Reconstruction of the Hjortspring Boat. Sailing Tests.

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Preface.

This paper succeeds two former papers by Valbjørn et al., 1997 and Fenger et al., 1997 both dealing with the reconstruction of the Hjortspring Boat. These papers report on the philosophy, the organisation, the building process, and the characteristics of the boat, as it was interpreted by Rosenberg and Johannessen, 1937, such as the hydrostatics and -dynamics as well as the stress and strain picture.

Subsequently the present paper and the above mentioned two papers should be considered a unity that describes the replica work and its results, although each paper may be read separately.

Introduction.

In 1921/22 a boat was excavated in a little bog by the name Hjortspring. This bog lies in the middle of the island of Als, an island situated in the South of Denmark. Together with the boat was excavated a considerable amount of weaponry such as spears, swords, shields and mail coats together with various wooden artefacts.

The find was interpreted as a sacrifice, and it was dated by the excavator to be from the Celtic (Preroman) Iron Age. (Rosenberg, 1937.)

An excavation by Rieck in 1987 produced sufficient amount of "fresh" wood to perform a carbon 14 test. It was confirmed, that the find was from 350 BC. (Rieck, 1991).

The boat was 18 metres long with a beam of two metres. The shell of the boat was formed by five wide planks of lime wood, that were lashed or sewn to each other by some organic materials. In either end of the boat the two side planks and the two gunwale planks were sewn to a stem part, that was stepped onto the narrow elongation of the bottom plank.

Both ends carried horns like the horns that characterise the thousands of rock carvings in Norway, Sweden and Denmark.

The Replica Building.

Organisation.

In 1991 a group of persons on the island of Als decided to spread the knowledge of the Hjortspring Find and as a major aim build and sail a replica in full scale of the boat.

A legal organisation, Hjortspringbådens Laug (The Guild of the Hjortspring Boat), was founded in order to organise the work and to act as a platform for fund raising.

The guild attracted a wide variety of persons as to professional background, interests and personalities.

The various motives for joining the guild were reflected in the philosophy of the work and in the organisation of the guild.

We decided to build the boat employing the latest interpretation of the find, using contemporary tools and let quality be our first priority, while time was the free parameter. We decided to document all work, decisions and results and make them available to the scientific society and to the public.

The guild was organised in working groups such as design, tool forging, wood procuring, boat building, historic background, study of the find, fund raising, internal information and external information.

The member count reached quickly 100 and is now slowly climbing towards 150.

Figure 1. The Purpose of the Guild, Restoring the Hjortspring Boat to Life.

The Boat Building. (Valbjørn et al, 1997).

As none of the members had any professional background as shipwrigth nor carpenter, we decided to build two samples in scale 1:1, one of the middle section and one of the prow, partly for training and partly for studying details of the assembly.

Simultaneously, the tooling group studied tools from the Iron Age and forged samples. The wood procuring group looked for sufficiently large lime wood trunks, while the design group entered the drawing of Johannessen into a computer in order to print out shapes of the transversals and of the planks.

In the fall of 1993, we identified a forest of lime wood trees in Poland, and four trunks each with a diameter of 60-80 cm. and a length of 18 m. arrived to our hall in February 1994.

As each plank should have a width of 40-50 cm. the trunks were split in two, each half to render one plank only.

Chipping away wood became the major work, as the 12 tons of wood should be reduced to 530 kg., being the weight of the finished boat.

Each Tuesday and Thursday night for five years 5-15 persons met to form the boards, the stems, the horns, and the frame systems, to produce the bast sewing strings and to assemble the parts, accompanied by discussions, suggestions and choices.

A total of 10.000 man hours were logged for the boat building process.

May 29, 1999, early in the morning, the Hjortspring Boat kissed the waves once more after 2350 years of rest.

The boat, named **Tilia Alsie,** is judges by the archaeological society in Denmark to represent the latest in interpretation of the find, and its form, its finish and its elaborate details illustrate the advanced technology, that the boat builders of the North did command in the Celtic Iron Age.

The Boat.

The Construction.

The Hjortspring Boat as documented by Rosenberg and Johannessen (1937) consist of five planks, two stems, four horns and ten frame systems, sewn together with strings of organic materials (probably lime wood bast).

