A History of Shipping and Propulsion

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Content

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Shipping and propulsion.

1 Introduction

The history of the Netherlands is inextricably linked to shipping, shipbuilding, and trade. The concept of The Netherlands Distribution Country was coined as early as the 13th century. This topic, the Netherlands Distribution Country, and especially the history of origin lends itself to describing the origin of the propulsion of modern ships and paying attention to the associated scientific research. Then you cannot ignore the Netherlands Distribution Country and you can see the development of the Netherlands as a Transport Economy.

2. The Netherlands a Country for Entrance to Europe

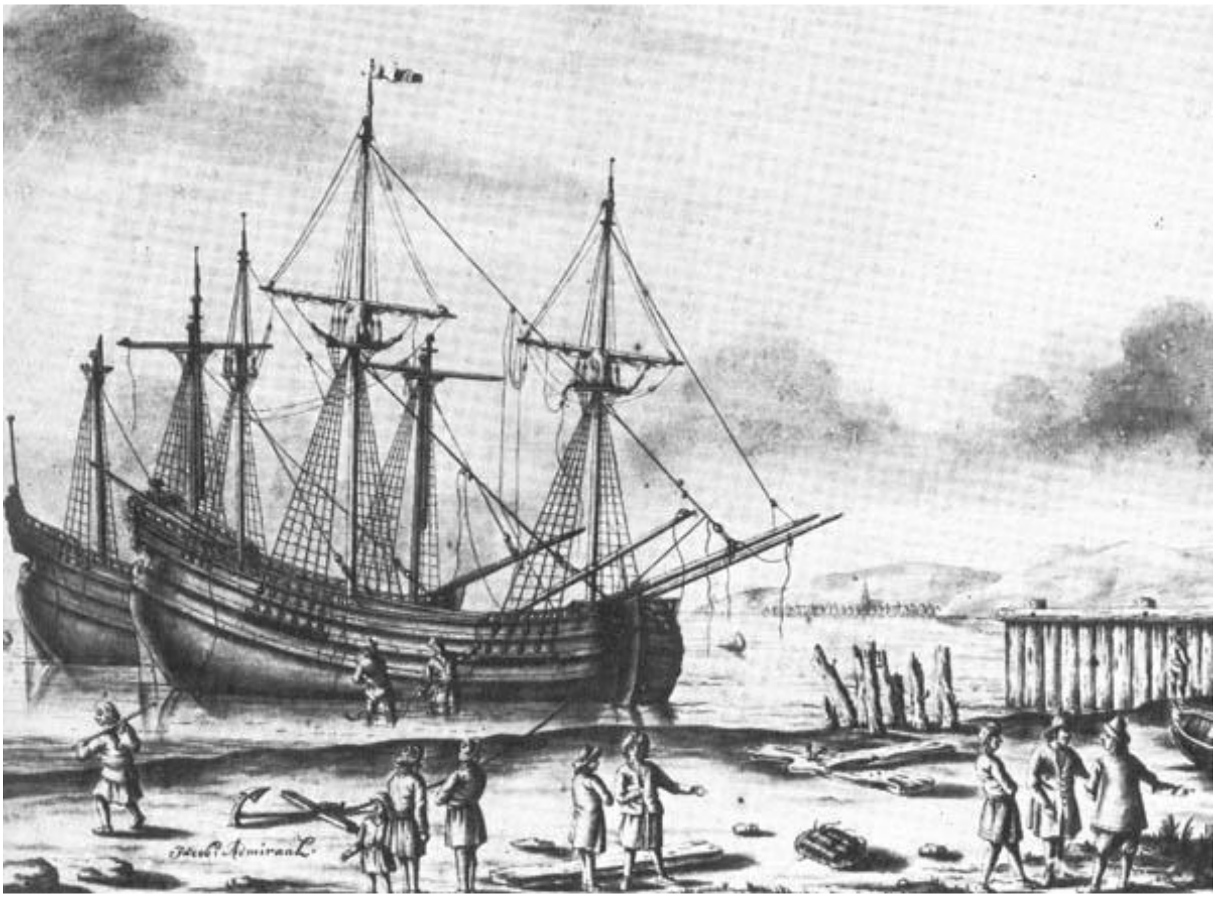
Transport by water and the resulting developments in shipbuilding have strongly influenced the Netherlands. And that goes back in the history of Holland for up to eight hundred years. This can serve as one of the first examples of the so-called 'competitive advantage' of a country. This competitive advantage is strongly linked to the development of the territory of Holland. Until the 13th century, the natural environment (delta, dunes) was an obstacle to the expansion of Holland. It was not until the 12th century that the natural environment around the Zuiderzee stabilized, and the inhabitants were able to build ports there. Towards the end of the 13th century, the conditions for the later growth of Holland were present:

1. A landscape that could only be made suitable and suitable for animal husbandry with a lot of maintenance costs.
2. Geographical location at a crossroads of connecting roads between surrounding leading areas (such as Flanders).
3. A population surplus in rural areas looking for other means of subsistence.
4. Location on large rivers and long coastlines, making shipping traditionally a natural activity.
5. Natural environment stabilized (Around the Zuiderzee).

These circumstances also explain the late time of the development of cities in Holland, which only started well in the 13th century, about two centuries later than in Flanders. The circumstances also make it understandable why, from the late Middle Ages onwards, Holland housed a high proportion of the total population in the cities in comparison with the neighboring countries: there was truly little employment on the flat lands (Netherlands) due to the limited opportunities for intensive agriculture. Also typical was the fact that the population was settled in many small cities. Relative compared to Flanders and Brabant. As a consequence, no city states developed.

The Dutch managed to turn these conditions in their favor. Livestock farming produced dairy products that could be preserved (cheese) and exported to the large urban markets in Flanders and Brabant. The disadvantaged position could thus be exploited as an advantage: Dutch people took advantage of the purchasing power elsewhere. The same thing happened with the imitation(copying) of products developed elsewhere.
Beer (the hoppebier that emerged in the 14th century) was introduced thanks to the transit

route from northern Germany to Flanders and Brabant. So due to the possibility to grow barley on light peaty soils and the presence of pure water, fuel (peat) and good transport possibilities by water, the brewing of beer in Haarlem, Delft and Gouda during the 14th century could take off in such a way that with this beer, the southern Dutch markets could be lavishly foreseen.



3. Shipping and shipbuilding

From the end of the 14th century, the Dutch also received a rapidly growing share in the international trade of barrel-preserved herring. Innovative (We now say) was the creation of the herring ‘buis’. We would call it now a special purpose vessel avant la Lettre.

Figure 1 The Herring 'buis', a special purpose vessel

A ship that was built to process the fish on the return journey - a return journey that took longer and longer, because the fishing grounds in the North Sea were increasingly farther away. Herring was an important part of the food package at the time.

Cheese, beer, and barrel herring were the preserves of the Late Middle Ages, products that the Dutch had copied from the North Germans, but which the Dutch better marketed. From the late 13th century, for example, the drapeniers and craftsmen of Leiden and Amsterdam also managed to gain a place in the international market for cloths.
In doing so, they took advantage of the fact that their Flemish predecessors had to contend with commercial (commercial) difficulties and the significantly lower labor costs in Holland. The absence, late and weak organization of guilds, but especially the wide range of labor offered this "low-wage country", Holland, a competitive advantage (competitive advantage).

Dutch people were able to imitate and adapt products, their costs were lower, but they also had to show initiative themselves to compensate for their structural shortage of wheat to make bread. Trading/barter was very necessary. By being forced to focus on import and export, we get to the heart of the Dutch economic position, which has maintained itself to date and has increasingly strengthened itself: those of intermediaries, freight forwarders and suppliers of cheaper imitations of products developed elsewhere (To think in more recent concepts: "The Chinese of Europe avant la lettre").
Two other factors play an essential role: shipbuilding and shipping. Ships were built in many coastal villages, but international competition also did sit on their hands and innovation remained necessary. Shipbuilding therefore concentrated in several cities, such as Zaandam, where new types with greater payload, higher functionality and greater maneuverability were built than in neighboring countries. Shipbuilding became an important industry, which in turn stimulated various subcontracting companies.
In agriculture, the crops of hemp and flax were necessary to make ropes and sails. Other materials had to be supplied from a long way: wood from Norway and the Upper Rhine region, iron, and steel also along the Rhine, tar, and pitch from Prussia, with Prussia also functioning for ware housing and transit. If you also add to the employment in shipbuilding the crew of shipping, it will be clear the role of the Dutch from the 14th century onwards as the great freighters of North-West Europe was an industry that made considerable use of the available labor force.

