising its speed.

1. Introduction

Over the centuries, along with the desire to increase the size of vessels, the desire to achieve the highest possible speed were stimulated the evolution of sailing ship design. The technical characteristics of power-driven ships, which are now mandatory in ship's documentation, adopt several types of speeds. These are:

- Economical – the speed that makes it possible to travel a certain distance at the least possible cost. This value is most frequently used for merchant ships, as well as warships and sailing vessels. What makes it special among the other discussed types of speed is that it is the basic value during the design of both the propulsion system and the hull of the vessel. It is determined in sea trials.
- Maximum constant – the speed which makes it possible to cover a given distance in the shortest time. It is the value with which this distance can be travelled without any damage to the propulsion system (Mayur, 2020). It is determined in sea trials.
- March speed – the speed that results from tactical assumptions. It usually applies to warships operating in groups. Its value depends on the economic speed of the slowest vessel (Pape, 2020). It is determined by sea trials for specific vessels.
- Peak speed – the speed which makes it possible to achieve the maximum speed of a vessel at an excessive load to the propulsion system (Pape, 2020). It is determined in sea trials.

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- Minimum rudder speed – the speed at which the vessel continues to respond to a change in rudder angle. It is determined during sea trials or is determined experimentally by the ship's crew (DNV-GL, 2017).

Only some of the presented speed types of power-driven vessels apply to sailing vessels as well. The very character of sailing vessels thus justifies the introduction of new and modified definitions. Nowadays, the following speeds are most often given for newly built sailing vessels:

- Economical speed under engine – the speed that makes it possible to travel a certain distance at the lowest possible fuel consumption. It is determined in sea trials.
- Maximum speed under engine – the speed that allows traveling a certain distance in the shortest time without damaging the propulsion system. It is determined in sea trials.
- Nominal speed under sail –the speed achieved by a sailing vessel under a full set of sails. It is determined by sea trials carried out in optimal hydrometeorological conditions (wind force up to 5°B (on the Beaufort scale)).
- Maximum speed under sail – a speed often found in the literature, however its unambiguous definition is missing. Usually, its value refers to instantaneous speed, the average for a very short period (1 min); hourly average, or daily average. It is determined in operation (usually during races).

Please note that the most important value describing the speed of sailing ships is the nominal speed under sail. When designing the rigging (masts, standing and running rigging, and sails), it is assumed that in winds up to a force of 5°B, a ship can sail safely with all the sails set (Choreń Design and Consulting, 2020; Conrad Shipyard, 2021). Once the wind force exceeds 5°B, the number of sails must be reduced due to the strength of the masts and rigging, and above all, the safety of the sailing ship. It can be assumed that for modern sailing ships, it is the speed declared in the ship documentation. For sailing ships built several dozen years ago or even older, the situation becomes more complex. Shipowners often only quote the speed achieved under mechanical propulsion, which probably corresponds to their values at the nominal load of the propulsion unit. If publications on this subject include information on speed under sail, it is usually given without specifying whether it refers to maximum speed under sail or nominal speed under sail (for optimal weather conditions, up to 5°B) (Giorgetti and Abranson, 2007). Sometimes other criteria have also been used in determining the vessel speed but without them being precisely defined.

A similar lack of precision applies to historical sources and publications on the historical perspective on sailing ships' speed. Contemporary sailing ships replicas play a special role in assessing information on actual nominal speeds under sail (Batchelor and Chant, 2006; Bennett, 2009).

The speed of square-rigged vessels depends on many variables. The factors affecting the speed of a sailing vessel can be divided into external and internal factors. The external factors mainly include hydrometeorological conditions. The internal factors are the rigging parameters (number of sails, their trim, yard bracing in relation to the direction of the apparent wind and their positioning in relation to each other – the so-called fanning) and displacement parameters (draught, trim, heeling, metacentric height) (Marchaj, 1970, 2000; Scott, 1992). Internal factors also include the hydrodynamic efficiency of the hull, which, to a great extent, depends on the shape and surface condition of the underwater part of the hull (Chapelle, 1967). A foul bottom, with a damaged paint coating, poses greater resistance. Hydrodynamic resistance also varies according to changes in trim and heel (Zborowski, 1980; Bertram, 2000; Marchaj, 2013).

Upon reviewing scientific publications on maximising the speed of sailing ships by optimising their rigging, it can be concluded that this topic is not often discussed in professional scientific studies. Similar issues concerning modern regatta sailing have been subject to scientific discussion, but they do not relate to square-rigged vessels. This is probably due to the very small number of square-rigged sailboats in the world (fewer than 100) and the fact they are mostly used for youth sail training. Only during a few regattas (Tall Ships Races) do these vessels sail at speeds greater than nominal, striving for maximum speed, while maintaining a reasonable safety margin, of course.

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To conclude the analysis, it should be noted that:

- Power-driven and sailing ships, as well as warships, have different types of speeds provided in their technical documentation.
- The most commonly quoted speed values for square-rigged vessels are nominal and maximum under engine speed, which is relatively easy to determine based on sea trials carried out in favourable hydrometeorological conditions.
- The rigging and hull structure of modern square-rigged vessels are designed for a wind force of 5°B, hence the nominal speed under sail should be given in their technical documentation.

The documentation of modern sailing ships does not include data on the maximum speed under sail, as it depends on a large number of factors and can only be achieved in sailing conditions that often exceed the nominal values.

This paper is the first publication in this series with the aim to:

1. Determine the rigging parameters and other (displacement) variables that have a significant influence on the speed of a square-rigged vessel and its achieving maximum speed (theoretical aspect).
2. Chose the range of variation in each of these parameters to be tested based on the theoretical and measurement aspect combined with the long-term experience of one of the authors as the commander of a full-rigged ship, the *Dar Młodzieży*.
3. Develop a method enabling experimental research based on an integrated INS/GNSS (Inertial Navigation System/Global Navigation Satellite Systems) system (2 RTN – Real-Time Network antennas).
4. Run actual sea trials on a square-rigged ship, under varying conditions and parameters as defined in points 1 and 2.

The first three points will be discussed in this paper. The first chapter reviews the speed of sailing ships and measuring methods. The second chapter analyses the types of sailing ships and their speed over the centuries (3500 BCE. – 21st century). The third chapter describes the variables that have a significant influence on square-rigged ships achieving high speeds, and the fourth chapter proposes a measurement system to be used for experimental studies. The paper ends with conclusions and a plan for future research.

2. Measurement of ship speed at sea

According to the definition, speed is a physical quantity that describes the rate of change in the position of a body relative to a reference system. Speed is a basic value in kinematics and classical mechanics that describes the motion of bodies. For motion along a straight line, speed is defined as the derivative of the displacement with respect to time, that is the limit of the displacement increments to the increment of time in which the increment occurred. For an infinitely small increment of time, speed is defined as:

$$v = \frac{dx}{dt} = \lim_{\Delta t \to \infty} \frac{\Delta x}{\Delta t} \tag{1}$$

where

v – speed,
dx – change in the coordinate with respect to a straight line (direction of movement),
t – time in which the change occurred.

The concept of ship speed, as it is understood today, does not appear in ancient literature. The duration of travel necessary to cover a certain distance between two ports was most frequently used instead. This information was often provided together with the season to which it applied (Casson, 1951). Alternatively, speed was expressed as the duration of the voyage in a particular season. Nevertheless, as early as in the 1st century BCE, Marcus Vitruvius designed a device to measure the distance travelled by

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(a) (b)

Figure 1. *Logs. (a) Outboard log–chip log (2021). (b) Walker's mechanical log (paradeantiques.co.uk).*

a ship. It was conceived as a wheel immersed in water at the ship's side, whose rotation corresponded to the distance travelled (Cotter, 1970; Köberer, 2020). We would now call it a mechanical log.

To analyse the speed of a sailing vessel, we should first recall that two types of distances are distinguished in maritime navigation: the distance over the ground and the distance through the water. The difference between these values is due to the influence of currents and tides on the moving vessel. To measure the distance over the bottom travelled by a vessel, it is necessary to be able to determine the exact geographical position (start and end points) for the measurement period. Astronavigation methods of determining position do not provide sufficient accuracy and are not available at any time. It was only in the 20th century that radio navigation and satellite navigation systems made it possible to ensure high accuracy and availability of a position, so measuring the speed of a ship over the ground has not been a problem since the launch of GPS (Global Positioning System) (1995) (Specht, 2007).

The oldest instrument used to measure ship speed was the outboard log, in which a special board on a rope of a specified length was thrown overboard while measuring the time to unroll the entire rope. It was necessary to have a reasonably accurate time-measuring device; otherwise, this method was an estimation only (Cotter, 1970). One of the first commonly used devices of this type was the 'chip log' (Figure 1a), operating together with a 30-second hourglass that allowed speed to be measured quite accurately. Knots (markers) were tied on the rope every 50 feet (about $14 \cdot 4$ m). When the board was launched overboard, the knots were counted for 30 s, and the number of knots was equivalent to the speed of the ship expressed in knots (nautical miles per hour). Please note that many other rope divisions were used for differently scaled hourglasses or other units of distance and speed (Reaveley, 2010). The invention of Walker's log in 1861, measuring the distance travelled by a ship by mechanically counting the revolutions of the towed propeller (Figure 1b) provided a breakthrough in this field. Mechanical logs were widely used until the second half of the 20th century, when hydrodynamic, electromagnetic, and acoustic (based on Doppler effect) logs came into general use and are still widely used to measure the speed through water (Woliński, 1961; Wyszkowski and Kon, 1967; Crone, 1969). On modern ships, GPS is primarily used to measure the speed over ground (SOG), which provides high accuracy in determining the vessel coordinates (Specht, 2007), currently being $2 \cdot 0$ m ($p = 0 \cdot 95$) (Specht, 2021a).

Apart from measuring the distance travelled by a ship, measuring time was even more of a problem. Until the 18th century, it was impossible to accurately measure time on ships. Hourglasses were used to measure short periods, and daytime period was determined by cyclical astronomical phenomena (e.g. culmination, sunrise, sunset). In 1759, Johan Harrison constructed the first mechanical chronometer (Gould, 1921). A chronometer is a precision mechanical clock that is resistant to changing conditions (temperature, humidity, tilt). Above all, this device allowed a determination of the exact astronomical position (in particular longitude), but also made it possible to calculate the speed (Gould, 1921; Woliński, 1961; Wyszkowski and Kon, 1967; Reaveley, 2010). Nowadays, electronic (quartz) chronometers are commonly used at sea together with time readings from satellite navigation devices (GPS) (Specht, 2007).