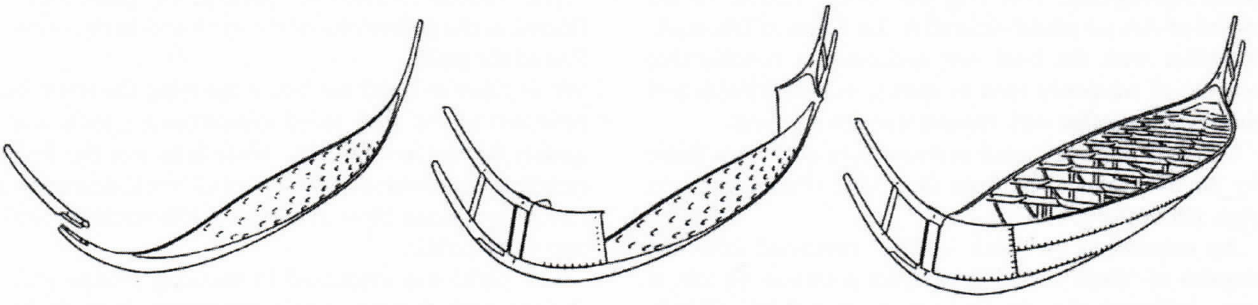
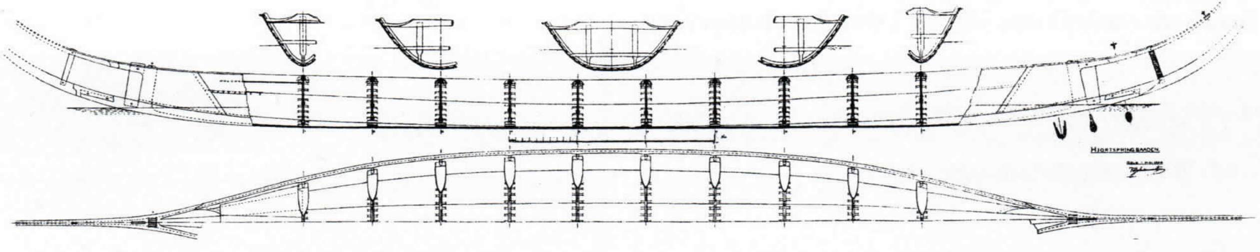


Figure 2. Schematic Drawing of the Construction. (Kaul,1988).

The five planks are each in one whole length. The lower horn (the keel horn) is assembled to the elongation of the bottom plank by means of a grove and feather assembly as in the find. How the gunwale horn was fixed to the stem could not be established. We used a grove/feather assembly there as well. The two locking plates in either end of the boat, connecting the two horns, were made of oak, fixed to the horns with oak keys.

The designs and functions of the plank steppings, the tightening mechanism and the frame systems will be dealt with in the chapter: "Hypothesis".



Figur 3. The Hjortspring Boat (Rosenberg, 1937).

Differences between Tilia and Johannessen´s Drawing.

The major difference between the replica and the interpreted boat as shown in Rosenberg (1937) is the sheer and the keel line of the bottom plank.

At the root of the keel horn the keel line is raised 24 cm. in Johannessen's drawing compared to the keel line at the middle section of the boat, while the same distance in the replica is 36 cm.

The gunwale at the middle section of the replica is 3 cm lower than that of Johannessen's drawings.

The reason for this deviation is the curve required of the gunwale, before the gunwale plank is bent when mounting it. Johannessen's solution requires a 30 cm high curve, while the replica requires only 12 cm.

The difference changes the characteristics of the boat (Fenger, 1997, table 1) as follows:

	Replica		**Johannessen's Drawings**	
Coefficient	**Draft 0.3 m**	**Draft 0.2 m**	**Draft 0.3 m**	**Draft 0.2 m**
Length - Beam Ratio	8.4	8.3	10.0	10.8
Length – Draught -	40.8	50.3	47	66
Beam – Draught -	4.9	6.1	4.7	6.1
Fineness Water Plane Coeff.	0.61	0.66	0.60	0.61
Mid Ship Section Coeff.	0.68	0.67	0.75	0.75
Block Coeff.	0.35	0.38	0.41	0.43
Prismatic Coeff.	0.51	0.55	0.55	0.58
Vertical Prismatic Coeff.	0.57	0.56	0.69	0.70
Manpower Coeff.			14.7	
Active Paddlers Coeff.			13.3	
Constants:				
Length Constant	9.96	10.4	10.5	11.8
Breath Constant	1.19	1.26	1.05	1.10
Draught Constant	0.24	0.21	0.22	0.18
Wetted Surface Constant	8.1	9.3	8.1	9.3
Section Area Constant	0.198	0.176	0.172	0.147

Table 1. Coefficients and Constants.

The definitions of the coefficients and the constants are found in Rawson, volume I, p. 13 and volume II, p. 383 and in McGrail, p. 136.

Some constants and coefficients were determined on the basis of Johannessen´s drawings, (Fenger et al., 1997, table 1). After completion of the replica in 1999 the shape was measured by The Centre of Maritime Archaeology (NMF), and the same quantities were computed. They are listed in table 1 for comparison. The boat was measured again in October 2000, but only few of the new data are available yet.

Table 1 shows that many of the coefficients and constants of the replica differ considerably from those determined from Johannessen´s drawings due to the fact that the replica has a much more pronounced sheer. This means that the middle of the boat is carrying more load and the ends less. The waterline length is shorter and the draft is increased slightly. The beam at the waterline is also increased a little. This implies that the length – beam ratio and the length – draught ratio of the replica is less indicating a lower directional stability. The beam - draught ratio is slightly increased, which means a higher stability due to shape. It has been observed that the measured stability is higher than the computed value. The length constant is decreased, indicating that the wave making resistance is a little higher compared to the calculated value. This tendency is also in agreement with the experimental data.

The mid ship section coefficient based on the measurements in table 1 is 0.68, which is very close the value of a section with the shape of a parabola. Johannessen´s drawings give the value 0.75 indicating a more flat bottom. This will also cause a higher block coefficient. The tendency could be counteracted if the hull were more slim towards the ends. But this is not the case because the fineness coefficient of the water plane is almost the same in the two cases.