At the end of the 16th century, shipbuilding in Holland received a huge boost due to the lifting of the trade ban by Philips II. We are then on the threshold of the Golden Age and the creation of one of the first public companies in the world: the VOC. This created a high demand for transport by ship, resulting in standardization in shipbuilding. This resulted in a huge boost for shipbuilding. After 1570, the Dutch shipyards developed a new merchant ship, the ‘vlieboot’ or flute, again a special purpose vessel. See Fig.2 on the next page.
The etymology of ‘vlieboot’, or flute is clear in connection with the route to and from Amsterdam. In view of the period in which the ship was used, ‘vlieboot’ is obvious. Amsterdam had no direct access to deep water. Ships from the North Sea could arrive at Amsterdam via the Zuiderzee. A shallow water open connection to the North Sea.
The designation "Flute" was used since the shape of the ship is like the musical instrument. De Flute is a product of Dutch shipbuilding. An innovation of classic designs, such as the Herring ’Buis’. The etymology of vlieboot or flute is clear in connection with the route to and from Amsterdam. In view of the period in which the ship was used, vlieboot is obvious. The designation "Flute" was created because the shape of the ship is like the musical instrument. De ‘Flute’ is a product of Dutch shipbuilding. An innovation of classic designs, such as the Herring ‘Buis’.

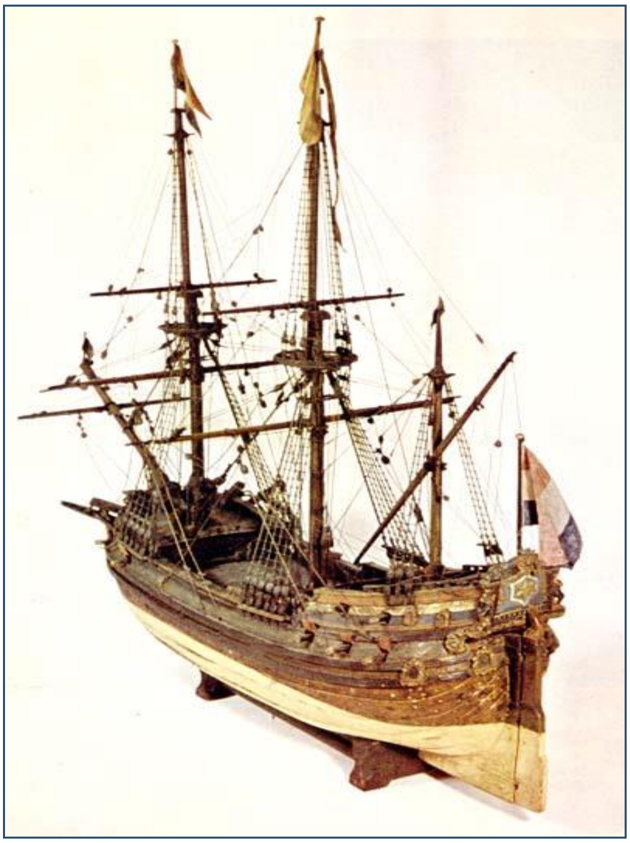


Figure 2'Vlieboot' or flute

The Netherlands focused on the development of ships that were easier to manage and could carry more cargo. [1]

The Flute, a robust round-bellied ship with hefty tonnage, could be operated with a smaller crew, 20% less than on other foreign ships of equal tonnage. A significant advantage. Especially when one realizes that the personnel costs (wages, food) on the long routes (The far East, Levant = De Morgenlanden, all eastwards of Italy) were the most important expenditure item. Dutch thrift would be given free rein here. The daily cost on board was sparse: "fish and barley-gruel (peeled, sharpened and glossed barley)". Even the captains had to settle for a slice of cheese or a slice of salted beef 2 or 3 years old.

Wine was not served there and sometimes in heavy seas a little arak (rice brandy or aniseed brandy) was distributed sparingly.

[1]Unger, R., *Dutch ship design in the fifteenth and sixteenth centuries*, Viator 4, 1973.

Of all the seafaring nations, the Dutch are the most thrifty and austere. They are the least likely to surrender to luxury and unnecessary spending. Holland was the ruler of the seas. Reflections on "the decline and fall of the VOC empire" could be a subject (Sociological and macroeconomically) for research.

4. Propulsion

An important aspect of the ship is how it is propelled. Propulsion – the force needed to keep the ship moving by overcoming the frictional force and the force due to wave generation. One of the oldest forms of propulsion was rowing, followed by the sail. In the case of the older sailing ships, the propulsion was generated by the direct pressure of the wind in the sails. A so-called cross-rigged ship. The flute is another example of this type of rigging. Cross rigging limited maneuverability. An important innovation for the sailing ships was the transition from transverse to longitudinal rigged ships. That transition came extremely late in Western Europe. Certainly, as early as the ninth century, ships with a Latin(longitude) sail sailed on the Mediterranean Sea.

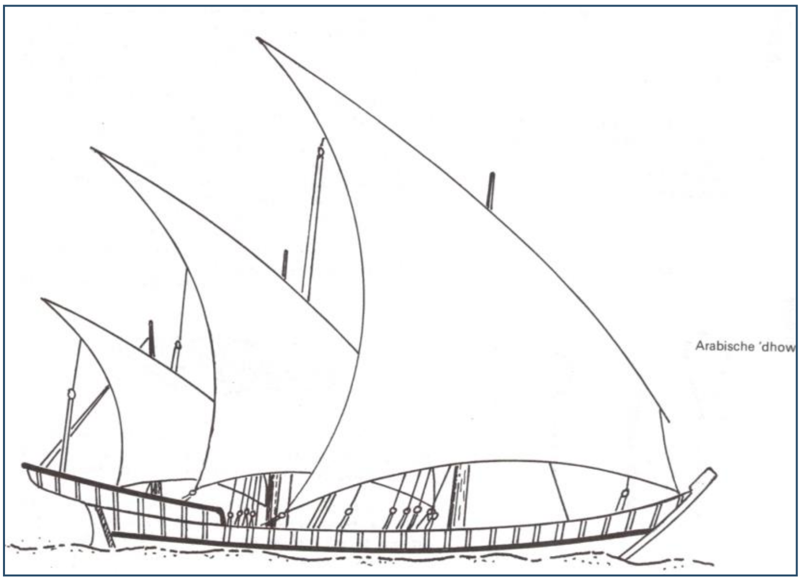


Fig. 3. Latin sail, longitudinal rigged ship. The Arabic dhow.

The Latin sail, a triangular sail with a sloping ra. It was not until the 13th century that this also occurred in Western Europe. The ships with more masts sometimes rigged the rear mast with a Latin sail. Overall, the typical Dutch gaff sail also emerged from this. If we look even further into the world, we can learn from history that even well before the beginning of our era, sailing on the Pacific Ocean was incredibly fast with ships longitudinal rigged with one or two floats (catamaran) fitted. The great significance of the transition from transverse rigged ships to longitudinal rigged ships was to beat up the wind. This led to the construction of long sharp ships modelled after a galley and Arabic dhow. The propulsion force is now created in a completely unique way: the sail for the longitudinal rigged ships functioned more like a wing and the propulsion originates form the lift force, similar with the wings of

an aircraft.
An otherwise important innovation in sailing ships was that the shape of the hull is being sharpened. A development that found its cause in the need to be able to sail sharper. This last type of sharp sailing ships was getting bigger and bigger. However, the limits to the growth of these ships were determined by the stability of these types of ships.

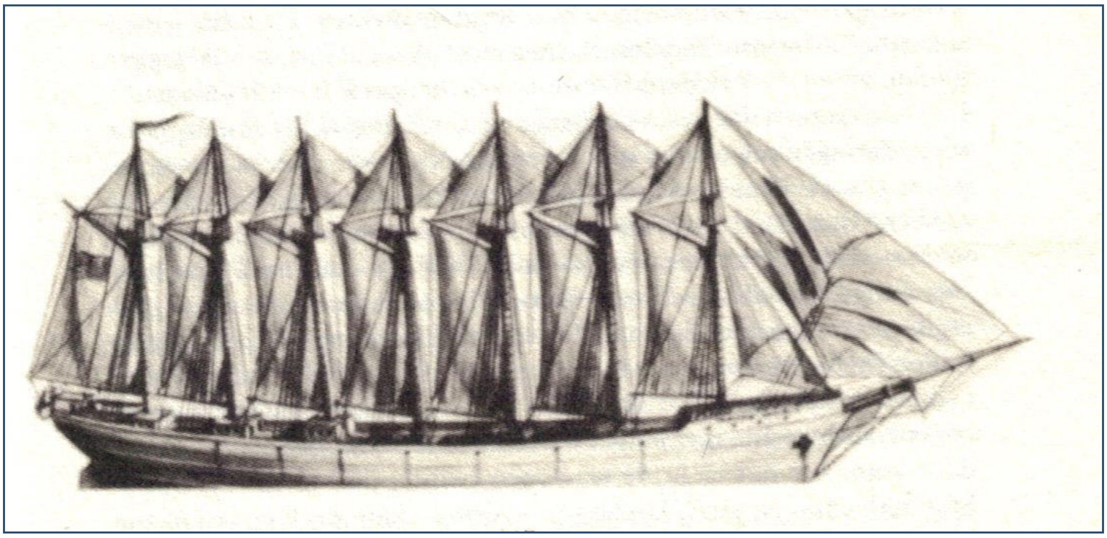


Fig. 4. Thomas Lawson.