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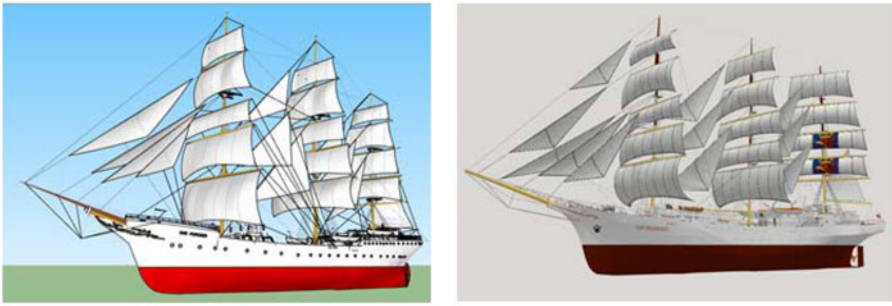

***Figure 2.** Full-sail rigging of the Dar Pomorza and Dar Młodzieży square-rigged ships (3dwarehouse, 2021).*

3. Speed analysis of sailing vessels from 25th century BCE – 20th century CE

Speed comparison between sailing vessels throughout history requires the adoption of a uniform criterion for comparison, which should be one of the types of speed. The use of nominal speed should be considered reasonable. This is the speed that sailing ships can develop with the whole basic set of sails under optimal weather conditions (i.e. up to 5°B) (Morgan and Cormac, 2014). Figure 2 shows an example of the full sail rigging of the *Dar Pomorza* and *Dar Młodzieży* square-rigged ships.

Unfortunately, for most historical sources, even if speed is given in the literature, no details as to its types are provided. Usually, data on maximum speed is unavailable or are unreliable. Practically, no accurate instrument capable of measuring the spot speed of ships was available until the 20th century. Speed was measured as the time taken to transit a transcontinental distance under varying weather conditions (from calm to violent storms). These were thus the average speeds or the average daily speeds.

It is important to note that most estimates of speed refer to its nominal value, with basic rigging. Only for sailing warships, clippers and windjammers did speed play a key role. From a military point of view, it was about efficiency in sea combat (naval forces, pirates and corsairs) (Winfield and Roberts, 2015, 2017), while from an economic point of view, it was about transporting goods as fast as possible (tea clippers, windjammers, etc.) (Morgan and Cormac, 2014).

The earliest evidence of sailing vessels dates from around 3500 BCE. – the era of Sumerian power (Giorgetti and Abranson, 2007). Sailing vessels were commonly constructed in the Mediterranean, the cradle of subsequent civilisations. The earliest vessels include Egyptian reed boats, which, according to researchers, navigated on the Nile as early as 3400 BCE. The first sails used were mostly square-rigged types. They were installed as auxiliary propulsion on rowing boats and worked only when sailing with the wind (Mickiewicz, 1971; Batchelor and Chant, 2006). The fact that, to date, there is no reliable data on their speed under sail should be stressed. However, contemporary replicas of these vessels, under favourable conditions (on the open sea and under sail), could develop a speed of 2–4 kn (Giorgetti and Abranson, 2007). Thor Heyerdahl constructed a papyrus raft replica, the *Ra II* (length: $11 \cdot 9$ m; beam: $4 \cdot 9$ m; draught: no data; rigging type: one square-rigged sail; sail area: 48 m^2; displacement: no data, speed: 2–3 kn), and managed to cross the Atlantic (Heyerdhal, 1974). In Ancient Egypt, in the 2000–500 BCE period, wooden rowing ships equipped with a single square-rigged sail became the basic vessel. Elements of such a ship built for the pharaoh Khufu were found in Giza (length: $43 \cdot 6$ m; beam: 5,7 m, draught: $1 \cdot 5$ m, type of rigging: one square-rigged sail, sail area: no data; displacement: 94 t, speed: no data). Unfortunately, the speed under sail is not known. There is evidence that such ships sailed not only in the Mediterranean but also in the Red Sea and even reached India (Mickiewicz, 1971; Gulas and Pevny, 1985). The Phoenicians started building merchant ships as early as about 2000 BCE, and their maritime expansion peaked in the 12th century BCE. They were the first to build ships with keel and frames, which made the structure more resistant to sea conditions and allowed for increased size (length: 30 m; beam: 10 m, draught: 2 m, type of rigging: one square-rigged sail, sail area: no data; displacement: no data; speed: up to 6 kn). There is archaeological evidence that the Phoenicians sailed around Africa

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on a similar ship. However, they were still rowing ships with sails (Mickiewicz, 1971; Smith, 2012). The Greeks and Romans also had war and trade fleets in the Mediterranean. Greek sailors traded goods using wooden ships with a relatively high freeboard and one large square sail. Unfortunately, no remains of such ships have been found, and it is difficult to determine their size. The Greek's rowing warships were also equipped with sails, which were used only to reach and return from the battlefield. During a battle, rowing was used to manoeuvre the vessel only. The trireme was the ideal ship of this type and a replica, *Olympias*, built in 1987, had two masts with single square-rigged sails (length: 37 · 06 m; beam: 5,2 m, draught: 1 · 5 m; rigging type: two masts with single square-rigged sails; sail area: no data; displacement: 165 t; speed: 8 kn) (Batchelor and Chant, 2006; Bennett, 2009; Haładaj et al., 2014). From the 3rd century BCE onwards, the Romans kept improving the design of Egyptian and Greek ships, building vessels with an impressive displacement of up to 1,600 t (length: up to over 60 m; beam: up to 15 · 2 m, draught: 2 · 5, type of sailing: one square-rigged sail on the mast and another under the bowsprit; sail area: no data; displacement: 20 -1,600 t; speed about 6–7 kn) (Douglass, 1968; Mickiewicz, 1971; Batchelor and Chant, 2006; Giorgetti and Abranson, 2007; Bennett, 2009; Whitewright, 2011; Haładaj et al., 2014).

The design of sailing ships in Asia developed quite differently. The Chinese and Japanese junks, known since the first centuries AD, did not feature the rigging type dominating in Europe. According to modern nomenclature, junks had slanted lug sails. On the masts, up to nine of them per junk, single bamboo-ribbed sails made of rice mats were set. Such rigging allows for effective sailing not only downwind, but, like contemporary yachts with Bermuda (triangular) sails, almost upwind. They had no keel, but lowered daggerboards (either outboard or centreboard), a central, often lifted, rudder, and the hulls were divided by watertight bulkheads (completely unknown in Europe). At the peak of their development (15th century AD), great armadas of Chinese junks made oceanic voyages to the Indian and Pacific Oceans. The ships reached dimensions monstrous for those times (length: up to 160 m; beam: up to 30 m; draught: no data; type of rigging: junk; sail area: no data; displacement: up to 5,000 t.; speed: 10 kn (sometimes even reaching 15 kn and more). This dynamic development was halted by a political decision on China's isolation. The fleet was burned and never reconstructed (Mickiewicz, 1971; Manguin, 1993; Batchelor and Chant, 2006; Wei, 2014). The Indian Ocean basin (and especially the Arabian Sea) was a region explored by the Arabs. Researchers believe that as early as the 5th century BCE they sailed across this basin as far as the southern limits of East Africa. They used one- or two-masted (daw – dhow) boats with a very peculiar lateen rigging. The most representative of the dhow ships were the two- or three-masted Baghlah. They could still be encountered in the waters of the Indian Ocean (photo by the author) even at the end of the 20th century (length: up to 43 · 3 m; beam: up to 10 m; draught: no data; sail type: lateen dhow, sail area: no data; displacement: up to 500 t.; speed: 12 kn). Modern sport replicas achieve speeds of more than 20 kn (McMaster, 1966; Batchelor and Chant, 2006; Izaguirre-Alza et al., 2014; Sail World, 2021) (Figure 3).

In the 10th century, Scandinavian boats called langskips (long boats) (length: 30 m; beam: 3 · 8 m; draught: no data; rigging type: one square-rigged sail; sail area: 112 m^2; displacement: 26 t; speed: 8 kn (*Old Skuldelev 2* replicas)) used by the Vikings, with only one square-rigged sail could make speeds of 6–8 kn (2 · 5 kn with oars), and under favourable conditions, their top speed even reached 13–17 kn (Mickiewicz, 1971; Batchelor and Chant, 2006; Haładaj et al., 2014; Viking Ship Museum Roskilde, 2021). Based on the Viking boats, further types of ships were developed in the 13th century in medieval northern Europe. The 'Cinque Ports' ships built in the ports of southeastern Great Britain had a higher freeboard and were bulkier than the langskips. However, they sailed only in the waters of the North Sea and the English Channel (length: 24 m; beam: 6,7 m, draught: 2 · 25 m, type of rigging: one square-rigged sail, sail area: ca. 150 m^2; displacement: 80 t; speed: 4 kn) (Batchelor and Chant, 2006; Giorgetti and Abranson, 2007).