It has been reported from NMF (Hocker,F.,2000) that the mid ship section coefficient of the replica according to the new measurements in October 2000 is 0.715, which is higher than the value 0.68 measured the year before. The reason for this difference could be that the boat is a highly elastic structure. Consequently the shape of the boat will depend upon, how it is supported, and how much the truss rope is tightened. This will to some extend influence the coefficients.

Hypotheses.

Many questions arose during the building of the boat. Some of them were answered through consultations with the National Museum, some we had to answer ourselves based on common sense and analogies with other parts of the boat. Finally some major questions and interpretation possibilities appeared that could not be confirmed right away, thus they must be treated as hypotheses.

These hypotheses have been studied during the tests of the boat.

Tightening Mechanism.

The find indicates that the sewing seams were covered by an organic mass both inside and outside, interpreted as resin (Rosenberg, p. 82). The planks were overlapping.

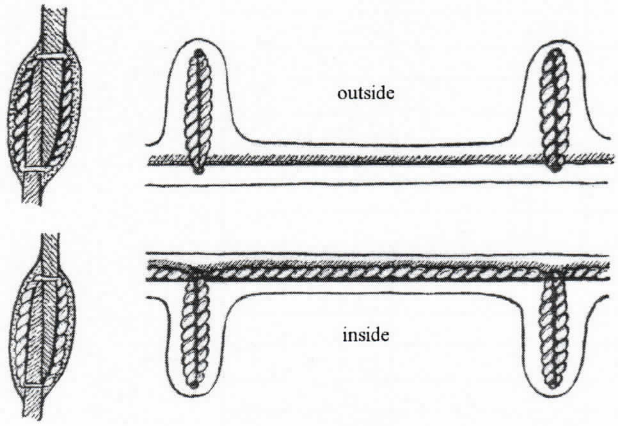
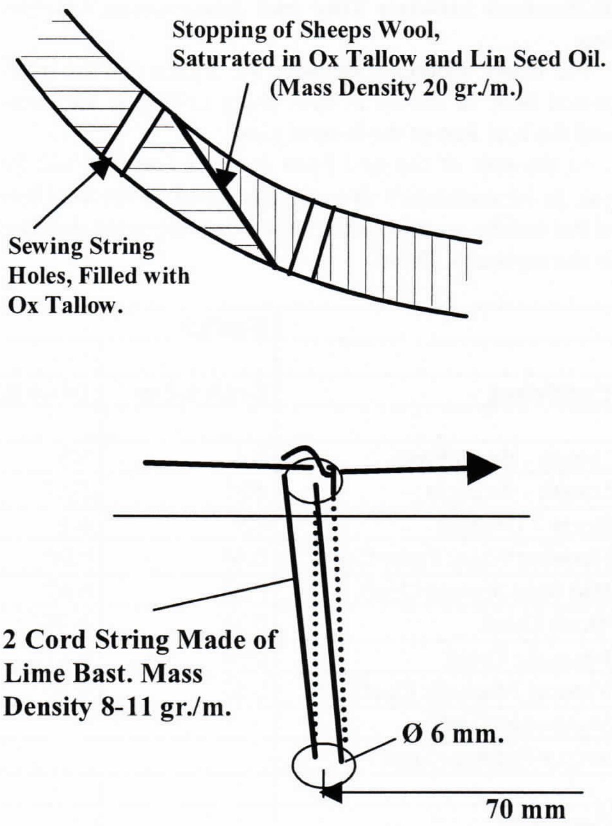


Figure 4. Rosenberg´s Interpretation.

After consultations with the National Museum (Rieck), we decided to deviate from this solution and make the plank stepping, the sewing and the stopping as follows:



Self Locking Knot or Stitch Seen from the Inside.

Figure 5. Plank Stepping, Stopping and Sewing.

During sailing there were several leakages at the sewing seams and at the string holes. They were stopped by means of ox tallow. Back on land we started smearing the seams with a mixture of spruce resin and ox tallow, 2:1. Should we continue to smear the seams with resin over the years, we will end up with an appearance of the seams like "the Rosenberg solution".

A total covering of the sewing seams on the outside will according to calculations reduce the hydrodynamic friction resistance of the boat by 10%, thus increasing the attainable velocity with approximately 2.5 % at a velocity of 8 knots.

Deck Planks.

Rosenberg (1937,p.85) describes that the find contains at least 85 boards, 105-118 cm in length.

28 have a width of 10 cm and a thickness of 1 cm. 56 have a width of 6 cm and a thickness of 1.5 cm.

Materials are lime and ash wood. All boards are tapered in the ends over 10-20 cm.

The planks were interpreted as deck planks. There were exactly space for the narrow ones on the deck beams, outside of the columns. Consequently we lashed them to the deck beams at that position.

The sailing tests showed, that they functioned well at this position as support of the feet of the paddling crew. They were, however, very elastic and did not give sufficient reaction to the thrust from the feet of the vigorously paddling crew.

Before the foremost frame (10) there was, however, no possibility of fixing a similar support for the feet of the pair of paddlers. (In the tests they used the blade of the extra steering oar as support).

The wide planks should probably cover the bottom of the boat between frame 1 and 5 and again between frame 6 and 10, leaving the bottom between frame 5 and 6 free for bailing. This mounting will eventually be performed. (The reason for not doing that in the sailing tests so far were, that we needed the lower seam to be accessible for inspection and stopping of leaks).