In the early morning of Friday, December 13, 1907, the sailing ship Thomas W. Lawson sank near the Scilly Isles of The Channel. All persons on board, except the captain and a crew member, were killed. This was not just a shipwreck on Friday the 13th and the Thomas Lawson was not just any ship: it was something special. It was a beautiful ship, a huge seven mast ship. A clipper. It had to be able to compete with the new steamships, which began to displace the sailing ships from the sea freight transportation business.
The Thomas Lawson, built in 1902 by the Fore River Ship and Engine Building Company in Quincy, Massachusetts, was able to reach a speed of twenty-two knots (nautical miles/hour; or 41.5 km/h; nautical mile is the length of a meridian minute; the Dutch nautical mile was 5.6 km). But this speed was at the expense of maneuverability: the ship was particularly difficult to steer. It was also so unstable that it capsized in a violent storm while it was anchored.
An eyewitness said that when it was found in the morning, the ship was reminiscent of a whale's back... the large hull lay on its side and was flooded by the sea. No one has ever tried to design a faster sailing cargo ship. The time of the commercial sailing ended with the Thomas Lawson – the steamships took possession of the seas. The Thomas Lawson was a tragic example of what happens on the market when a technique reached its limits

Clippers (operated between 1840 and 1850,a type of wooden/later steel sailing ship with sharp bow and somewhat streamlined hull; derived from clipper/sharp object) were already clearly approaching the limits of their possibilities 50 to 60 years before the Thomas Lawson was due to sail.
By the 1850s, the sailing ships had reached their natural speed limits if they had to remain agile. And that was not the case with the Thomas Lawson. Here we also touch on the remarkable effects of innovation and how processes develop. It was clear early on where the limits of growth lay in sailing shipping. Yet the Thomas Lawson was still being built 50 years later. So, it took 50 years for the steamships to displace the sailing ships.
This phenomenon is very recognizable where the limits of a technology are reached. It is only a matter of time before the technological discontinuity comes into full force. There were already alternatives to sailing such as steam powered shipping, which began to take effect around 1840. This question of time of a technological breakthrough is estimated differently in our time. Although the last word on the subject matter is not uttered yet. Very readable in this respect is the article in The Economist of 2013-01-12: "*Briefing, Innovation pessimism. Has the ideas machine broken down?* ". The availability and accessibility of information plays a vital role in the subject matter.

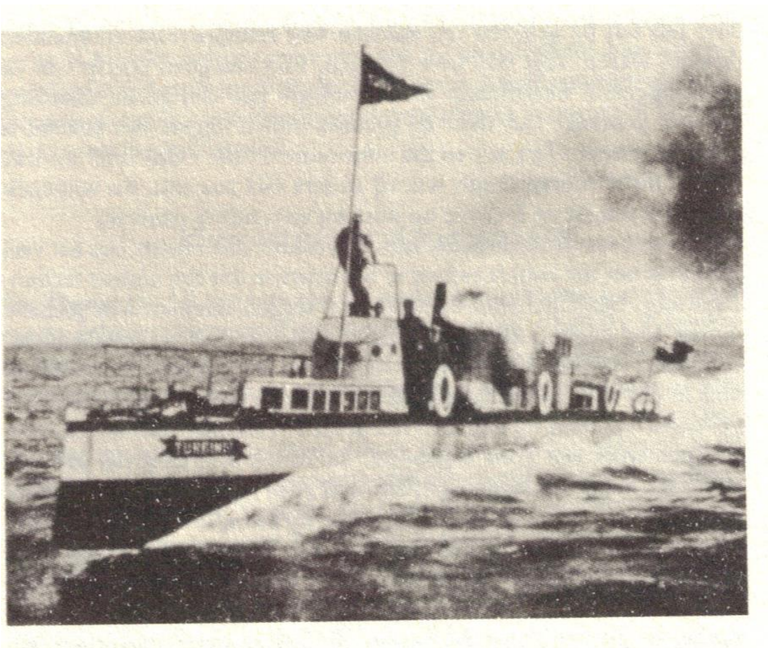


Fig.5. Turbina.

The propulsion by means of turbines, instead of the piston steam engine, as applied to the English ship Turbina also took effect, is true experimentally, but the changes were clearly visible. It was also known that these ships could sail much faster than ships powered by sails and therefore their breakthrough was inevitable. We do talk about discontinuity. And that often is the case. But from the proven technology - in this case powered by sails - the counterattack was deployed. Successful defenders often add elements of the modern technology to the old technology. The literal example of this is the installation of a steam engine in a ship powered. For a while, these so-called hybrid ships were more cost effective than the ships powered by sails or steamships. Hybrids were in operation for almost one hundred years. That was the situation when the Thomas Lawson was designed, built, and put into service. It was an experiment that was doomed to fail. So, we are talking about discontinuity, but breakthrough times of 50 years are common. The application of electricity is also an example of long lead times.

5.Propulsion: Research

So, steamships became it. A completely different propulsion than propulsion via sails. Propulsion, the term/word has already fallen a few times. What does this mean? The concept indicates that we need to exert a force on the ship to make it move. Why is that? The ship, the moving hull, experiences a counter-force due to the movement of the hull through the water. This counterforce is called resistance and it is made up of two components: the wave resistance and the friction resistance.

These phenomena are studied/investigated in hydrodynamics. Aerodynamics is a more well-known concept than hydrodynamics. This is probably because the concept of aerodynamics relates to streamlining the popular means of a transport car. For example, aerodynamics deals with the interaction between the moving car and the surrounding air. Hydrodynamics treats, among other things, the interaction between liquids and solids such as a moving ship's hull. So, if there's movement. This is contrasted by hydrostatics. Hydrostatics shall cover the interaction between liquids and solids as far as these liquids and solids are in a state of relative calm.

A ship that sails at a certain speed through the water (the liquid) experiences a counterforce from that water, called the resistance. As the speed of the ship increases, as a rule, resistance will also increase. The speed of the ship will remain constant if the driving force (thrust) is the same as the counterforce (resistance). Then we have an equilibrium between the two forces. Newtons third law. For a ship, with a given thrust, to achieve the highest possible speed, the resistance must be as low as possible. Consequently, the resistance is significant for the speed to be achieved So, a lot of research has been done to be able to predict the speed. The total resistance experienced by a hull sailing in the water is split into the two components.
These components are:

- Wave-forming resistance.

- Friction resistance.

Both types of resistance are determined by the shape of the ship and the speed at which it sails.

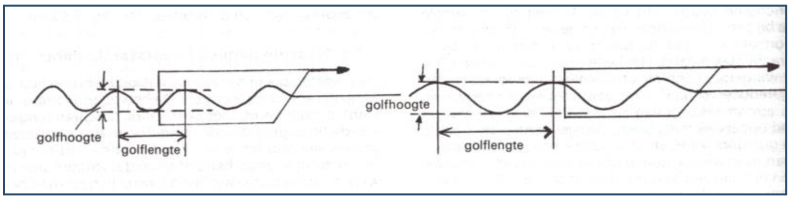


Figure 6 Wave resistance

In Figure 6 above, two waves are presented for a low speed, on the left, and for a higher speed on the right. Notice the differences between the wavelength(golflengte) and wave height(golfhoogte).