Hanseatic single-mast cogs from the 13th–14th centuries (length: 23 · 3; beam: 7 · 6 m; draught: no data; rigging type: one square-rigged sail; sail area: 200 m^2; displacement: about 50 t; speed: 5–6 kn), were capable of speeds of ca. 5–6 kn. Their special feature included the first widely used central (hinged) rudder, which replaced the steering oar fixed to the side of the ship. This steering method resulted in reduced resistance and therefore had a significant effect on speed. Cogs were commercial vessels and

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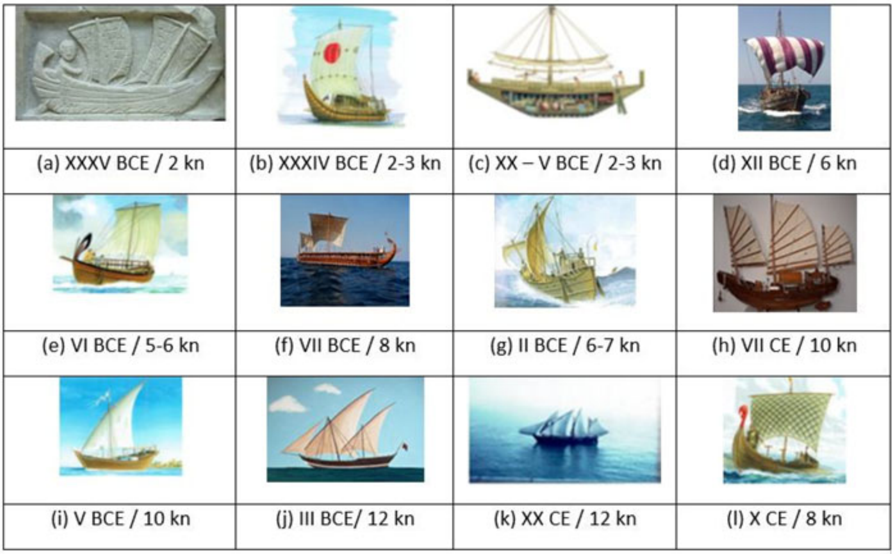

Figure 3. *The first sailing vessels. (a) Sumerian boat. (b) Egyptian reed boat. (c) Egyptian ship. (d) Phoenician ship. (e) Greek merchant ship from 6th century BCE. (f) Greek trireme Olympias. (g) Roman ship from 2nd century BCE. (h) Chinese junk. (i) Small dhaw. (j) Bagala. (k) Baghlan. (l) Langskip. Sources: (a) Bright Hub., 2021; (b, c, e, g, i, l) Batchelor and Chant, 2006; (d) Global News., 2020; (f) Hellenic Navy, 2021; (h & k) author's photo; (j) Wikimedia Baggala, 2009.*

operated only in coastal trade (Smolarek, 1963; Mickiewicz, 1971). It was not until the 15th century (the period of great geographical discoveries) that history witnessed a dynamic development of ship design and sailing. In the middle of this century, three-masted caravels suitable for ocean navigation appeared.

In the 16th century, carracks (enlarged and reinforced version of the caravel) became the dominant type of sailing vessel (length: up to 61 m; beam: 15·2 m; draught: no data; type of rigging: three- to four-masted, up to three square-rigged sails per mast, a lateen sail on the stern mast; sail area: no data; displacement: up to about 1,500 t; speed: no data) with a high stern and bow castles. On such ships, travelled Vasco da Gama (*Sao Gabriel*, *Sao Rafael*) (length: 25·6 m; beam: 8·5 m, draught: 3 m; rigging type: three-masted carrack – lateen sail on the stern mast, the rest square-rigged; sail area: no data; displacement: 150 t; speed: no data); Columbus (*Pinta*, *Santa Maria*, *Niña*) (*Santa Maria* – length: ca. 19 m; beam: 6 m, draught: 3 m; rigging type: three-masted carrack – lateen sail on the stern mast, the rest square-rigged; sail area: no data; displacement: 150 t; speed: no data) and Magellan (*Concepcion*, *Trinidad*, *Vittoria*) (Chapelle, 1967; Bergreen, 2003; Batchelor and Chant, 2006; Giorgetti and Abranson, 2007). In 1545, John Hawkins modified the carrack, thus starting the era of galleons (Golden Hind – 1,580 – length: 21·3 m; beam: 5·8; draught: 2·75 m, type of rigging: three-masted galleon, sail area: no data; displacement: 150 t; speed: no data), which were built in many variations and variants until the 17th century (Bathe et al., 1967). Francis Drake sailed on the *Golden Hind* galleon and the Great Spanish Armada consisted mainly of this type of sailing ship. The *Mayflower* that brought the first European settlers (Pilgrim Fathers) to North America was also a galleon. These were three- or four-masted ships (the first two masts with square-rigged sails and the rest with lateen sails) characterised by high seaworthiness, capable for ocean crossing. Their nominal speed is estimated to be around 8 kn (Chapelle, 1967; Mickiewicz, 1971; Batchelor and Chant, 2006; Giorgetti and Abranson, 2007) (Figure 4).

In the 16th century, the structures of sailing vessels slowly evolved with their hulls becoming slenderer, thus consequently making the vessels faster and easier to manoeuvre (Chapelle, 1967). Back then, the division (still valid today) of the rigging types of large sailing vessels into frigates, brigs,

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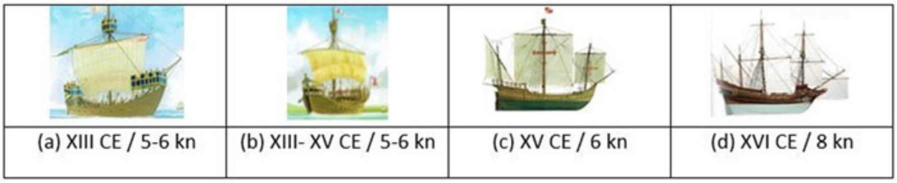

Figure 4. *Ships. (a) Cinque Ports. (b) Cog. (c) Caravel. (d) Galleon (Batchelor and Chant, 2006).*

and barks carrying two, three, or even five square-rigged sails on each mast were developed. The 17th century marked an important period in the history of sailing ships. The 1790s saw the introduction of an important solution – the rudder wheel replacing the low-precision tiller (McGowan, 1980). It provided for the possibility to steer accurately and react quickly to changes in the wind direction, which had a significant influence on the sailing speed. A particularly important feature of the sailing ships developed in the middle of the 17th century was the increase in the number of the front (fore and aft) sails, allowing sailing at a smaller angle to the wind direction, increasing speed made good to windward (Marchaj, 1970, 2000; Harland, 1985; Roger, 2004; Reid, 2017). The so-called East Indiaman also presented a particular vessel type. These vessels were built by national East Indian Companies to transport cargo and passengers between Europe and the Far East (Solar and Hens, 2016). A representative example of these armed merchant ships is the Swedish *Goteborg* (a faithful replica built in 2005) (length: 58 m; beam: 11; draught: $4 \cdot 95$ m, rigging type: three-masted frigate; sail area: 1,964 m^2; displacement: 780 t; speed: 5 kn) (Unger, 1997; Söderberg, 2010; Solar and de Zwart, 2017) and *Endeavour*, in which James Cook circumnavigated the world on his first voyage, provide examples of commercial frigates from the late 17th century (length: $29 \cdot 7$ m; beam: $8 \cdot 9$; draught: $3 \cdot 4$ m, rigging type: three-masted frigate; sail area: 930 m^2; displacement: 550 t; speed: 8 kn). A faithful replica can be admired in Australia (Australian National Maritime Museum, 2021).

It is important to distinguish between a frigate in the sense of the rigging type (three or more masts, each of them square-rigged) and a frigate in the sense of the type of warship, that is a light, manoeuvrable and fast ship (compared to ships of the line). At the turn of the 18th and 19th centuries, frigates were the most popular warships (Bathe et al., 1967; Batchelor and Chant, 2006). A ship of the line could be, and often was, fully square-rigged and therefore a frigate with respect to rigging type, as it was the with the giant *HMS Victory* (length: 69 m; beam: 15,8 m, draught: $8 \cdot 8$ m, rigging type: three-masted frigate; sail area: 5,440 m^2; displacement: 3,500 t; speed: 8 kn) (Bathe et al., 1967; Mickiewicz, 1971; Batchelor and Chant, 2006; Giorgetti and Abranson, 2007). Another innovation introduced from 1775 onwards that had a significant impact on the speed of sailing vessels was the covering of the underwater part of the hull with copper sheets that prevented it from fouling, which in turn reduced the hydrodynamic resistance (Harris, 1966; Roger, 2004). Hulls also changed their shapes to eventually achieve the slender lines of clipper ships. At the same time, significant changes were made to materials and deck equipment. The introduction of iron elements to the rigging promoted better use of wind power. The use of iron structural elements made it possible to improve the strength of the hull, thus allowing more sail area and, therefore, faster sailing in heavy weather conditions (Chapelle, 1967). These innovations resulted in the construction of ever-larger vessels. According to some researchers of this subject (Shepherd and Walton, 1972), the speed of sailing ships in the peak development period (17th–18th centuries) did not increase at all and even decreased temporarily. At the cost of reduced speed, ever-larger ships were built, which, in effect, improved their transport efficiency (Reid, 2017).

With the advent of the clipper ships, the 19th century saw the greatest increase in the speed of sailing vessels. Speed was the priority in the construction of clipper ships, only followed by the amount of cargo they could carry. These ships had slimmer hulls, higher masts and longer yards. Fast and small ships, the first to be called clippers, the Baltimore clipper ships, had already become famous before 1840. These were mostly schooners or brigs used for smuggling opium from India to China and transporting slaves. The most famous was the legendary schooner *America* – the first winner of the

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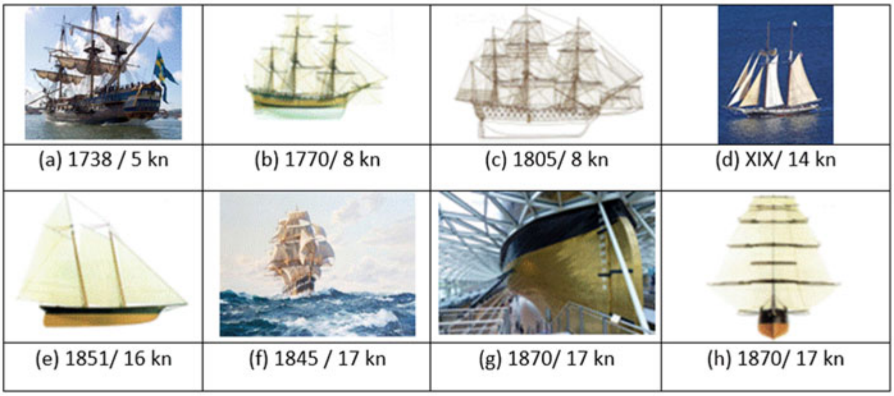

Figure 5. *Vessels. (a) Gotheborg. (b) Endeavour. (c) HMS Victory. (d) Baltimore Clipper. (e) America. (f) Rainbow. (g) Cutty Sark – slender hull covered with copper sheets. (h) Cutty Sark – with stud sails. Sources: (a) Universite de Montreal, 2021; (b, c, e, h) Batchelor and Chant, 2006); (d) Wikimedia Baltimore, 2004; (f) MutualArt., 2009; (g) Wikimedia Cutty Sark, 2012).*