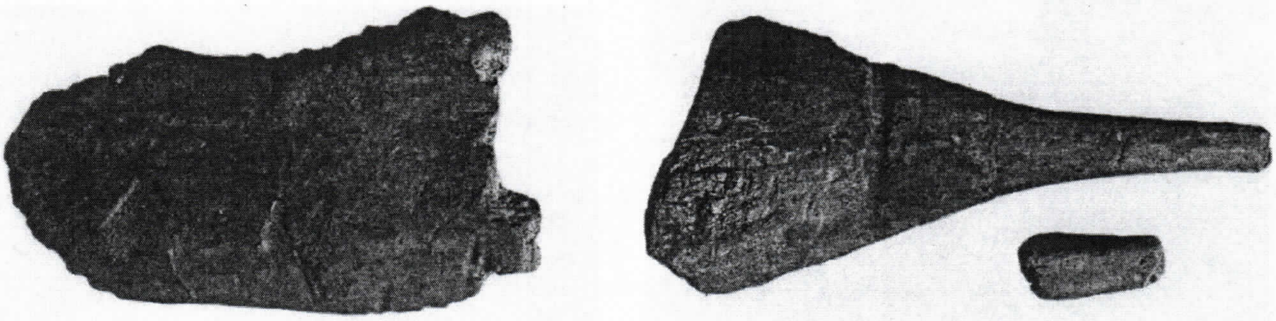


Figure 6. Fragments of Steering Oars in the Find (Rosenberg p. 87)

Steering Oar Mounting.

In the find were established two steering oars, one in each end. There was no indication, as to how the steering oars were mounted. Initially one oar was lashed with a short piece of string to the top of the most aft frame, where it protruded over the gunwale. Due to the rather pronounced rocker in the keel profile, giving a low directional stability, the boat easily sheared away from its intended course, and one had to act very quickly to bring her back on her track with the help of the steering oar, especially if the turn was to starboard. The instability appeared to be dynamic, i.e. the further the boat sheared, the quicker the turn became.

Obviously, this mounting was completely insufficient to steer the boat.

Figure 7. First Steering Oar Mounting.

The first attempt of cure was to apply two steering oars aft, one on each side. This cure was partly a success, but it occupied the two rowing positions. With a strong quartering wind the boat was refractory as ever.

During an attempt to correct the course during a broach, one of the steering oars actually broke.

In order to gain better control we extended the water line by taking 600 kg sand ballast onboard. With the mass of the crew of 1400 kg and the mass of the boat of 550 kg, it amounted to total displacement of 2550 kg.

The result was a more stable boat as to initial stability, but the directional stability remained unsatisfactory.

The hypotheses of the above described steering oar mounting was consequently rejected.

A practical solution to the steering problem was found as follows: The steering oar was lashed to the root of the lower horn, where this protruded out of the stern.

Thus the steering oar could be turned around its own axis like the side rudder of a viking ship. A cramp was fixed atwartships on the top end as a handle, and with only one helmsman right aft, sitting on the very top of the sternpost, this arrangement performed excellently.

From now on we had no difficulty making the boat go in the direction we wanted, and as an extra award, we got two more seats available for paddlers.

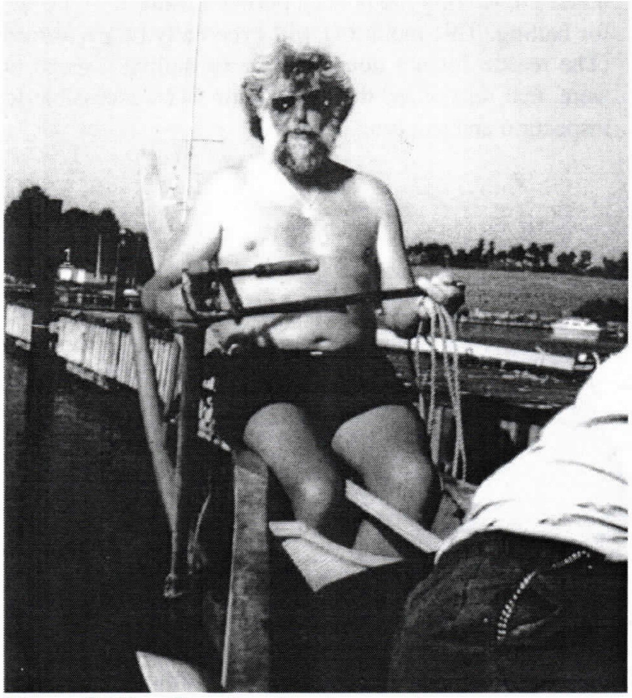


Figure 8. New Steering Arrangement.

As mentioned above there were found one steering oar at the stem post as well. An additional steering oar was subsequently mounted, lashed to the forward keel horn on the port side. The effect was a further advance in steering. With both oars the boat was under full control, sailing in the cove of Dyvig. A sailing through a narrow and meandering fairway leading to a neighbouring cove was performed steering with the forward rudder alone.

The boat was easily steered with either the aft rudder, the forward rudder or with both rudders in action.

The original hypothesis was thus replaced by a new one.

Apart from further tests in the future, one must study the various solutions in African, Indian and Oceanic more recent canoes. Furthermore the original boat that is on display in the National Museum in Copenhagen must be scrutinised for traces of steering oar mounting.