A moving ship generates a wave system. A V-shaped wave pattern consisting of a bow wave, a stern wave and transverse waves is created. We have all seen this from a passing ship. There's energy in this wave system. The energy required to generate this wave system is supplied by the ship. The faster a ship sails, the greater the wave forming resistance. The theory for wave resistance, was translated by William Froude around 1870 into the practical application for the design of ships. Under certain conditions, the wave resistance of a ship can be reduced. This is achieved by adding a spherical body to the front(bow) of the ship: a bulbous bow. This type of bow is designed to reduce the wave resistance at most for the designed cruise speed.
A clear application of a hydrodynamic analysis of Bernoulli (1700-1790), a Japanese invention and a Dutch application (innovation). An example of such a bulbous bow is shown in Figure 7 below, in a dramatic situation, March 2021[2].

Figure 7 A Bulbous bow in a dramatic and spectacular situation March 2021 Suez Canal

[2] What really happened in in the Suez canal drama is a matter of further investigations and probably research. On the other hand, I assume a model of this huge container vessel has been evaluated under Suez canal conditions. Wind , manoeuvrability, etc.

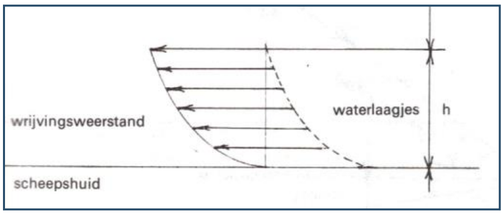


Figure 8 Resistance due to friction

The other component of the resistance, which is not as visible as the wave resistance, is the friction resistance(wrijvingsweerstand). The water is slowed down by the hull. Illustrated in Figure 8. On the hull(scheepshuid) there is a layer of water(waterlaagje) that is connected to the adjacent layer. This creates the frictional force. The friction resistance is proportional to the square of the speed. The hydrodynamic knowledge is of immense importance to be able to design ships. In the past, more than 150 years ago, this knowledge was based on practical experience transferred from father to son. Why something worked or did not work was hardly understood.

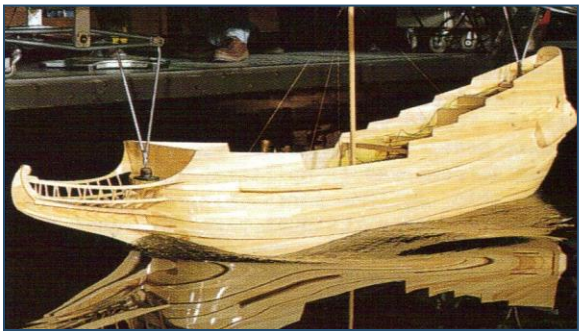


Figure 9 A model of the Batavia

Despite that, there were many successful shipbuilders. An example of such a ship is the Batavia (17th century, Figure 9). The ship was designed to carry a certain cargo at a certain speed (given the wind).

The design of the ship was therefore mainly based on experience and only the stability (hydrostatics) was the subject of scientific research related to shipbuilding. The knowledge of the stability of ships is vital for shipping. Some shipwrecks, such as those of the Thomas Lawson, but also those of more recent date off the coast of Zeebrugge in 1987 and November 2007 when the ship ACIT III capsized off the island of Sulawesi (It flipped over after passengers climbed on the roof to have better range with their mobile phones). The ship became unbalanced and capsized. Extremely wry: to use modern technology, one forgets the ancient science of hydrostatics) harrowingly demonstrates what can happen

when a ship is no longer stable.
Stability is part of the hydrostatics, which were first studied by Archimedes (287-212). Not only is the hydrostatic ab ovo (Latin, but it should also actually be in Greek. Archimedes' studies, however, have been translated from Arabic into Latin) but also done with high mathematical rigor and elegance. Even today, the depth and – outright – genius of Archimedes' study of floating bodies are impressive.
Archimedes' book "From Floating Bodies" was the first study in which mathematics and physics go hand in hand. This Greek methodological innovation still dominates physics to this day. The person who took over the torch from Archimedes was Simon Stevin (1548-1620). Stevin specifically covered the stability of ship (such as ladders on ships associated with warfare. So how high were ladders allowed to reach?). However, his work does not reach the level of Archimedes. Which problems need to be solved? Does a ship turn easily, is a ship wobbly? All things that we know well with our current pleasure ships, sailing yachts, etc. It is about knowing the conditions under which a ship easily stabilizes. So, these were critical issues and still are. Christiaan Huygens (1629-1695) also dealt with this matter. He reached the level of Archimedes, but this aside. This theoretical work was significant in the design of ships. But for the development of a theory for the resistance of ships further work must be done.

Even though ships have been built for thousands of years, predicting the resistance of a ship (hydrodynamics) has only become urgent when slaves and sails were replaced by machines. But until about 150 years ago, experience was the basis for the design of a ship.
Shipbuilders are always faced with the question: how do you know in advance that the ship will meet the requirements?
The relationship between the main dimensions of a ship (length, width, and draught: the waterlines), the shape of the hull and the sailing characteristics were hardly supported by theoretical and experimental research.
The idea might be that real research was only done in the development of the first steamships. To assess the speed of a ship with a given engine (steam engine) it is necessary to know the resistance. Fulton constructed the first steamship in 1807. However, before then, scientific studies were already being conducted on the movement of ships.

The first study devoted to movement of bodies in water was written by Leonardo da Vinci (1458-1519). This document surfaced three hundred years later. In 1687 Isaac Newton was the first to develop the theory of the resistance of a moving ship in water. This study was published in De Principia. In 1749 Euler developed a theory for the flow around a ship. Yet the shipbuilders hardly used the results of science. This also had to do with the fact that the experiments and the theory were unsuitable to predict the full-size performance of a ship. This is unlikely to be a full explanation. The application of science and the development of physics only started after the Renaissance and enlightenment.

Laboratory tests/model tests with scale models of ships were conducted for the first time around the beginning of the second half of the 19th century. So as now wind tunnel trials are done with cars.

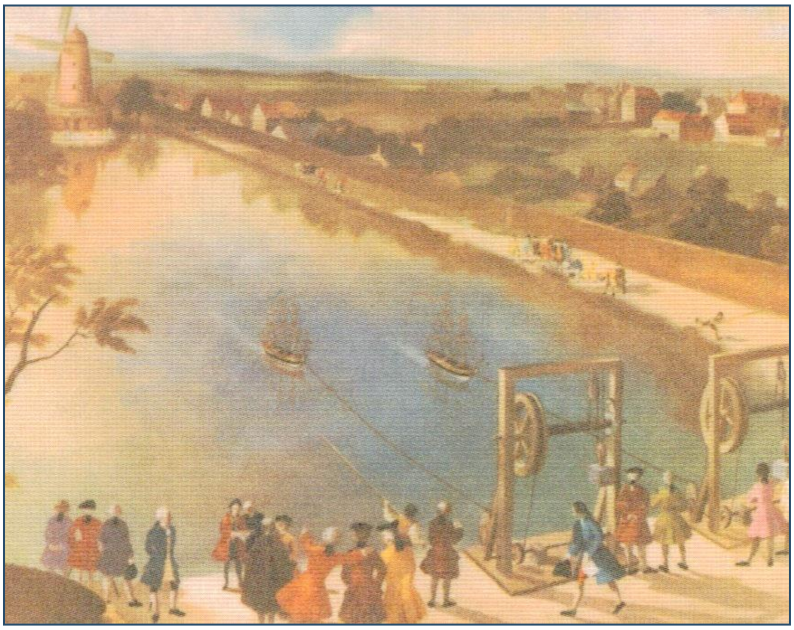


Figure 10 Towing test with ship model

These towing tests – the scale model was towed through the water, Fig.10 – were conducted to determine the full-size resistance of the ship. This method failed because no meaningful conclusions could be drawn from these measurements. Of course, this conclusion can only be drawn if one had full-size measurements, the real ship. Full-scale measurements, in those days, must have been very inaccurate. However, the errors in the predictions from model measurements were probably that large making a meaningful prediction impossible.
Around this time with an increasing need for meaningful predictions, wood as building material for ships was replaced by steel and sailing ships by steamships.

Figure 11 A ship propeller

Steamships, first propelled by paddlewheels, then by the much more efficient ship propellers. Under the influence of the fast steamships – the modern technology – society changed significantly. Globalization and the need for leisure time arise. It was about 1850.

Because of these changes, the experience in shipbuilding, transferred from father to son, was no longer sufficient to build ships. The experience accrued for building wooden ships could not be used for steel steamships. These changes, from wood to steel and from sailing ships to steamships, were significant because essential questions had to be answered, such as how much power does the steam engine have to deliver to allow the ship to sail at the desired speed?
It was, of course, too expensive to build the ship first and then to find out from practice that it was good or not. The idea of using scale models became increasingly strong. The problem was to fill the gap between science and practical application. This clear need stimulated enough creativity to bridge this gap and start applying science. It was William Froude who invented a practical method, to make scale tests meaningful, based on the scientific knowledge of that time.