'America's Cup' (length: 31 · 8 m; beam: 6 · 9; draught: 3 · 33 m, rigging type: three-masted gaff-rigged schooner; sail area: 492 m^2; displacement: 100 t; speed: up to 22 kn). The first vessel to be recognised as an extreme clipper ship was the *Rainbow*, launched in 1845, which was lost at sea with its all crew in 1848 (length: 48 m; beam: 10 m, draught: 5 · 6 m, type of rigging: three-masted frigate, sail area: no data; displacement: 750 t, speed: up to 17 kn) (Bathe et al., 1967; Chapelle, 1967; Batchelor and Chant, 2006; Giorgetti and Abranson, 2007; Rönnbäck, 2012). British clippers were famous for their relatively high speeds in lighter winds, when, in addition to all the usual sails, stud-sails were set on the sides (on spars, an extension of the yards). It is difficult to say which of the clippers was the fastest, as literature points to several of them: *Flying Cloud* (New York – San Francisco 89 days), *Comet* (San Francisco – Boston 76 days), *Sir Lancelot* (Foochow – London 89 days), *Thermopylae* (London – Melbourne 63 days), *Lightning* (Melbourne – Liverpool 63 days). The legendary *Cutty Sark* holds the record of 67 days from Sydney to Ushant and is said to have sailed at an average daily speed of greater than 17 kn. Some information on ship speed seems unreliable, such as the average daily speed of 19 kn (the 465 miles that the *Champion of the Sea* covered in 24 h, thus giving over 19 kn) (Bathe et al., 1967; Giorgetti and Abranson, 2007; Jefferson, 2014). It is difficult to compare the speed of ships from this period due to the variety of designs, their intended use, and size. In his 'The Search for Speed under Sails', Chapelle Howard attempted a comparison based mainly on block, midsection and prismatic coefficients, and the ratios of camber to length, speed to length and displacement to length. The author showed that clipper builders, despite lacking adequate computational apparatus and model testing basins, achieved excellent results in reducing hull drag (Campbell, 1954; Chapelle, 1967) (Figure 5).

It should be mentioned that clippers were (and are) the epitome of beauty under sail. The *Ariel* (Figure 6), built in Greenock in 1865, which had one continuous deck without forecastle and poop, was considered one of the most beautiful (length: 60 · 2 m; beam: 10,3 m, draught: 6 · 4 m, rigging type: three-masted frigate; sail area: 2,415 m^2; displacement: 1,028 t; speed: 17 kn). In 1866, the *Ariel* lost the great regatta (The Great Tea Race) by only 20 min to the *Taeping* clipper. Over a distance of about 16,000 nautical miles, she achieved an average speed of 6 · 7 kn (Campbell, 1954; Mickiewicz, 1971; Giorgetti and Abranson, 2007; Dash, 2011; Haładaj et al., 2014).

The year 1875 marked the beginning of the iron windjammers era, which surpassed all previously built sailing vessels in size. Thanks to their seaworthiness, these ships were widely used for trading fertilisers from Chile to Europe (via Cap Horn) and grain from Australia to Europe (via Cape of Good Hope), where they successfully competed with steamships until the early 20th century. One of the significant innovations on these vessels included the bracing winches designed by Jervis, which were first installed

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Figure 6. *The Ariel sailing ship designed for high speed (Wikimedia Ariel, 2011).*

Figure 7. *The Preussen under full sail. (1908).*

in 1875 on the *Duntrune*. Bracing winches were widely used in the windjammer fleet owned by E. Leaeisz, one of the largest operators of sailing cargo ships. His fleet included the largest windjammer in the world, the five-masted iron *Preussen* frigate (Figure 7), which reached up to 17 kn, and her record-breaking passages gave an average speed of 15 · 3 n (length: 124 · 3 m; beam: 16,3 m, draught: 8 · 3 m, rigging type: five-masted frigate; sail area: 5,560 m^2; displacement: 5,081 t; speed: 17 kn) (Underhill, 1938, 1946; Batchelor and Chant, 2006; Giorgetti and Abranson, 2007). The last grain race from Australia to Europe, involving 13 windjammers, took place in 1939, although these vessels continued to transport cargo on various transoceanic routes even after World War II (Haładaj et al., 2014; Jefferson, 2014). Windjammers thus remain a pinnacle achievement in the history of merchant sailing ships as they managed to achieve high speeds (17 kn) combined with the relatively high displacement (about 5,000 t).

As power-driven ships became more widespread, making the transport of goods by sea largely independent of the vagaries of the wind, the participation of sailing ships was first reduced, followed by their complete elimination. The construction of two canals: the Suez and Panama, was significant for these changes. Establishing of bunker stations (i.e. places where steamers could replenish their stocks of coal, and later, of liquid fuel) in sufficient number considerably shortened the routes between the continents (Underhill, 1938, 1946; Douglass, 1968; Batchelor and Chant, 2006; Giorgetti and Abranson, 2007; Leggett and Richard, 2012).

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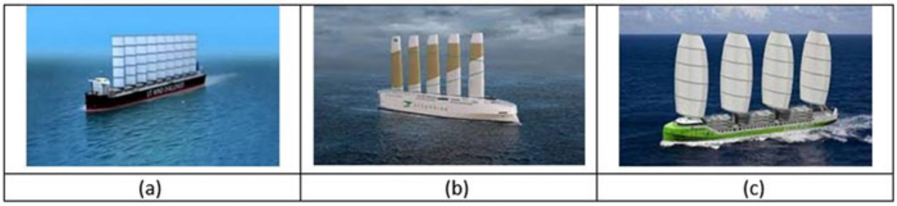

Figure 8. *Vessels. (a) Wind Challenger. (b) Oceanbird. (c) Ecoliner.*
Sources: (a) MFAME, 2019); (b) New Atlas, 2020; (c) North Sea, 2020.

Nowadays, for both economic and ecological reasons, new concepts for cargo ships with auxiliary sail or wind propulsion are occasionally being developed (Forfang, 2021) (Figure 8).

Training (school), tourist and even passenger sailing ships are still encountered on the seas. Some of them are over 100 years old, there are many replicas of centuries-old ships, but modern structures are also found. Among the oldest and largest is a steel bark built in 1926 as the *Padua – Kruzensztern* (length: 97 · 7 m; beam: 14,1 m, draught: 7 · 7 m, rigging type: four-masted bark; sail area: 3,400 m^2; displacement: 4,700 t, speed: no data). The *Pauda* is the last-ever built great cargo sailing vessel (Batchelor and Chant, 2006; Haładaj et al., 2014). The frigate *Stad Amsterdam* is one of the world's youngest sailing ships. She was the first clipper built after a pause of more than 130 years (length: 76 m; beam: 10,5 m, draught: 4 · 8 m, rigging type: three-masted frigate; sail area: 2,200 m^2; displacement: 1,036 t, speed: no data). Commissioned in 2000, the ship is one of the fastest sailing ships of its size currently afloat. The shipowner quotes a speed under sail of 17 kn. This is obviously not the nominal speed (in the previously mentioned understanding of this term) (Giorgetti and Abranson, 2007; Stad Amsterdam, 2021). The *Dar Młodzieży*, built in 1983 (length: 106 · 8 m; beam: 14,0 m, draught: 6 · 4 m, rigging type: three-masted frigate; sail area: 3,000 m^2; displacement: 2,946 t; speed: 12 kn) and *Fryderyk Chopin* built in 1992 (length: 55 · 5 m; beam: 8,5 m, draught: 3 · 8 m, rigging type: brig; sail area: 1,200 m^2; displacement: 400 t; speed: 12 kn) are two of many sailing ships designed by Zygmunt Choreń. Both the *Fryderyk Chopin* and the *Dar Młodzieży* (and the other four sister ships *Mir*, *Khersones*, *Drużba*, and *Palada*) are the fast sailing ships and often win regattas. Their nominal speed can be assumed to be about 12 kn (Giorgetti and Abranson, 2007; Haładaj et al., 2014; STS Fryderyk Chopin, 2021).

The Tall Ship Races, organised by Sail Training International, create an opportunity for testing sailing ship capabilities as well as crew training and skipper abilities. The regatta is usually followed by endless discussions among the masters and crews about tactics, bracing, rigging and similar issues. The knowledge about sailing comes from the experience gathered over centuries and is very rarely verified in research and multi-criteria analysis.

Figure 9 summarises the performed analysis of the nominal speed of sailing ships. Note that for some structures, the data on nominal speed under sail may raise doubts as to their reliability and validity. However, it is evident from the presented figure that ancient and medieval vessels developed speeds between 2 and 10 kn. This was mostly due to the low efficiency of their rigging. Gradually, rigging solutions were developed that not only allowed sailing fast downwind but also at an ever-decreasing angle to the wind. It was not until the 19th century that sailing ships appeared for which high speed was a priority already at the design stage.

The following conclusions can be drawn from the historical analysis presented above:

1. Information on the speed of sailing ships allowing a full-fledged comparison of their nominal speeds under sail is difficult to find in historical sources on sailing ships.
2. Until the 12th century CE, the sail was mostly only an auxiliary propulsion on rowing ships.
3. In the late Middle Ages, second and further sails were introduced, and as time went on, sailing ships with more than one mast started being built, which had a great impact on increasing the nominal speed of sailing ships.