Stresses and Strains in the Boat.

A major hypothesis was the application of a "trussing rope", connecting the set of four cleats on top of one stem to the correspondent set on the other stem using the cleats as a tackling block.

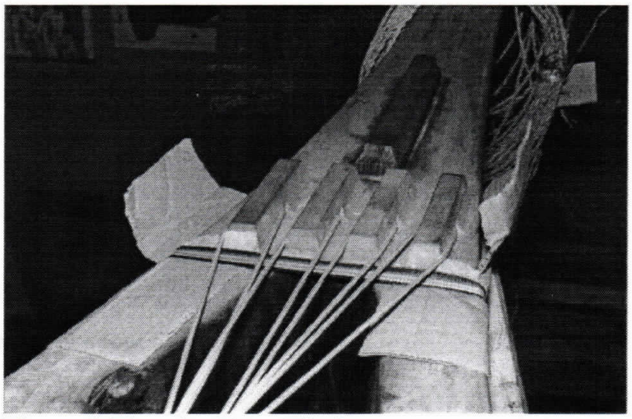


Figure 9. Trussing Rope Block.

The original idea of suggesting a trussing rope stems from the existence of the stem cleats and a wish to explain their use. Furthermore initial calculations showed, that the boat shell was expected to be extremely flexible.

Calculations (Fenger et al, 1997) shows, that when submitting the boat to a standard wave (length 13.5 m., height 0.65 m.), the maximum stresses in the keel plank and in the gunwale was quiet acceptable. The stems would, however, vibrate 30 mm in a vertical direction during hogging/sagging sailing, not considering the "pea-pod" effect.

That this wave condition is not just a theoretical assumption is illustrated in the below figure.

Figure 10. Tilia Alsie in High Seas.

The boat has been submitted to such high waves for thirty minutes only, as we were not convinced that the sewing seams could stand the shearing stresses over long period of time. Calculation shows that such stresses will exceed the elastic range of the lower sewing seam between frame 2 and 4 (and 7 and 9) leading to wear at the seams.

The trussing rope with a reasonable force (10.000 N) will, however, not reduce the stresses at these seams sufficiently to bring the stress within the elastic range.

Introduction of two poles that let the trussing rope form a polygon would have been much more useful in that respect. That would, however, be stressing the hypothesis too far.

Another weak point in the boat is the stepping of the side and gunwale planks onto the stems. The trussing rope introduces a normal, compression stress at these seams thereby reducing the opening of the seams. The many hours of sailing with the boat, have introduced some opening of said seams, however, but not sufficiently to require tightening the sewing again, probably due to the trussing rope.

The third weak point is the bottom plank, which over 6 metres in the middle is practically flat. Consequently the plank is not very resistant to perpendicular loads. Here the load in the boat is transmitted to hydraulic pressure on the bottom plank by means of the sewing seams only, as the frames elements do not support the bottom plank. At this section of the bottom plank, the trussing rope will reduce the tendency of the lower seams to open.

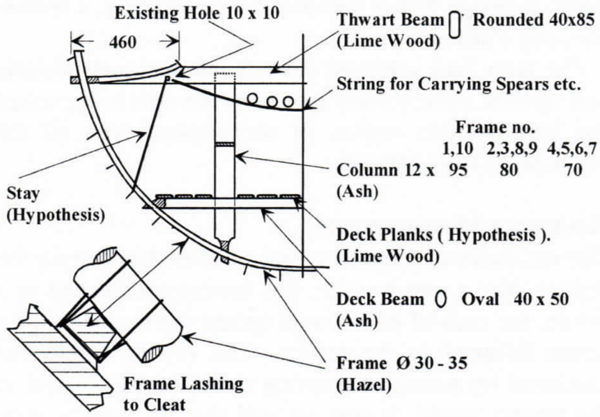
We have regretfully not measured the stress and strain variations in the trussing rope during our sailing yet. The hypothesis of a trussing rope is consequently still a hypothesis, but the feeling of its usefulness is still present, when manning the boat and sailing it.

The Frame Systems.

The design of the frame systems is interesting. The frame system consists of a frame, lashed to cleats that are integrated parts of the planks. This frame pierces through the thwart at both ends, through the deck beam and through the lower end of the two columns. The parts of the frame system are not fixed to each other by keys and the frame system feels rather lose, before the frame itself is lashed to the boat shell.

The frame itself does not strengthen the shell, but it transmits the forces of the other elements of the frame system through the two cleats on either side of the end of each internal frame element to the shell.

The thwart may either be supported by its ends, where these could rest on the cleats just below the seats, or it could rest on the columns. We decided to choose the first solution. Thus the columns may be considered as elements used for avoid twisting the thwarts.



Figur 11. The Frame System.

Under each seat were situated a square hole. We suggested to use these holes as anchor for a stay or rather a shroud thereby stabilising the thwarts. It functioned well.

Figure 12. The Row of Frame Systems.

Sailing Tests.

Introduction.

Apart from several sailings since the first launching in May 1999, Tilia has undergone two sessions of test sailings in corporation with the Centre for Maritime Archaeology and the Viking Ship Museum in Roskilde.