How did this work? As we have seen before, the resistance of a ship consists of two parts: the wave resistance and the friction resistance.

For model/laboratory tests to make sense, Froude inferred the scale rules the test had to comply with to make meaningful predictions for full scale. However, the wave resistance scale rule is different from rule for the friction resistance. If the wave resistance scale rule was met during the test, it was known that of the total resistance measured, the wave resistance was simulated correctly but the friction resistance was not. Both forms of resistance cannot be measured separately either. In the jargon, failure to comply with the scale rules is called "scale effects". To be clear: the ratio of dimensions between the ship and the model ship is called scale. Hence the expression scale effects. However, with the help of the friction theory from hydrodynamics, correction factors can be derived. Froude proposed and applied these factors..

Froude's example of building a towing tank. A container with water where the model was towed through. The first towing tank was followed by the construction of a second towing tank in the Netherlands for the Benefit of the Dutch Navy. A Navy maintenance dock was used as a towing tank. This facility was commissioned in 1873 and served until about 1900. Many tests were conducted for the Dutch Navy, but models of commercial vessels were also evaluated to determine the optimal shape.

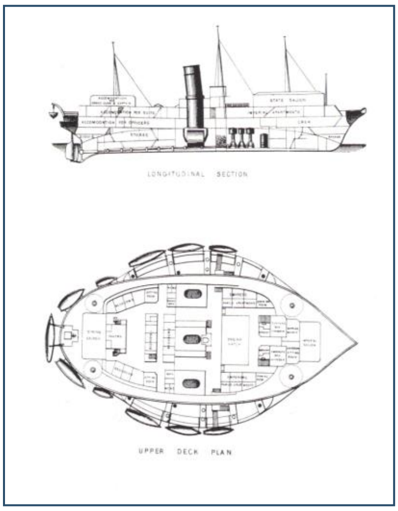


Figure 12 The Livadia

It is worth noting that the model of the yacht "Livadia", Fig.12, of the Russian Tsar was also evaluated in Amsterdam around 1878. Around 1910 there were about twenty towing tanks/laboratories available for the seafaring nations. Around 1900 the first Dutch towing tank was closed. It is not clear exactly what the reasons were for abandoning further use. In any case, the construction of a new towing tank was waived because of the cost.

Figure 13 Towing Tank NSMB(MARIN)

However, attempts were made over time to build another test laboratory. Around 1932 the decision was made and on 9 May 1932 the inauguration of MARIN (then NSMB, Fig. 13) took place. 3 Years after the Foundation for the Research facilities was constituted. MARIN was founded by the Dutch State, the "Stoomvaartmaatschappij Nederland", the "Koninklijke Rotterdamse Lloyd", the "Koninklijke Pakketvaart Maatschappij" and the " Nederlands Indische Tankstoomboot Maatschappij".

If we make a leap in time to 2007, we know it is MARIN’s anniversary 75 years. Quite a bit has happened in those 75 years of MARIN's history. How do you run a research facility over the years with difficulties of shipbuilding? Shipbuilding as we know it from the 60's and 70's of the last century has completely disappeared from the Netherlands. How do you adapt the company to that? Which developments are being followed and which are not? All aspects of shipping and offshore activities are investigated in the eight facilities located in Wageningen and a branch in Ede. Experimental as well theoretical.

Let us focus now on the science of shipbuilding.
We took notice of the necessity to be able to predict how a ship will behave in full scale. We want to achieve with simulating in the laboratory, reality is approached as closely as possible.

So, we want to know/predict several things:

- What is the resistance of a ship at the desired cruising speed.

- What propulsion power is required for this.

The law of conservation of misery also applies. When conducting laboratory tests in a towing tank, we suffer from the scale effects. Resistance cannot be easily predicted from a laboratory measurement. We have seen we need to introduce correction factors. How good or how bad are these correction factors? We only have one way to determine this and to make measurements on real ships (on full scale). Measuring under real - non-laboratory - conditions is no easy task. A profession. But still necessary. As soon we have an opportunity to measure at full scale, MARIN uses this opportunity. MARIN has a database from the model measurements (laboratory), theory and practice (full scale). With the help of this database, model tests and theory, good predictions can be made for new ships to be built. Alas, if we now think the law of conservation of misery no longer applies, we end up deceived. Due to all kinds of new developments in shipbuilding – related to energy saving – research will always be necessary.

The resistance of a ship is balanced by the propulsion force. This power to create this propulsion force is supplied by the marine engine. The power of the engine is converted via the ship's propeller (Fig.11) into the propulsion force balancing the resistance force. How does this propulsion come about? Simply put, one can take a propeller as a collection of wings. A moving wing generates lift. Like a wing of an aircraft. The lift, in case of a propeller, is converted into a horizontal force pushing the ship. This propulsion force is also measured in model tests (laboratory) and translated into full scale propulsion force. Also, for propulsion, the full-scale force cannot be precisely predicted. Here, too, scale effects play a role. Reality cannot be simulated on the right scale in the laboratory.
As with the resistance, for prediction of propulsion a database can be developed by a combination of model tests, theory, and full-scale measurements. With this database, reliable predictions can be made for the required power of the ship and how the ship's propeller should be designed.

6.The Ship's Propeller

We are going to take a closer look at the ship's propeller. We all know when water boils: 100° Celsius or 212° Fahrenheit. However, water also boils at a much lower temperature if, for example, you are at high altitude in the Himalayas. Whether in space, where pressure is much lower, the boiling point is at 0° Celsius.

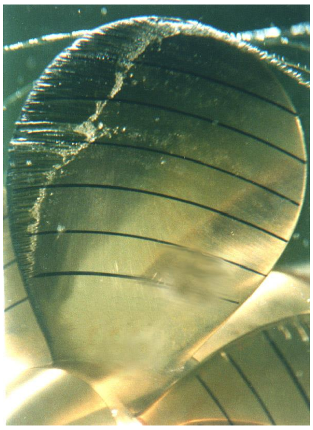


Figure 14 Cavitating Propeller

Also, on and behind a rotating ship's propeller, water boils. The simplest explanation of cavitation – because that is what it is all about – is cold cooking, caused by the intense pressure reduction for a rotating propeller. Moreover, the lift, the propulsion force, is caused by this reduced pressure.

Cooking in this case is a hydrodynamic problem that has occupied the experts for more than a century. Since water vapor is a bad medium that hinders the propeller create effectively and efficiently lift. However, it is not only this aspect but also the vibrations and damage to the ship's propeller caused by cavitation.

Figure 15 Turbina 1897

Back in time. It is June 26, 1897, more than 110 years ago and thousands of people have gathered for the annual Royal Navy naval review. The review has been held since the 14th century. This naval review is special and more beautiful than the previous versions. It is also the celebration of Queen's Victoria 60th anniversary of government. 160 Mighty warships can be seen by the spectators. 4 Rows wide and twenty-five miles each. A spectacular view indeed. Yachts and passenger ships transport many foreign dignitaries and European royalties to witness the spectacle.
The Royal Yacht Victoria carries the Prince of Wales preceded by the Trinity House yacht Irene. The Enchantress transports the Lords of the Admiralty, while the Danube has the entire House of Lords on board. The awe-inspiring Cunard Lines Campania has all members of the House of Commons on board, while the Eldorado has the foreign dignitaries on board. The exception is Prince Heinrich of Prussia, who came with his own ship the König Wilhelm. Then Prince Edward - the Prince of Wales - appears and the first tones of God save the Queen sound. But then what? A small ship, Fig. 15, shoots through the lines at a dizzying speed of thirty knots. Much faster than any ship is capable of in those days.
Onlookers have fun as a patrol vessel almost sinks into the intruder's wake. The fast ship sails close to a warship with the result a sloop slams into the wall. The Prince of Wales liked it so much that he asked for a repeat.
The ship was the Turbina**,** which we have encountered before when innovation in shipbuilding was discussed. The Turbina was the fastest ship in the world. The ship was completely different from the warships at the time. It was powered by a steam turbine, the future system designed for powering the warships. The ship was the brainchild of Charles Parson, who extended the work of Swedish engineer Gustaf de Laval. It took some time, to say the least, before the Turbina could perform as demonstrated on the naval review. The ship initially performed well below the design specifications.
We must realize that he was the victim of a completely new phenomenon. Who had ever heard of cavitation until then? Sailing ships were of course not affected and the steamships at the time sailed so slowly that the phenomenon did not occur either. Not only had Parsons shifted the speed limit, but he also discovered a phenomenon from physics. And while today's engineers are building ships that can sail faster than the Turbina, the mystery of cavitation is still not entirely solved.