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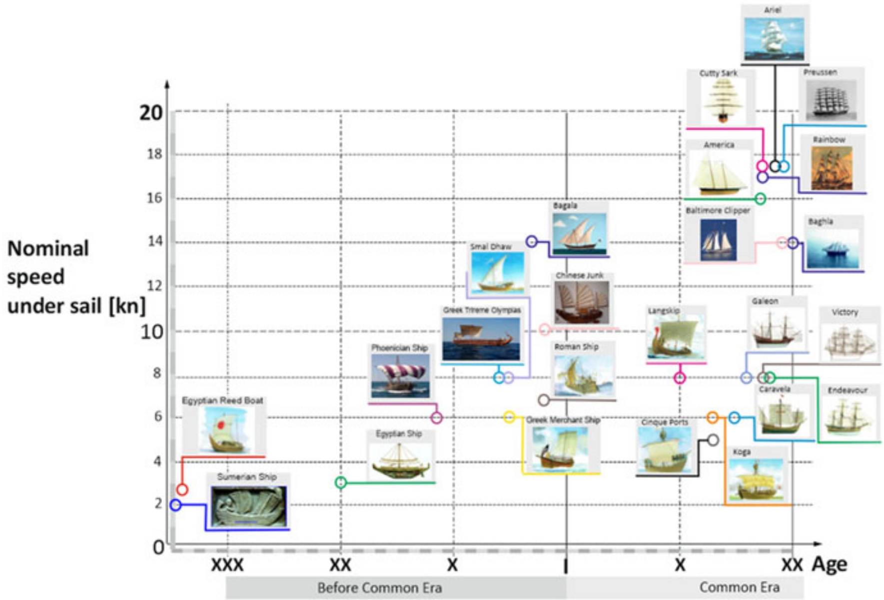

Figure 9. *The nominal speed of sailing vessels throughout history.*

4. The development of shipbuilding technology and the introduction of innovative technical solutions, such as replacing the steering oar with a rudder, metal elements of hull structure, better protection of hulls against fouling (copper sheets), the use of bracing winches, and so forth made it possible to increase the speed of sailing ships.
5. The development of shipbuilding technology allowed both for an increase in the speed of sailing ships without changing their size and to increase their carrying capacity at the expense of increasing speed. After a period of dynamic development of clipper ships, a compromise prevailed, with the windjammers as the final (from the economic point of view) result.
6. Clippers were the only ships constructed with priority to increase speed.
7. It is only since the 20th century that there have been very accurate instruments and methods for determining ship speed, which allows us to measure any speed: instantaneous, maximum, average; over the ground and through water, and so forth.
8. With the data available, it is not possible to precisely compare the speed of sailing ships. This is due to the inconsistent or missing definition of speed in different sources.

4. Parameters affecting the speed of square-rigged sailing ships

To run an experimental study to determine the optimum rigging setting of a square-rigged sailing ship to obtain maximum speeds, it is necessary to analyse several factors. It is proposed that these be divided into two main groups:

I. External – related to the sailing environment, which includes:

   a. Wind speed and direction.
   b. Sea state – wind waves and swell.

II. Internal – related to the sailing vessel, which includes:

   a. Sail condition – the number of sails used (set).
   b. Yard bracing – the angle at which the yards are set in relation to the direction of the apparent wind.

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c. Displacement and stability parameters – including a whole group of variables such as draught, trim, heel, metacentric height.
d. The condition of the hull surface (underwater), related to maintenance.

4.1. Wind speed and direction

The choice of internal parameters of a sailing ship depends to a large extent on external factors, mainly connected with hydrometeorological conditions. That is why their careful measurement and monitoring are very important. The correct measurement of hydrometeorological parameters on a sailing ship is not without difficulties and is often prone to human error.

The kinetic energy of the wind is given as:

$$E_k = \frac{m\,v^2}{2} = \frac{\rho V v^2}{2}[J] \tag{2}$$

The pressure of the wind speed can be expressed by the formula:

$$q = \frac{\rho {V_A}^2}{2} = 0 \cdot 6125{V_A}^2\left[\frac{N}{m^2}\right] \tag{3}$$

It causes the emergence of an aerodynamic force in the sail that can be computed as (Marchaj, 1970, 2000):

$$T_A = q\,S_A\,C = 0 \cdot 6125\,{V_A}^2 S_A\,C\,[N] \tag{4}$$

where

m – mass of air $[kg]$
v – speed of the wind $\left[\frac{m}{s}\right]$
ρ – air density = 1,225$\left[\frac{kg}{m^3}\right]$
q – wind speed pressure$\left[\frac{N}{m^2}\right]$,
T_A – aerodynamic force $[N]$,
V_A – apparent wind speed $\left[\frac{m}{s}\right]$,
S_A – sail surface area $[m^2]$,
C – experimentally determined coefficient of aerodynamic force.

This relationship shows that the aerodynamic force, which determines the speed of the sailing vessel, is directly proportional to the square of the wind speed.

Wind speed and wind direction are the two basic parameters characterising the wind that drives the sailing vessel.

Wind speed is measured using anemotachometers that show instantaneous values and anemometers that provide the average value over a selected time interval. The currently used devices often provide for the option of setting the time interval for which the wind speed value is averaged (most often it is 100 s) (Czajewski, 1988; Trzeciak, 2011). Due to the vertical wind speed gradient (speed increases with altitude), the results of wind speed measurements depend on the altitude above sea level at which the sensor of the measuring device is located. On the *Dar Młodzieży* sailing ship, the wind sensors are located at the top of the mizzen mast, that is approximately 40 m above sea level. It is generally accepted in meteorology worldwide that an altitude of 10 m above sea level is the standard height for measuring wind parameters. The relationship between wind speed and height is presented by the following relation:

$$v_w(h) = v_{10}\left(\frac{h}{h_{10}}\right)^{\alpha} \tag{5}$$

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Table 1. *Friction coefficients of various land spots.*

Landscape type	Friction coefficient α
Lakes, ocean and smooth hard ground	$0 \cdot 10$
Grasslands (ground level)	$0 \cdot 15$
Tall crops, hedges and shrubs	$0 \cdot 20$
Heavily forested land	$0 \cdot 25$
Small town with some trees and shrubs	$0 \cdot 30$
City areas with high rise buildings	$0 \cdot 40$

where

$v_w(h)$– wind speed [*m/s*] at altitude h,
v_{10} – wind speed [*m/s*] at 10 m,
α – Hellman exponent.

The Hellman exponent is closely related to the topography of the terrain and is often taken for an open area to be equal to $1/7$. Note that this parameter can change from $1/7$ in daytime to $1/2$ at night. The Hellman exponent (friction coefficient) is set empirically and varies with height, hour of the day, time of the year, land features, wind speed and temperature (Bañuelos-Ruedas et al., 2011). Table 1 presents values of friction coefficients for different terrain types depending on surface roughness (Bansal et al., 2002; Masters, 2004; Bañuelos-Ruedas et al., 2011; Patel and Beik, 2021).

The choice of a value for the Hellman exponent for a sailing vessel in the open sea can be debatable and values assumed in various sources range from $0 \cdot 06$ to $0 \cdot 27$ (Kaltschmitt et al., 2007). In practice, charts (Figure 10) are used that allow for converting wind speed for different altitudes (Genov and Kralov, 2018).

Wind direction is usually measured simultaneously with speed measurement. Wind-measuring devices record the speed and direction of the apparent wind, which, after taking into account the vessel's speed vector, are converted into true wind values. For the sailor, it is the apparent wind that is important, as it determines bracing and sail trimming. Note that the apparent wind direction, similarly to the increase of the actual wind speed, changes with altitude, so the angle of attack of the wind on the sail will increase with altitude (Marchaj, 1970, 2000; Lasher and Flaherty, 2009). Therefore, to make optimum use of the wind force, the so-called fanning pattern is used for bracing (how the rigging is set), as shown in Figure 11. The bracing difference between the lowest and highest yard, depending on wind strength and course relative to the wind, can be in the range of 1–3 points (Ghys and Dean, 1995).

The wind meter sensor must be located where the rigging does not interfere with the airflow. The top of the foremast would be the most appropriate place in this respect.

Note that wind speed is one of the main factors in determining the appropriate sail conditions (discussed in paragraph 3.2). However, the safety of the crew and the vessel should still be the priority. The direction of apparent wind determines how the rigging braced to generate the greatest possible aerodynamic force, which determines the speed of the vessel.

4.2. State of sea

Wind direction and speed can be accurately measured with a windmeter, while wave-related values are estimated rather than measured. The precise measurement of wave parameters (height, length, period) on a ship would require a complex apparatus. (The difficulty arises from the fact that the observer is moving in the medium whose parameters are to be measured.) The wave height (H_w) and its length (L_w) increase as the wind speed increases. The height-to-length ratio is called the wave steepness, and it decreases with the length of the wind action period and ranges from $1/7$ to $1/35$. The wave size also depends on the extent and depth of the sea. The speed of a wave is proportional to its length and is

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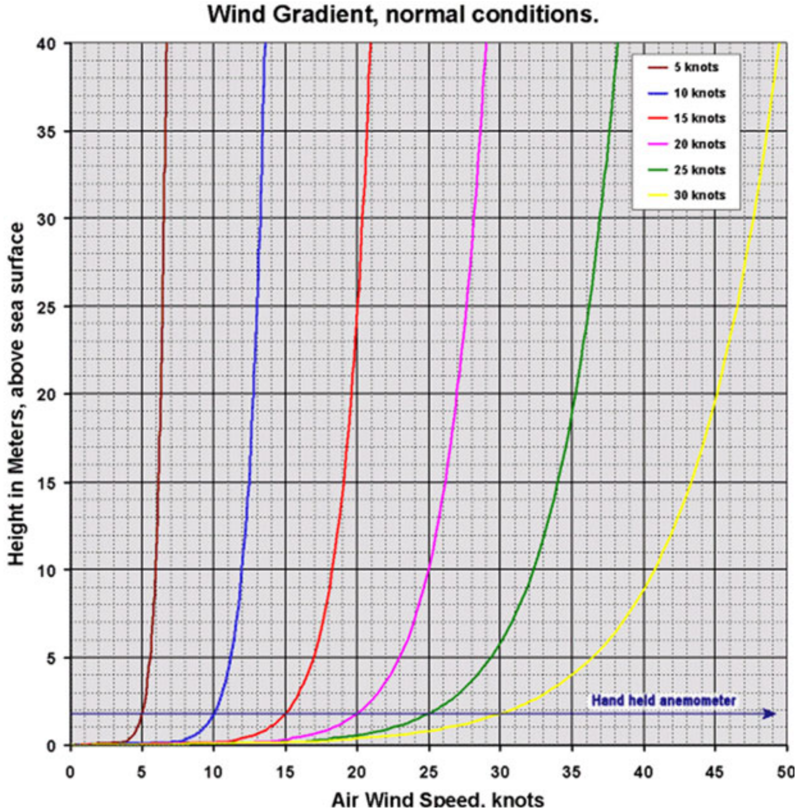

Figure 10. *Vertical wind speed gradient (Frank, 2003).*

Figure 11. *The Parama windjammer braced with fanning (Villers, 2009).*

calculated using the following formula:

$$C = \frac{L_w}{T} \tag{6}$$

where

C – wave speed $\left[\frac{m}{s}\right]$,
L_w – wavelength $[m]$,
T – wave period $[s]$.

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The wavelength can be assessed visually by comparing it to the length of a ship, for example, and thus the wave speed can be calculated using:

$$C = 1.25\sqrt{L_w} \tag{7}$$

Each ship has a natural rolling period, and if this coincides with the wave period, it can lead to resonance, causing rapid, increasing and slowly fading ship movements (rolling), resulting in energy waste and loss of speed. The wave period can be assessed by measuring the time taken by successive wave crests to pass through a specific point on the water (cork, buoy) (Marchaj, 2013).