In 1999 the crew consisted of members of the Guild of the Hjortspring Boat together with students from the training centre of the Viking Ship Museum. None of these possessed sufficient knowledge and experience in paddling. The results from this first test run are considered as initials, but the tests gave indications of problems. It was, however, during the 1999 tests that the new hypotheses of the steering oar mounting was developed.

In the tests in year 2000 a picked crew of 22 very competent dragon boat paddlers, all former elite canoe and kayak athletes. Today they are united in a mutual effort of competing internationally in the Chinese Dragon boats, a design that is powered by 20 paddlers, a helmsman and a drummer.

The crew had achieved several international rewards and medals, subsequently they were thought to represent the best possible replica of the original crew of the Hjortspring Boat 350 BC.

Resistance Measurements.
The resistance of propulsion was measured by towing the replica after a motor sailer. The towing rope ended in a bridle, the ends of which were spread out by means of a boom fastened to the replica. The towing force was measured by means of a spring dynamometer placed at the towing vessel. It was ensured that the towing rope was above the water, so that no extra resistance was induced. The speed vas measured by the GPS log of the towing vessel. During the test there was only a weak wind with a direction almost transverse of the sailing direction. The results are shown below in a double logarithmic diagram.

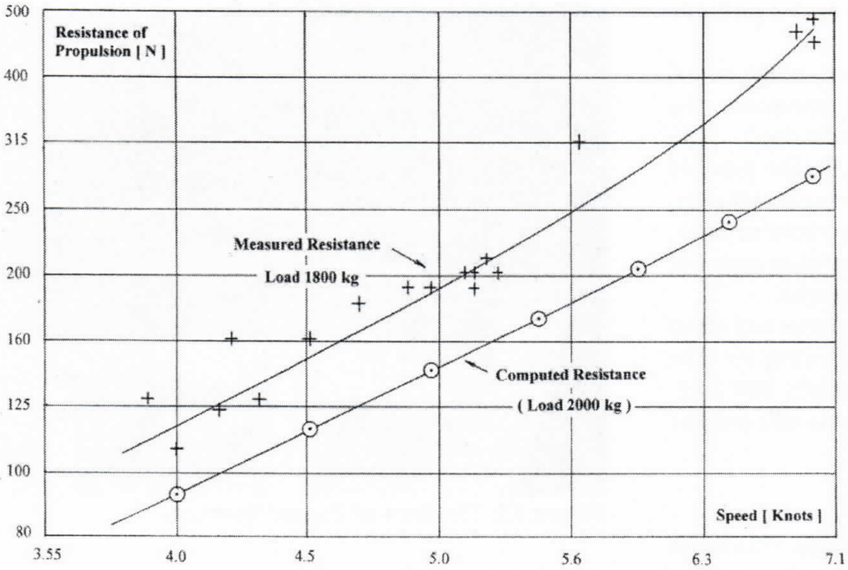


Figure 13. Resistance of Propulsion Versus Speed.

The data show some scattering due to difficulties of keeping the conditions stable. They are compared to the total resistance computed (Fenger et al., 1977, figure 9). It is seen that the measurements are about 30 % higher than the computed values up to a speed of 5 knots. There could be several reasons for this difference. The computations are based upon the assumption that the bottom of the boat is smooth. But the protruding chords of the sewing stings give some extra resistance. Information about single lines of resistance distributed over a surface is scarce in the literature. But some information can be found in Schlichting (1979). Using these data it is estimated that the resistance is increased by about 10%.

Air resistance was not taken into consideration in the computations. This resistance can be estimated in two ways. One possibility is to consider it being a rectangular plate perpendicular to boat direction. If the plate had a dimension of 3 m^2 this will give an increase of about 12 % of the hydraulic resistance.

Another possibility is to simulate the crew by vertical cylinders having diameters 0.4 m and height equal to 0.7 m. This will give an increase of 9 %. From this it can be estimated that air resistance will increase the hydraulic resistance by 10 %.

It is observed that the rudder creates eddies, indicating that this causes an additional resistance. This could explain the last 10 % of difference between the computed and measured values.

It is seen that the computed resistance is almost a straight line curving a little upwards at higher velocities. The reason is the residual resistance due to wave making, being more predominating at high speed. The measured values increase more rapidly at the highest velocities compared to the computations. One explanation could be that the resistance, due to wave making, commences at a lower speed compared to what was found by the computations. In table 1 it is seen that the length constant of the replica is lower than the value based upon Johannessen´s drawings. This indicates a higher wave making resistance. Stem waves at the boat were observed from the towing vessel.

The stern wave from the towing vessel has to be taken into consideration as well. If a crest of this wave is just at the stem of the towed boat, it causes additional resistance, whereas a trough will cause less resistance. The relative position will vary with the speed. The length of the towing rope is essential. It should be as long as possible to avoid this interference. But it should not be so long, that it dips into the water, as the dynamometer was placed on the towing boat.

The major part of the resistance is the so-called frictional resistance caused by the water flow past the bottom of the boat. The rudder can be regarded as a foil with a rather high aspect ratio and contributes to the resistance. These two parts of the resistance depend upon Reynolds number and hence speed in different ways. This could be the reason for the larger resistances measured at the highest velocities. It should be mentioned that only rather few data are available for the higher range of velocities. New measurements should therefore be made in the future.