Of course, progress has been made since then. Cavitation is now much better understood than in Parsons' time. Because he had to determine the source of the malfunction. The first question he asked himself was whether it was related with the turbine or with the ship's propeller. He soon found that it was due to the propeller and described the phenomenon as a kind of vacuum behind the propeller blades. And from a publication two years earlier (Thornycraft, 1895) he found the necessary evidence: if a propeller exceeded a certain propulsion threshold, a vacuum was created on the propeller blades, called cavitation by Froude. The propulsion force that Turbina was able to exceed this threshold by a factor of five! It was only after much experimentation with the ship's propeller that Parsons reached the speed of thirty knots which he demonstrated so spectacularly during the naval review in 1897. Parsons also designed the first test setup in the laboratory. The application of the steam turbine as the source of propulsion was thus frustrated by cavitation in those days.

Today we know that the cavitation problem involves more than just the speed or better the speed limitation of the ship. In the 1950s, we knew that speed was just one of the problems. Sound, vibration of the ship and erosion of the propeller are other problems. Vibrations, pressure fluctuation on the hull and noise were very annoying for commercial ships. However, for navy ships, the effect was even more disastrous. In the 1960s, the problem was exacerbated by the appearance of the first super tankers. With the development of faster vessels, it became especially important to further control the problem of cavitation. The problems became even more topical with the arrival of the larger and faster container ships..

So, there is no end to the problems. And we are used to that. To summarize, the problems of cavitation – cooking phenomena on ship propellers – are:

Vibrations of the ship,
On board and Outboard Noise,
Erosion of the propeller.

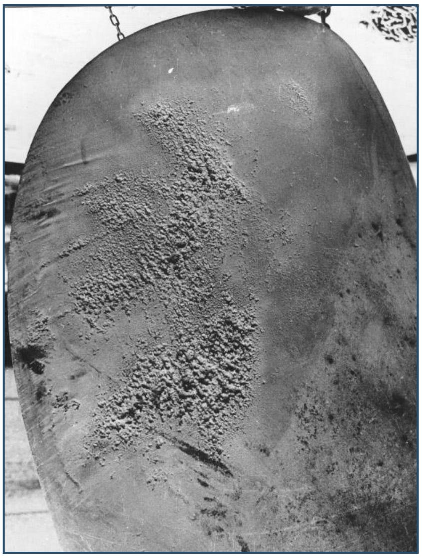


Figure 16 Erosion of a propellor blade due to cavitation

In hindsight, of course, we know everything, but when ships were docked in the 1950s and erosion was detected, there was no immediate connection to cavitation. But with faster and larger ships, erosion became more common.

Erosion as a phenomenon in the landscape is clear to us, but erosion of a ship's propeller is not immediately obvious. How does this come about? This has everything to do with the appearances of cavitation. Erosion occurs because small vapor/cavitation bubbles collapse and generate shock waves (waves with large pressure differences) which rip the metal (bronze) from the surface on the propeller blade.

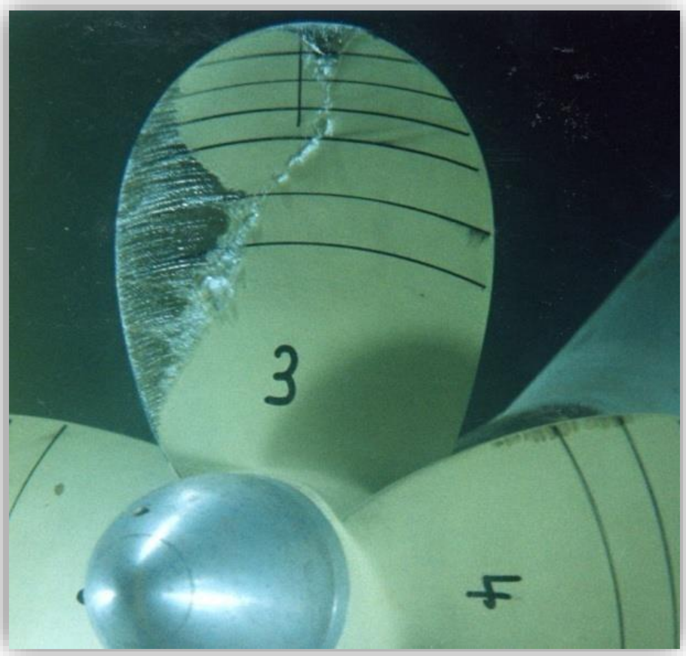


Figure 17 Cavitation and vibrations

The cavitation, cavity, or volume of vapor on the propeller blade, Figure 17, fluctuates with the rotation of the ship's propeller. The growth and shrinkage of the cavity causes pressure fluctuations in the water around the propeller (think also of the pressure waves in the water pipe at home when operating the washing machine, water hammer). This manifests itself at a great distance from the ship as sound and close by as vibrations of the ship. The vibrations can become so dangerous/unpleasant that the ship must sail at a speed lower than the speed at which the ship was designed. This happened in the 60s and 70s of the last century. Large container ships sail at a speed of twenty-five knots, transferring the entire power of the marine engines to a propeller with a diameter of up to ten meters. Today, just because fuel costs are also being looked after, speed is of less importance in relation to fuel efficiency. As a result, the vibration problem is less large. But is the cavitation problem less? No, I am not. A ship's propeller is also experiencing resistance. And that consumes fuel too. In view of the fuel efficiency, ship propellers are therefore designed differently than in the past (slimmer propeller blades) resulting in a greater risk of erosion. The design of the ship's propeller is optimized in such a way that some cavitation is acceptable.

Where did we get that knowledge? Research and development form the basis of the design of the ship's propeller just as in the design of the shape of the ship to which the propeller is applied. Fig. 16 shows an example of cavitation on a model propeller.
How does it look like in the real world?
Below some videos are shown of so-called high sea testing-full scale. The videos are recorded from a view through a window in the stern of the top of the propeller. Vortex cavitation is shown. Click on the link. A video of full-scale cavitation: A side view of the propeller through a window in the stern of the ship. Dimensions: a propeller with a diameter of about 6 m.
https://videos.files.wordpress.com/Ijl0SvG5/full-scale11_fmt1.ogv
or, on Youtube,
full scale 11 fmt: https://youtu.be/-tMrAZvaK9E
A view from above of the same propeller. Part of the rudder is shown.
https://videos.files.wordpress.com/d1yY8F8a/full-scale1_fmt1.ogv
or, on Youtube,
full-scale1-1.mpg: https://youtu.be/JxuDj8lIP0s

Cavitation observation such as shown in these videos are conducted already for several decades.

7.Cavitation

We are digging a little deeper into cavitation now.

Since the 1950s, cavitation on ship propellers has become a mature field of research. Cavitation appears in several forms:

1. Sheet cavitation.

2. Bubble cavitation.

3. Tip[3] Vortex cavitation.

We are now looking at the three types of cavitation mentioned above. The following figures, 17 to 19, show these forms of cavitation. The model propellers shown here are designed in such a way that they show a certain cavitation shape.

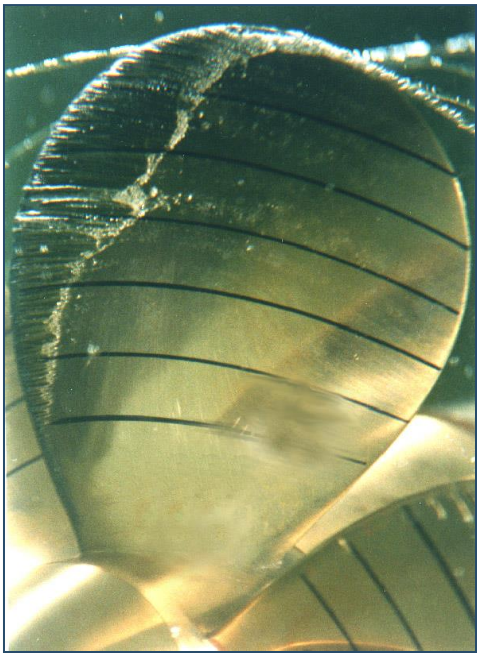


Figure 18 Sheet Cavitation

Fig.18 also shows vortex cavitation at the tip of the propeller.