Both wind waves and swell should be considered. A careful observer can sometimes distinguish between several waving systems (Trzeciak, 2011; Montazeri et al., 2015). For simplicity, one dominant swell system can be assumed alongside the wind wave. What matters for ship speed is the relative wave direction (course angle) (Czajewski, 1988). Each hull works differently on waves, and the captain, especially in severe weather conditions, experimentally determines the optimum wave heading angle at which the ship behaves most stable and does not resonate (rolling and pitching). From the point of view of speed optimisation, any movement of the ship resulting from wave influence causes a reduction (rarely a temporary increase) in speed, due to an increase of the hydrodynamic resistance and a decrease of the rigging efficiency. As a result of heaving, a sailing ship also loses its ability to sail sharply upwind, which, when tacking, translates into a loss of speed in moving towards the target. Rolling and swaying cause a deterioration in sail performance due to changes in wind attack angle and apparent wind speed, which causes sail fluttering in light winds.

When planning research, it is essential to assume external conditions (wind speed and direction and sea state) that allow for drawing conclusions of greater practical relevance. Therefore, it is advisable to conduct individual experiments under similar hydrometeorological conditions. Periods with excessively developed swell and wind waves should be avoided.

4.3. Sail condition (set)

In this paper, internal factors that are out of the scope of influence of the Master and the crew, for example, resulting from the ship's structure, will not be taken into account. We are only interested in variables that, during normal ship operation, can be influenced by the sailor. Such parameters that have a significant influence on the speed of the vessel include the sail condition. The sail condition is defined by a specific set of sails, usually calculated at the construction stage and verified during sea trials. The selected set of sails is included in the ship's stability documentation in the section entitled 'Stability Information for Ship with Sails'. For the example sailing ship, the *Dar Młodzieży* frigate, this includes six sets of sails which may be set depending on the wind force. Such limitations result from stability criteria, and the main parameter is the ship's flooding angle (Scott, 1992; Lasher and Flaherty, 2009; Jespersen, 2015; ChD& C, 2020). Flooding angle refers to the heel angle at which water begins to enter the ship interior through openings that cannot be watertight sealed.

Table 2 presents three sail conditions (for two sailing ships: *Dar Pomorza* and *Dar Młodzieży*) used for sailing from nominal conditions (5°B) up to wind force of 7°B.

If hydrometeorological conditions are difficult, for safety reasons, it is necessary to reduce the number of sails by furling them starting from the highest ones. Table 3 presents three sail conditions used during storm sailing.

For research considerations, the three storm sail conditions should be omitted. In storm conditions, speed is not a parameter of priority for any prudent Master. As mentioned, a basic set of sails can be safely used up to a wind force of 5°B. Of course, various intermediate sail conditions variants are used in practice. However, the full sail condition at 4–5°B wind speed should be condition to be analysed.

In conclusion, to achieve the highest possible speed on a sailing ship, given the existing limitations, as many sails as possible should be set to obtain the maximum aerodynamic force. As mentioned, the limitations are mainly due to stability criteria (sail conditions). Carrying a large number of sails may

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Table 2. *Sail conditions for sailing under nominal conditions up to 7°B.*

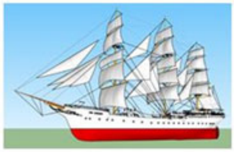
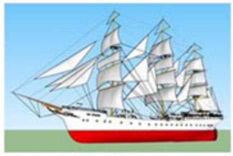
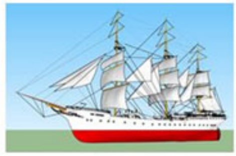
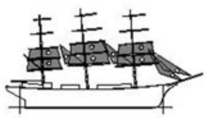
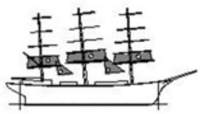
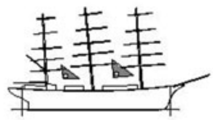
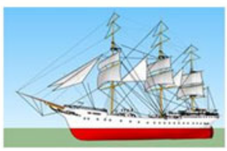
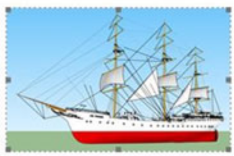
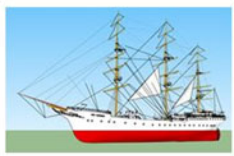
Sail Condition	Basic	Shortened I	shortened II
"Dar Młodzieży"			
"Dar Pomorza"			
Permissible wind force	5° B	6° B	7° B

Table 3. *Sail conditions for sailing under storm conditions.*

Sail Condition	Storm I	Storm II	Storm III
"Dar Młodzieży"			
"Dar Pomorza"			
Permissible wind force	8° B	10° B	12° B

cause the ship to heel excessively, which causes an increase in hydrodynamic resistance resulting from the asymmetry of the underwater part of the hull and is associated with a loss of speed. Therefore, the surface area of the upper sails (which causes the greatest heeling moment) should be reduced. When running downwind, consideration should be given to furl the triangular sails not in operation covered by square sails and, in light winds, some of the square sails on the stern mast can also be furled.

4.4. Yard bracing

Bracing principles on different courses to the apparent wind have been extensively described in the literature by practitioners and the differences are usually due to the characteristics of a specific sailing vessel (Dana, 1841; Harland, 1985; Daniels, 1990; Scott, 1992; Ghys and Dean, 1995). This is especially true for the course with the smallest angle to the apparent wind, called a close-haul Figure 12.

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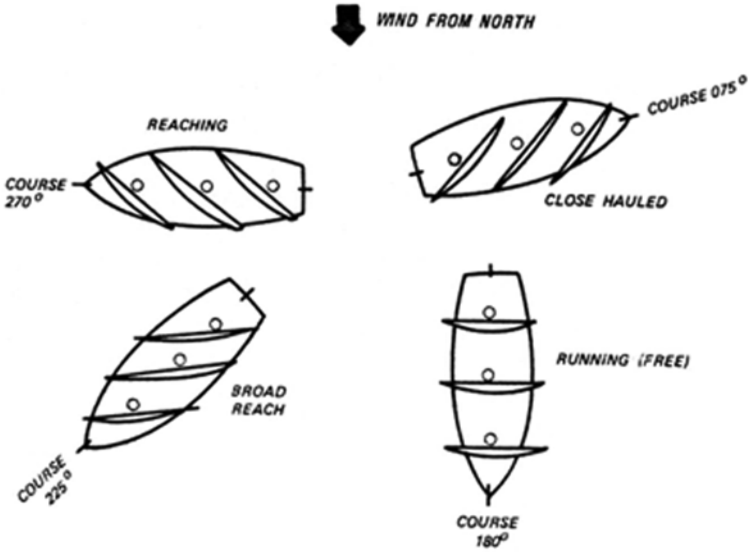

Figure 12. *Courses relative to the wind.*

The minimum angle at which she can sail in relation to the wind varies depending on the rigging type and the size of the vessel. For yachts, without square rigging, this angle is below 40 degrees (Figures 13 and 14).

The polar diagram shows the speed of a sailing vessel for different wind speeds depending on the wind angle. Each curve represents a different wind speed, and the ship's speed for the angle at which the wind is blowing can be read on the vertical axis. Designers usually draw up polar diagrams experimentally during sea trials. A correct chart should refer to the speed and heading angle of the true wind and the ship's speed through water and not over the bottom.

When sailing downwind, any sailing vessel, achieve maximum speeds around reaching (i.e. from close beam reach to close broad reach), assuming that the sail condition remains unchanged. This is because these courses exhibit the most favourable distribution of driving force (F_F) in relation to the drift (F_D) with simultaneously high force of the apparent wind. In broad reaching, the drift component still decreases, but the sails start interfering (blanketing), and the apparent wind speed decreases as well, resulting in a much smaller driving force than on courses closer to the wind (Figure 15).

As can be seen from the polar diagrams (Figures 13 and 14), the dead angle for a square-rigged sailing ship is at least 60°, and for a Bermuda-rigged yacht, it can be significantly below 40°. In practice, for a sailing ship such as the *Dar Młodzieży*, the dead angle is at least 6 points plus the drift (about 75°), so reaching the waypoint located exactly upwind is a very difficult and laborious task for a square-rigged vessel (Dana, 1841; Harland, 1985; Daniels, 1990).

For a square-rigged ship, it is crucial to properly adjust the angle between the ship's centre line and the yard whose minimum value is not less than 3 points lines (1 point = $11 \cdot 25°$) and which results from the physical limitation in yard movement in the horizontal plane due to the fixed rigging (shrouds and stays). The minimum angle between the direction of the apparent wind and the yard line (bracing angle) is assumed to be two points, and the optimum angle is assumed to be 27° (Marchaj, 2000; Willis, 2003). The sum of these angles plus the drift determines the ability of the sailing ship to sail upwind. While sailing close-hauled, the bracing angle cannot be changed, when sailing further from the wind (from rap full to downwind running) it is possible to set the bracing angle greater than two points. In practice, from the broad reach, the yards are braced square, that is perpendicular to the ship's centre line. Various sources provide different values. Table 4 presents these values for the American bark *Eagle* (Daniels, 1990).