Stability Tests.
The stability of the replica was measured by pulling upwards in the gunwale by means of a tackle as shown in figure 14. The force was measured by a spring dynamometer, and the tangent of the angle of heel was determined by means of a plumb line and a ruler as shown in figure 14.

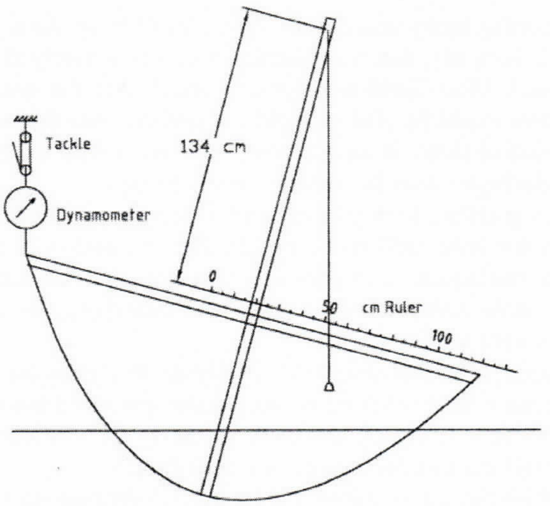


Figure 14. Arrangement of the Experiment.

The measurements were made in three conditions:

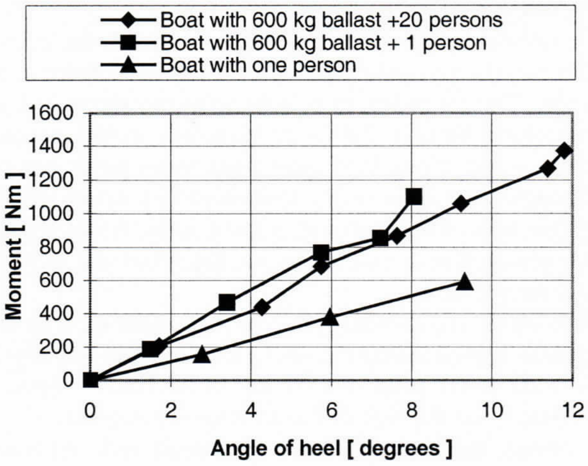


Figure 15. Righting Moment Versus Angle of Heel

The shape of the replica was measured by NMF, and from this the metacentre versus displacement and angle of heel was determined. The metacentre is somewhat higher than the values determined from Johannessen´s drawings. The reason is the more pronounced sheer of the replica. This means that the righting moment is about 25% higher compared to the value found earlier. (Fenger et al, 1997).

During heeling the crew kept their position relative to the boat. In practice they will tend to counteract the heeling by lean towards the heeling, thus giving a much higher stability.

From the measurements the centre of gravity of the empty boat has been calculated to be 0.47 m above the bottom of the keel plank. Also it is known that the mass of the boat is 530 kg. It is now possible to compute the righting moment for any load condition, if the mass and centre of gravity of the load relative to the boat is known.

Manoeuvring Tests.

The Hjortspring Boat was a highly manoeuvrable war canoe. In the tests in 1999 and with ballast resulting in a total displacement of 2550 kg, the boat could accelerate from zero to 5 knots within half a minute and a full brake stop from 5 knots to zero with all the paddles backing furiously in 5 seconds or half a boat length.

In 2000 with the dragon boat paddlers, the boat could reach 6 knots in half a minute (Total displacement 2290 kg).

In the tests in 1999 and at full speed (5 knots) the 18 m. long boat made a 180 degrees turn (a U-turn) in 37 seconds with a turning diameter estimated to be 30 metres. (Wind velocity 18 knots). Both steering oars (fore and aft) were used for this test.

Turning 360 degrees on the spot with no velocity, letting one side of the paddlers row forward and the other side backing, was performed in 38 seconds. This manoeuvre was only possible in calm conditions, i.e. up to 9 knots wind velocity.

Test run 2000 gave better result except for the turning on the spot. The reason for this lack of improvement was probably due to lack of training.

With regard to the full speed U-turn, the time was decreased to 23 seconds with a turning diameter estimated to be 25 metres. This was done with the stern rudder alone. However, the forward rudder was replaced with the three foremost paddles on the inward side being kept in the water with an angle of 45 degrees to the lateral plane.

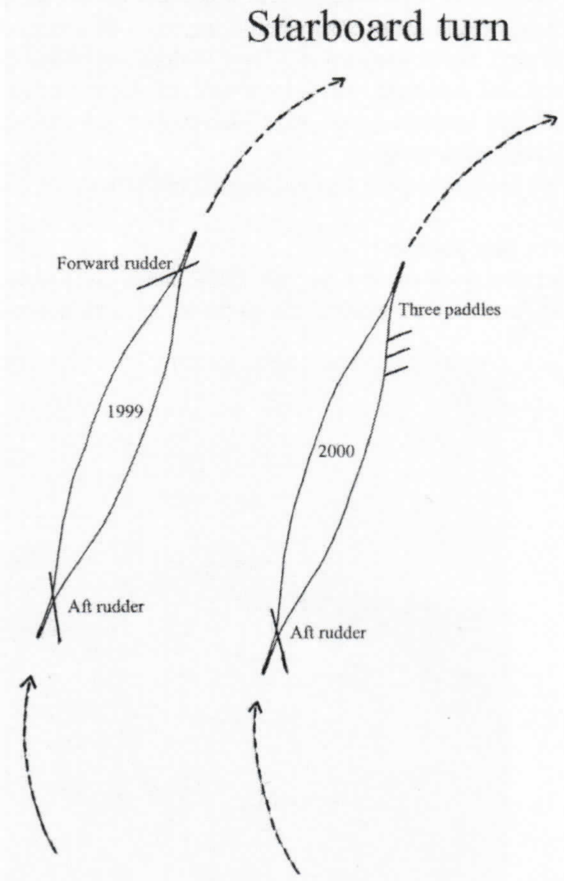


Figure 16. Turning at High Speed.