[3] Tip of the Propeller Blade

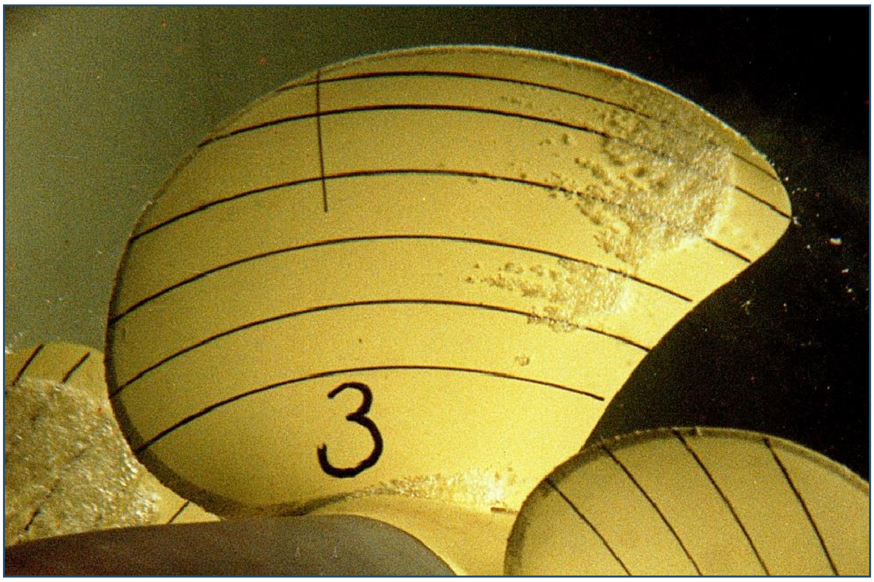


Figure 19 Bubble Cavitation

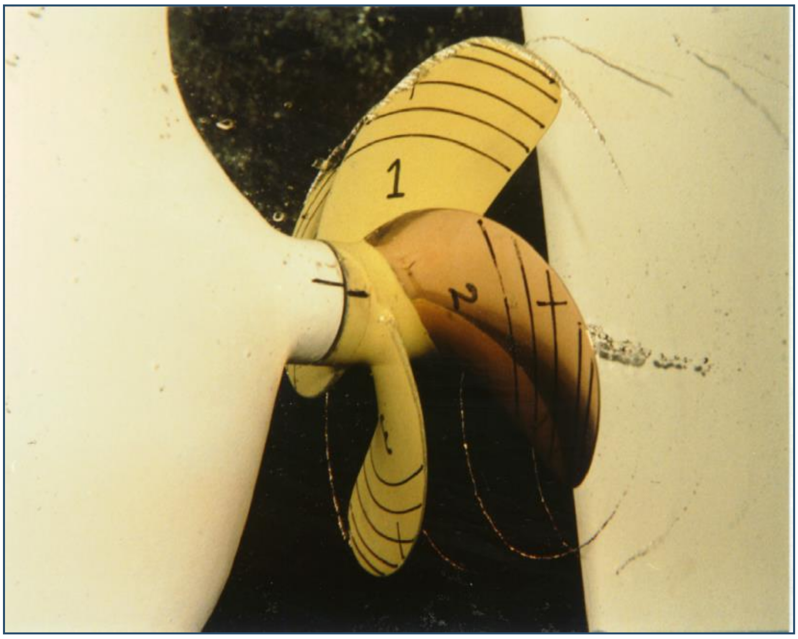


Figure 20 Vortex Cavitation at the tip and at the hub of the propeller

Fig. 20 also shows a mixture (sheet and vortex), otherwise small, of cavitation. However, for research, theoretical as well as experimental, propellers are designed and used to investigate the three types of cavitation mentioned.

8. Cavitation research

Figure 21 A Propeller used for Research.

Research in the laboratories is aimed at designing a propeller, in such a way, that with acceptable cavitation the ship meets the design specifications at full scale. To this end, the first design of the ship's propeller is evaluated at scale in the laboratory. To conduct the tests correctly, the conditions in the laboratory test in a hydrodynamic and hydrostatic sense shall be the same as at a full scale. The ship model or laboratory model is evaluated in a towing tank, as mentioned earlier. Then we know from the hydrostatics (pressure distribution) that the tests are not conducted properly. To this end, new laboratory facilities have been developed in the past. The first facility is the cavitation tunnel.

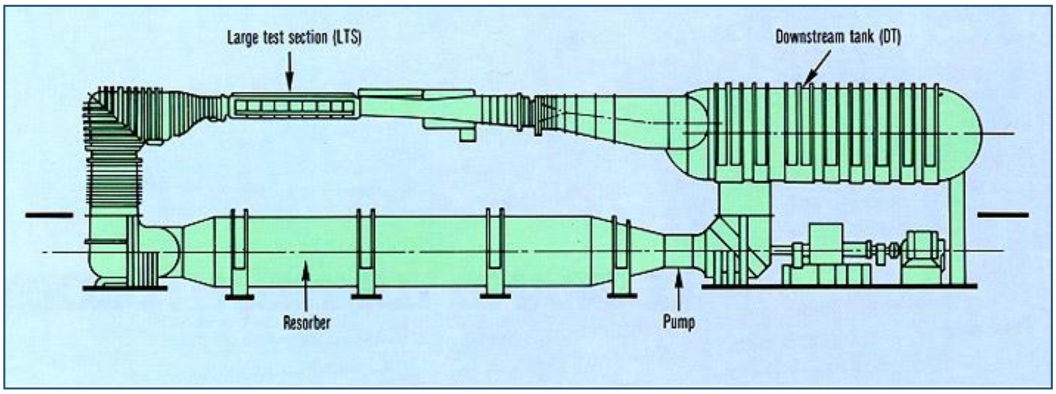


Figure 22 Cavitation Tunnel

Through clicking on the link below some observations in a cavitation tunnel are show: first a hydrofoil model for basic research and then a couple of videos of a cavitating propeller.

https://videos.files.wordpress.com/zNmSjgMl/part2_fmt1.ogv
or, on Youtube,
part 2 fmt: https://youtu.be/jSM-Z_eIWOM

Parsons initiated the development of such research facilities. The modern cavitation tunnel looks like the one shown in Fig.22. A closed continuous channel where the speed of the water and pressure can be varied. Trials in such tunnels and full scale gave a lot of insight into the development of cavitation erosion.

However, as with measuring resistance in scale models, cavitation tests had scale effects. The correct hydrodynamic conditions could not be simulated. Because cavitation is not only about erosion, but also about the vibrations generated by the cavitating ship propeller. The cavitation tunnels as used 30 to 40 years ago were unsuitable to do these tests. Unsuitable for assessing and improving propeller designs. To this end, a large test facility was built in the Netherlands in the 1970s by MARIN: The Depressurized Towing Tank.

Figure 23 Depressurized Towing Tank. A view inside the Towing Tank.

Fig.23 shows the interior of the Depressurized Towing Tank. The carriage towing the ship model is shown. The model about twelve meters long(yellow) is also shown, just below the middle of the picture.

The width of the Towing tank is about eighteen meters. The pressure in the towing tank can be reduced to twenty-five millibar. The length of the towing tank is about 240 meters.
The tank (painted grey) is at atmospheric pressure. So, if necessary personnel can be inside the Depressurized Towing Tank.

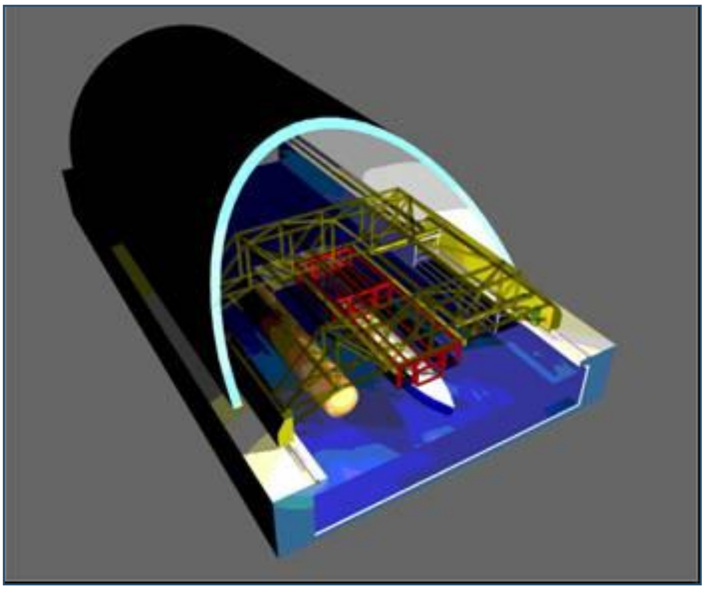


Figure 24 Schematic Representation of the Depressurized Towing Tank

Fig.24 shows the interior of the Depressurized Towing Tank in schematic form. The towing carriage and the ship model are shown.