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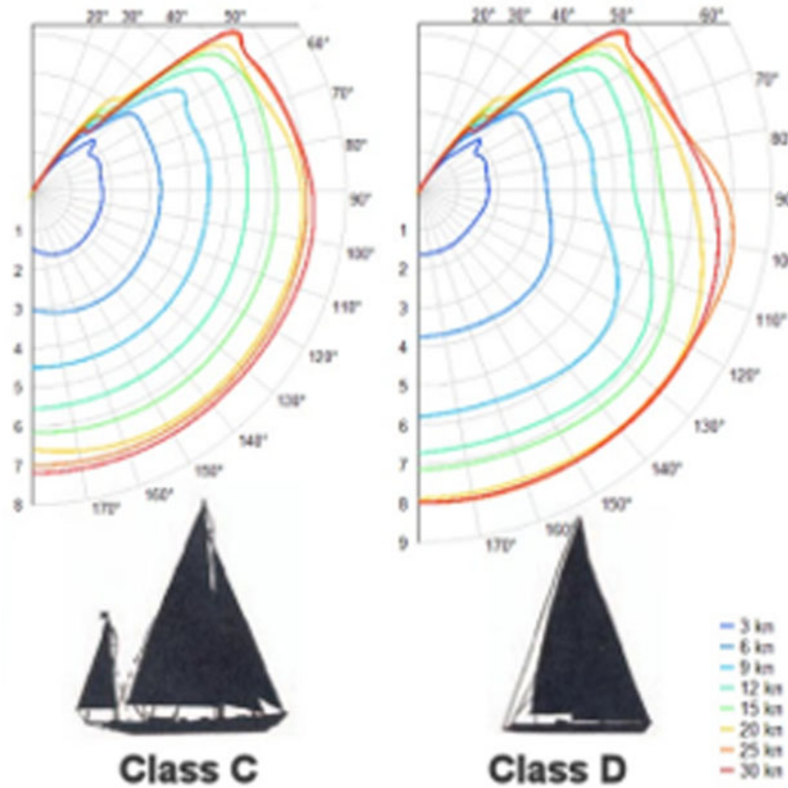

Figure 13. *Polar diagram of vessel speed in relation to wind speed and wind angle – for yachts. (Żegluj.net, 2014).*

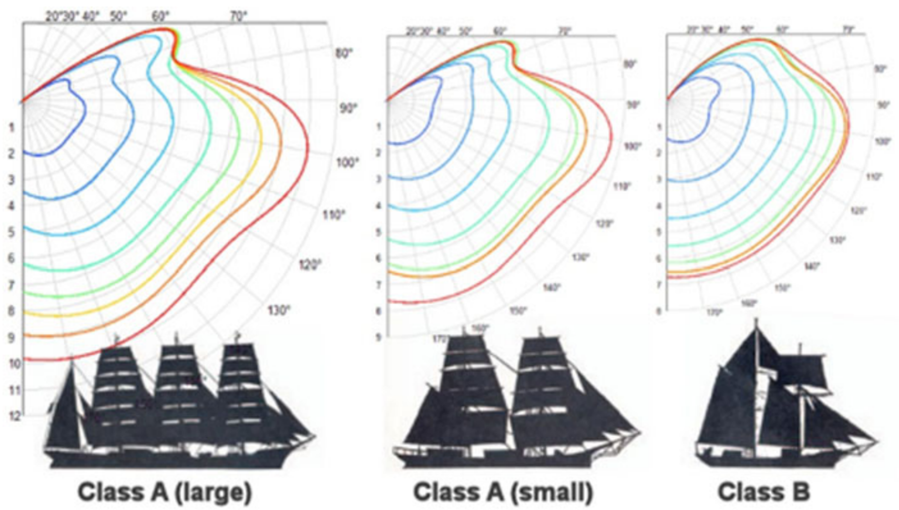

Figure 14. *Polar diagram of sailing vessel speed in relation to wind speed and wind angle – for sailing vessels of varied sizes (Żegluj.net, 2014).*

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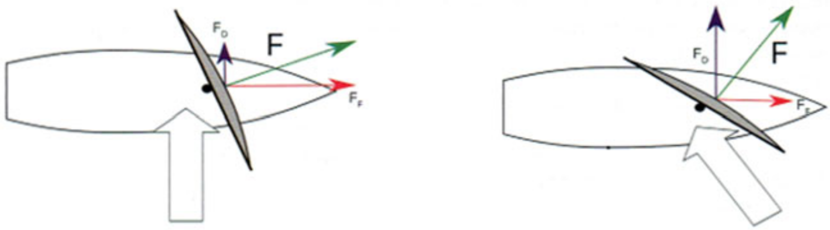

Figure 15. Components of aerodynamic force for beam reach and close hauled (Maracewicz, 2019).

Table 4. Theoretical optimum trim of square sails (expressed in points) to maximise the combined driving force for different points of sail using the example of the bark 'Eagle' (Daniels, 1990).

Relative wind angle to centre line	Best trim of yards from beam	Angle of yards to relative wind
4 points (045,00°)	Sharp	0,5 point
5 points (056,25°)	Sharp	1 point
6 points (067,50°)	Sharp – 4 points	2 points
7 points (078,75°)	Sharp – 4 points	3 points
8 points (090°) (abeam)	Sharp – 4 points	4 points
9 points (101,25°)	Sharp – 3 points	4–5 points
10 points (112,50°)	3 points	5 points
11 points (123,75°)	2–3 points	5–6 points
12 points (135,00°)	2 points	6 points
13 points (146,25°)	2 points	7 points
14 points (157,50°)	1–2 points	7–8 points
15 points (168,75°)	1 point	8 points
16 points (180°) (astern)	Square	8 points

For the bark *Eagle*, an apparent wind blowing from an angle of less than 6 points has been analysed, which, taking into account the authors' experience with *Dar Młodzieży*, seems unrealistic. The term 'sharp' means that the yard is set at the minimum angle to the ship's centre line.

When sailing downwind, thus with the yards braced square, sailing ships get into transverse sway resulting from disturbances in the airflow described in the literature as von Kármán vortices and are additionally effected by waves (Marchaj, 2000). Among other reasons, this rolling causes the speed of a vessel sailing on a downwind course to be lower, and it plays to 'tack' broad reaching. A broad-reaching sailing vessel is stabilised by the asymmetry of the wind action, usually rolling less and achieving higher speeds as compared with downwind running (Marchaj, 1970, 2000). However, the decisive factor why the efficiency of a square-rigged ship in downwind sailing is much lower than in reaching is mainly because the front mast sails are overshadowed by the sails of the rear masts (blanketing). Changing the angle of attack of the apparent wind from 180° to about 150° (and less) increases the efficiency of sails. The standard bracing of all the masts can be changed from square to expose the sails of the foremasts, or the sheets on the aft masts can be loosened to increase the airflow to the sails on the foremast. Sails on the mizzen mast may also be furled for the same purpose (Scott, 1992; Ghys and Dean, 1995).

4.5. Displacement parameters

The displacement parameters, of which trim and draught deserve special attention, are also limited by stability requirements. Under all conditions, the ship should meet the stability criteria and safety issues

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are an absolute priority. Thus, the Master cannot arbitrarily change the draught and trim. Undoubtedly, to increase speed, it is necessary to reduce the weight of the ship by reducing unnecessary stores, excessive fuel and ballast, which leads to a reduction of draught (PRS, 2013; Jespersen, 2015; ChD&C, 2020).

In sailing close hauled, it is important to reduce the sail lead, causing the ship to be prone to luff and requiring excessive weather helm, resulting in increased resistance and reduced speed. To a small extent, the centre of lateral resistance of the underwater hull may be shifted by appropriately trimming the ship aft. This can also be achieved by shifting the sails centre of effort (Marchaj, 1970, 2000; Jobson, 1990, 2004; Garrett, 1996).

Excessive permanent heeling of the ship due to wind pressure reduces the aerodynamic efficiency of the rigging and increases the hydrodynamic resistance of the hull, and obviously is not favourable to speed. Such listing should be reduced at least to the values resulting from stability documentation (flooding angle) and in practice to no more than several degrees.

The metacentric height (GM) determines the ship's susceptibility to heeling. The higher the GM, the more difficult it is to heel the ship, the greater the heeling moment required. Thus, at the same heel, a stiff ship can theoretically carry more sail than a tender one and, therefore, can sail at a higher speed. On the other hand, a stiff ship reacts more violently to waves than a tender ship, which may result in reducing speed. In practice, due to the constraints of meeting stability criteria, there is very little adjustment space for this parameter to improve speed.

The hydrodynamic resistance of the hull depends primarily on its shape but also on the surface condition of the underwater hull. Despite the use of modern self-polishing antifouling systems, ship hulls still suffer from fouling over time, particularly in warm waters and during long stays in roads or harbours. In addition to periodic dry docking and painting the bottom, the hull can also be cleaned on the water. The hulls of racing yachts are polished onshore before racing, which would not be easy to do on a large sailing vessel.

Before changing displacement parameters, the Captain should be aware of their effect on the ship's stability. As with other aspects related to ship and crew safety, meeting the stability criteria has absolute priority over increasing speed.

5. Experimental studies

The issue discussed herein requires extensive experimental research, for which we will use the *Dar Młodzieży* sailing ship, which is a three-masted frigate (displacement: 2,946 t, total length: 108 · 8 m; beam: 14 m; draught 6 · 6 m, number of sails: 26; sail surface: 3,015 m^2; height: 49 · 5 m) or STS *Fryderyk Chopin* brig (length: 55 · 5 m; beam: 8,5 m, draught: 3 · 8 m, rigging type: brig; sail area: 1,200 m^2; displacement: 400 t; speed: 12 kn).The measurements will be carried out in the Gulf of Gdansk (Baltic Sea, Poland). Three measurement systems will be mounted on the vessel.

1. A high-precision GNSS/INS (Global Navigation Satellite Systems/Inertial Navigation System) inertial system consisting of an inertial unit and two GNSS/RTK (Real-Time Kinematic) receivers – Ekinox2-U, whose basic characteristics are presented in Table 5.
2. A regular-precision GNSS/INS inertial system consisting of an inertial unit and two GNSS/RTK receivers – Ellipse-D, whose basic characteristics are presented in Table 5.
3. A high-precision GNSS/RTN system – consisting of four GNSS (RTN) (Real-Time Network) receivers with a measurement frequency of 20 Hz, whose technical characteristics are presented in Table 5.

The technical characteristics of these measurement systems are presented in Table 5 and Table 6. Technical data of GNSS receivers are presented in Table 6.

In addition, the measurements using systems 1, 2, 3 will be supplemented with data from the following sensors:

- Internal – intended to acquire data on the instantaneous real wind speed and the coordinates of the position and speed determined by an onboard DGPS receiver with an accuracy of 1 m ($p = 0 \cdot 95$).

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Table 5. *Precision characteristics of the GNSS/INS systems, models Ekinox2-U and Ellipse-D (SBG Systems, 2021a, 2021b).*

Error measure	Time elapsed from the loss of access to GNSS signal							
	0 s				10 s			
	Ellipse-D		Ekinox2-U		Ellipse-D		Ekinox2-U	
	DGPS	RTK	DGPS	RTK	DGPS	RTK	DGPS	RTK
$\sigma 2D$ [m]	1·2	0·01	1·2	0·01	3	1	2	0·35
σH [m]	1·5	0·02	2	0·02	3·5	1	3	0·15
$\sigma\beta$, $\sigma\alpha$ [°]	0·1	0·05	0·05	0·05	0·1	0·05	0·1	0·1
$\sigma\delta$ [°]	0·8	0·2	0·1	0·05	0·8	0·2	0·15	0·1

where
$\sigma 2D$ – standard deviation of a single 2D position measurement of the IMU;
σH – standard deviation of a single altitude measurement of an IMU;
$\sigma\beta$ – standard deviation of a single inclination angle measurement of an IMU;
$\sigma\alpha$ – standard deviation of a single heel angle measurement of an IMU;
$\sigma\delta$ – standard deviation of a single course measurement of the IMU.

Table 6. *Technical data of reference receivers that we plan to use for research.*

Parameter	Receiver Trimble R10
Signal tracking	GPS: L1, L2, L2C, L5, Glonass: L1, L2, L3, BeiDou: B1, B2, Galileo: E1, E5a, E5b, SBAS: QZSS, WAAS, EGNOS, GAGAN
Accuracy real time	Single baseline: Hz 8 mm + 1 ppm/V 15 mm + 1 ppm Network RTK: Hz 8 mm + 0·5 ppm/V 15 mm + 0·5 ppm
Accuracy post-processing	Static (phase) with long observations: Hz 3 mm + 0·1 ppm/V 3·5 mm + 0·4 ppm Static and rapid static (phase): Hz 3 mm + 0·5 ppm/V 5 mm + 0·5 ppm

- External – meteorological stations recording wind force and direction located around the measurement basin.

The analysis of the structure of the *Dar Młodzieży* sailing ship allows for the selection of locations for the research apparatus. Figure 16 shows the proposed locations for the three measurement systems.

The main INS/GNSS measurement system (Ekinox2-U) will consist of the following components (SBG Systems, 2021a):

- Inertial measurement unit (IMU) (INS/RTN), consisting of three accelerometers and three gyroscopes to measure acceleration as well as angular speeds along the horizontal longitudinal, vertical and horizontal transverse axes of the moving ship.

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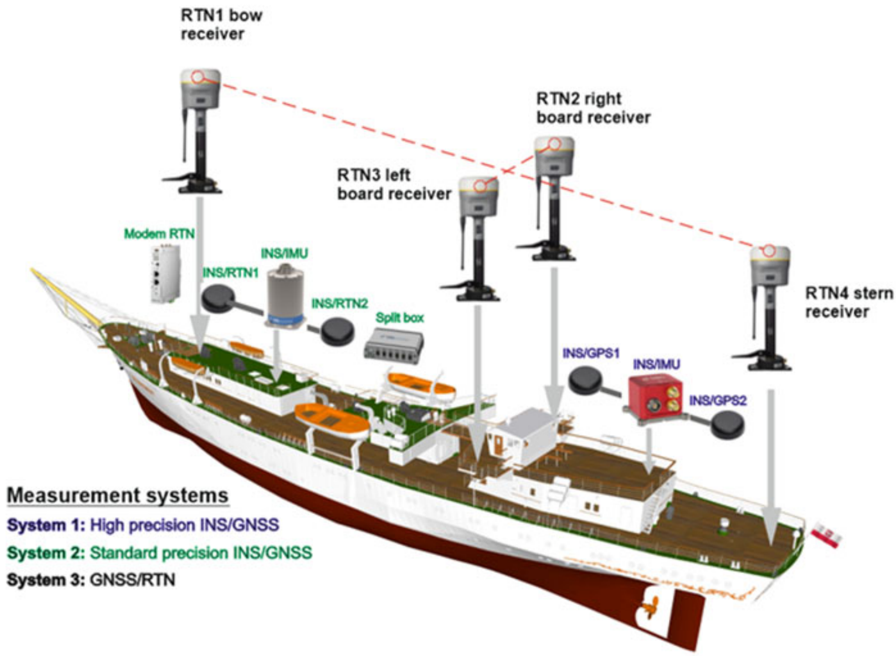

Figure 16. *Location of the measurement apparatus on the Dar Młodzieży sailing vessel.*

- Two AERO GPS and GNSS survey antennas AT1675-382 (INS/RTN1 and INS/RTN2) designed to measure the course of a moving ship. They track GPS, GLONASS Global Navigation Satellite Systems), and Galileo satellites.
- The SplitBox computer system is used to acquire and process data recorded in real-time by two GNSS receivers (built inside the SplitBox system), an IMU, and two external GNSS antennas.
- Modem for receiving RTK/RTN correction corrections (RTN Modem) and ensuring position accuracy of 1–2 cm DRMS (distance root mean square) in the horizontal plane and 2–3 cm RMS (root mean square) in the vertical plane.

In addition, the sbgCenter software will be used to set the measurement parameters and control the real-time operation for the Ekinox2-U system and Qinertia systems to process the data recorded by Ekinox2-U in the so-called post-processing mode.

The Ekinox2-U offers two operation modes:

- Differential Global Positioning System (DGPS) – the method consists in using a base (reference) station – a receiver positioned at a precisely designated point which, on an ongoing basis, determines differential corrections for all satellites in the station's field of view. Another (mobile) receiver must be able to receive these corrections, transmitted in RTCM (real-time correction message), CMR bb, or another format, for example via satellite, VHF, GPRS/WLAN link. This method can be used both in real-time and in the so-called post-processing mode. The DGPS method makes it possible to determine the position with accuracy of 1 m ($p = 0 \cdot 95$) (Specht, 2021b).
- RTK – a high-speed GNSS/INS survey method in which position coordinates are corrected based on real-time INS data.
- The frequency of recording data on angles, accelerations, and position coordinates should be as high as possible. It is recommended that the IMU data be recorded at a maximum frequency of 200 Hz.

Another GNSS/INS system that is planned for use in the study is Ellipse-D, which consists of the following components (SBG Systems, 2021b).

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- IMU (INS/IMU), consisting of three accelerometers and three gyroscopes to measure acceleration as well as angular speeds along the horizontal longitudinal, vertical and horizontal transverse axes of the moving object.
- Two TW7972 Triple Band GNSS antennas with L-band (INS/GPS1 and INS/GPS2) designed to measure the course of a moving vehicle. They track GPS, GLONASS, BDS (BeiDou Navigation Satellite System) and Galileo satellites.

The sbgCenter software will be used for data processing, setting the measurement parameters and controlling the real-time performance of the Ellipse-D system. The functionalities of the Ellipse-D GNSS/INS system that are relevant for the planned measurements are identical to those of Ekinox2-U. Therefore, they will not be repeated.

The accuracy of the GNSS methods is strongly related to the value of the HDOP (Specht, 2022), which is why we need to plan the time and date of the campaign in order to maximise accuracy.

6. Discussion

It should be emphasised that a square-rigged sailing ship is a highly complex system, and there are no simple methods to optimally set all possible parameters and achieve maximum speed. It is, therefore, necessary to select those factors that have already been tested in practice for centuries despite a lack of scientifically monitored experiments. Nowadays, thanks to the advent of very high-precision INS/GNSS systems, it is possible to carry out several experiments to experimentally optimise the sail settings from the point of view of speed.

Correct selection of the angle combined with bracing precision determines the speed of a ship. Setting the sail surface at the optimum angle to the direction of the apparent wind makes it possible to maximise the aerodynamic force obtained. In practice, even a few degrees of difference in bracing have been proven to be significant and have an impact on the speed of the sailing ship. Therefore, bracing experiments will account for the vast majority of the research on this topic.

To ensure the comparability of results, measurements must be made under possibly similar hydrometeorological conditions. It can be assumed that the research will be carried out at full set of sails and wind strength up to 5°B. Please note that for a large sailing ship to manoeuvre with sails smoothly and quickly, it is necessary to involve the whole crew; in the case of the *Dar Młodzieży*, this is about 100 people at a time.

For the experiment, the main variables will be bracing, and the selection of sail set and ship's trim. We plan several sessions depending mainly on hydrometeorological conditions:

Session I – Testing the influence of fanning on speed – nine experiments. In this experiment, for three selected courses in relation to the wind (close-hauled, beam-reach, broad-reach), comparative measurements will be made with the yard braced without a fanning, with a narrow fanning (about 1 point) and with a wide fanning (about 2 points).

Session II – Investigation of the effect of hull trim on speed – nine experiments. For the three selected courses in relation to the wind (close-hauled, beam-reach, broad-reach), measurements need to be made at three different ship trims (even keel, trim by stern, and trim by bow). To change the trim, it will be necessary to ballast the ship. Time-consuming ballast operations consisting of filling and emptying ballast tanks must be taken into account.

Session III – Investigating the effects of bracing on speed on broad reach – two experiments. On a broad reach course, speed measurements should be taken with the yards braced the same on all masts (beam) and masts braced unparallel: foresail – beam, mainsail – 7 points, mizzen-mast – 6 points.

Session IV – Investigating the effects of changing sail set on speed when running downwind – two experiments. When running downwind, measurements should be made with full sail condition and without sails on the mizzen mast.

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The proposed research plan applies only to one wind speed, so further measurements should be made at other wind speeds. These measurements should result in tracing polar diagrams. Additional measurements will collect data for tracing polar diagrams of the sailing vessel speed as a function of the wind speed (in the range of 5 to 20 kn) and wind angle. These tests are to be carried out with the ship in full sail condition.

7. Conclusion

Square-rigged sailing ships are a specific group of sailing vessels whose propulsion system (rigging) is very complex. The development history over the centuries proves that they were mostly constructed for the transport of goods as well as warfare, while the only sailing vessels whose design priority was to maximise speed were the clippers and some warships of the 19th century. Over the centuries, there has been no uniform system for describing the nominal speed of sailing vessels, and it is only since the 20th century that it has been possible to determine the speed of ships quite precisely, making it possible to measure any speed: instantaneous, maximum, average, over the ground or through the water, and so forth. However, it was not until the end of the 20th century that a measurement tool emerged (INS/GNSS RTN system) with enough precision to mark a new era in marine research.

This paper aims to present the most significant parameters influencing the speed of a square-rigged sailing vessel and to select those which are the most significant from the point of view of its maximisation. The paper also proposes methods and measurement systems that allow precise measurements to be made to optimise selected parameters and achieve higher speeds.

The paper concludes with a proposed method and a measurement system for experimental research aiming at rigging optimisation in a square-rigged sailing vessel from the point of view of maximising its speed.

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