Figure 25 The Depressurized Towing Tank Areal View. Length approx. 240 m.

In Fig. 25 an impression of the external of the tank. Compare the cars with the yellow ship models in the right upper part of the picture.

In this testing facility a completely scaled model can be evaluated with the cavitating propeller included. A video of the propeller can be observed by clicking on the link:

https://videos.files.wordpress.com/soMgu7bA/model_fmt1.ogv
or, on Youtube,
Model fmt 1: https://youtu.be/IBckHNMk-tI

The recording has been made from inside the ship model.

Though, a complete model can be evaluated. However, with this simulation, the hydrodynamic conditions are not exactly simulated. So, the conditions are different from those at full scale. Through the advanced theoretical research on cavitation, one knows how to simulate the true size conditions through several artifices. Is everything set up in such a way that the right full-scale cavitation patterns can be predicted from the laboratory tests? It turns not to be possible. Of the three types of cavitation: bubble cavitation, sheet cavitation and tip vortex cavitation, the latter cannot be accurately predicted. By using data from full size measurements, a practical rule could be developed for the start of tip vortex cavitation (inception).

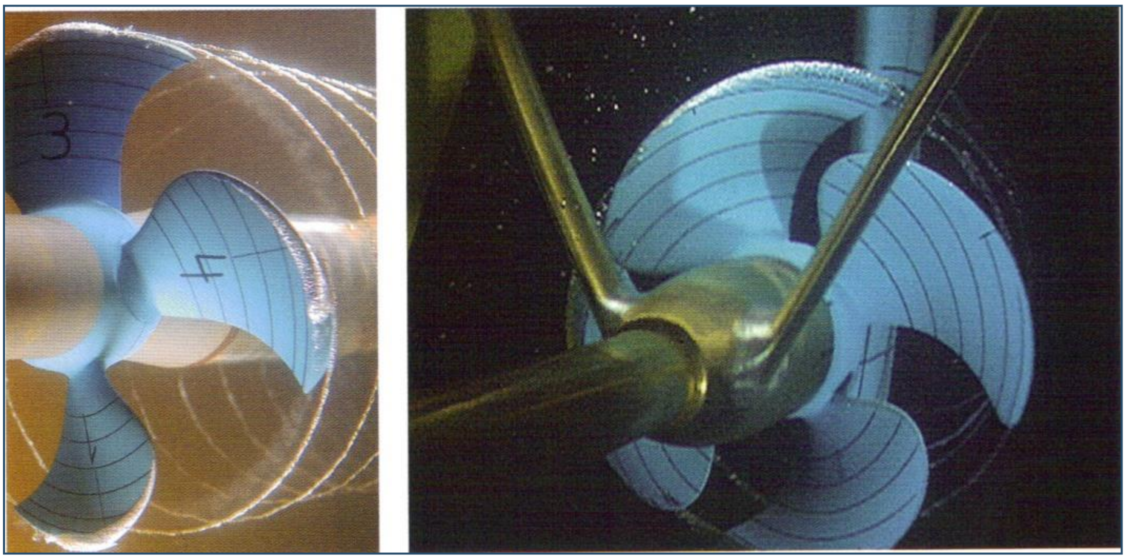


Figure 26 Tip Vortex Cavitation

Obviously, all problems are not solved. It has emerged that tip vortex cavitation contributes more to the ship's vibrations - and worse than just vibrations is resonance- as ever had been thought. A new field of research for hydrodynamics.

Research for shipbuilding is now strongly supported by computer simulation based on computational fluid dynamics (numerical fluid dynamics). The main advantage of this is that the number of tests to be conducted for a particular ship design or other offshore construction is decreasing.

The depressurized Towing Tank has been renovated and adapted. Wave generators have been built in to investigate the effects of waves on cavitation. This adjustment was completed in 2012.

9.To conclude: The Past meets the Future

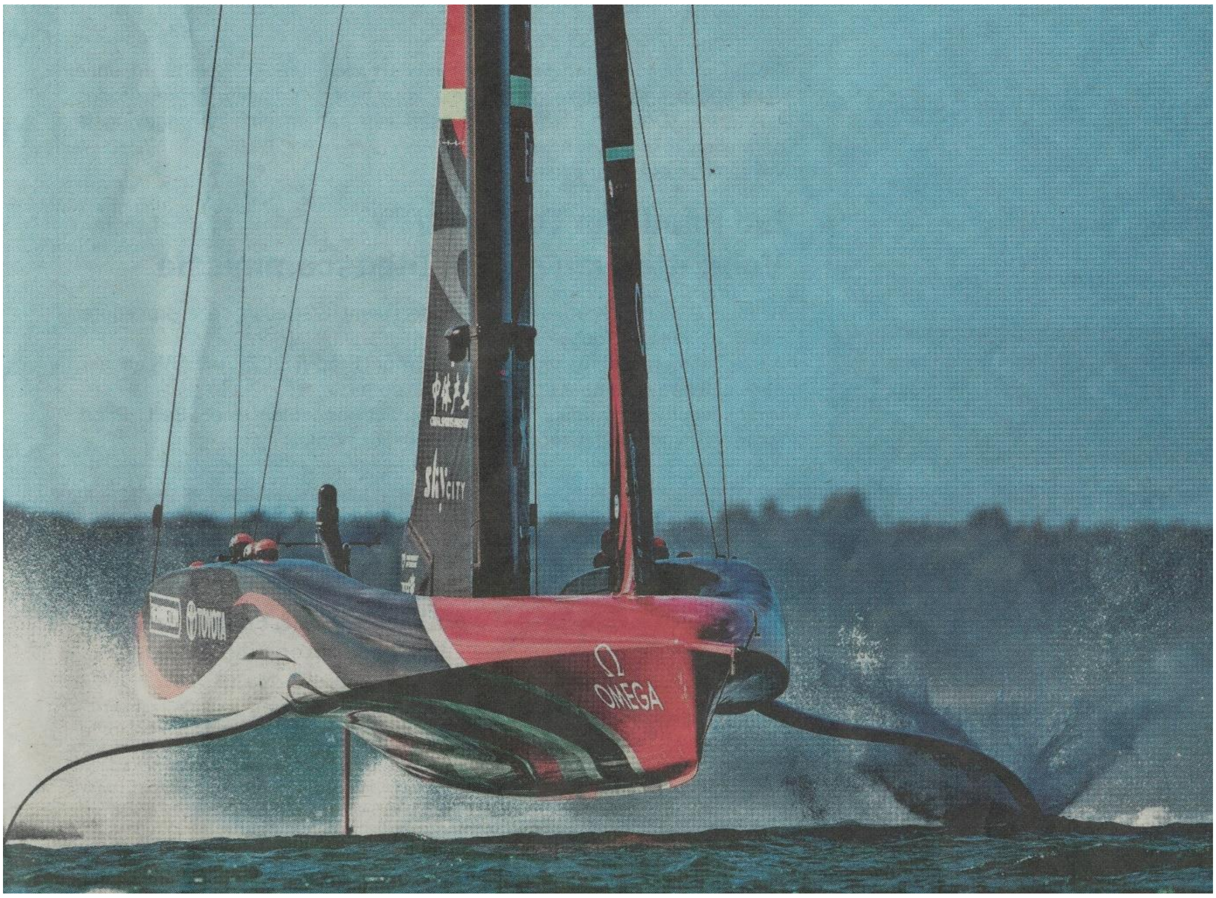


Figure 27 America's Cup 2021 won by Team New Zealand

A sailing vessel fitted out with hydrofoils.
A longitudinal rigged boat with submerged wings(hydrofoils). Sailing at speeds up to fifty knots (95 km/hour). The hull completely lifted out of the water reducing the hull resistance. However, you may expect the hydrofoils to cavitate. That is what you want to prevent.

The law of conservation of misery is still at work.
Imagine the research.
Another research topic is the combination of rotor sails, Flettner (1924), and propellor propulsion on a cargo vessel (The Economist, *Ship Propulsion, Wind power makes another comeback,* Section Science and technology, April 9th, 2016).
In The Economist a vessel is shown where Flettner installed two rotating cylinders with a height of 18.3 meter, Figure 28.

Figure 28 The Flettner experiments using the Magnus effect, The Economist.

The author was employed with MARIN from 1973-1979.

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