Velocity tests.

The velocity tests took place over a measured distance, determined by a GPS-navigator. In 1999 the track was 1160 metres. The untrained but spirited crew did its best and paddled all out, only to attain an average speed of 5.1 knots being the best of several tests. The condition was 9 knots wind from behind, a flying start and 47 strokes/minute with 16 paddlers being active.. At 40 strokes/minute the speed was reduced to 4.3 knots. When only 8 paddlers worked, the speed was reduced to 3.6 knots, a mere reduction in speed of 16 %. Theory calls for a reduction of 21%, but by coincidence, it might have been the strongest 8, that were paddling in this test.

In 2000 the track was 1148 metres. In the first run, the dragon boat crew reached an average speed of 7.6 knots. The conditions were a faint wind from behind, a flying start and 62 strokes/minutes. During the run the GPS-navigator was fluctuating between 7.4-8.2 knots.

It was established, however, that 8 knots were reached, a magic number, that have been discussed heatedly in the Guild during the building period of Tilia as an attainable maximum speed.

Further test trials gave no improvements in speed. As the crew was accustomed to much shorter periods of sprinting, the track was halved. This measure did not, however, result in better average nor top speed.

With regard to long distance paddling, the dragon boat crew estimated, that a cadence of 55 strokes/minute could be maintained all day long (for 10-12 hours).

This cadence was tried several times and gave a steady velocity of 6 knots in calm conditions, i.e. with moderate wind and wave resistance. Even with short stops for eating and relaxing, (or letting half of crew rest at a time), this average speed would result in a day distance of 50-60 nautical miles.

This hypothesis will be investigated in 2001.

Heavy Sea Sailing.

The last day of the test in year 2000 there was a strong wind from NNW, gusting up to 30 knots with a corresponding heavy seas outside the cove of Dyvig. An eight-mile long trip, that was planned, was subsequently abandoned. (The Guild was not convinced, that the sewing seams would be able to stand the stresses over that long period of time). It was decided, however, to test the boat in the high waves for a short period of time.

18 paddlers took part in this test, as the two foremost did not have sufficient long paddles and their foot rest was inadequate. The plan was to maintain a cadence of 55 strokes/minute. This cadence was kept during the two hours the test lasted.

Inside the sheltered cove of Dyvig this gave an expected velocity of 6 knots, but outside the speed through the water decreased gradually as the seaway increased. Simultaneously the leeway rose accordingly.

With the waves hitting the boat at 45 degrees on starboard, the speed was reduced to 4.8 knots and the leeway went up to 12 degrees (in 20 cm waves and 25 knots of wind). With 28 knots of wind and 75 cm. high waves the corresponding figures were 3.5 knots and 14 degrees of leeway.

Outside the lee of land in the fjord of Als the course was set directly against the wind that had increased to 36 knots. The waves had been built up to one metre with an occasional breaker. Tilia rose gracefully to the seas and was comparatively dry, apart from some water leaking through some of the seams. Occasionally a wrong sea did hit the boat on the stem with a lot of spray. It was not felt dangerous, but at such occasions, the speed was reduced to a mere 2 knots.

During the wave sailing it was paramount to keep the paddle vertical during the stroke and maintain a firm grip with the lower hand near the top of the blade. "Vertical Paddles" was the repeated order from the drummer.

During the turn when starting to head back, no water was shipped over the gunwale, even with the waves coming directly square on the side. The waves, however, produced a considerable side way pushing.

Figure 17. Tilia at 8.2 Knots with 36 Knots Wind on the Quarter.

With the wind on the quarter, high speed was again possible. 30 quick strokes brought the speed up to 8.2 knots in repeated readings. The steering became somewhat difficult, well known from sailing ships in the same position, being hard on the rudder.

As the boat turned the portside to the waves in the entrance to the cove the leeway became pronounced, 15 - 20 degrees at least, resulting in missing a buoy at the narrows to the cove.

The Paddling Process.

The Paddles.

The paddles of the find were all different indicating that each crewmember had his own individual paddle. For the replica it was decided to make a set of 20 identical paddles with a total length of 1.52 m and a blade length of about 0.5 m. Modern experience of paddling has shown that the optimum length of a paddle is from the ground to the middle of the forehead of a standing person (Haupt, 2000). During the tests it was observed that the paddlers at the two front and the two most aft thwarts had difficulties reaching the water with their paddles. The reason for this is the sheer of the boat, which is more pronounced compared to Johannessens drawings. This shows that there are good reasons for paddlers to have their own individual paddle.

The dragon boat team tested their own paddles with the replica. These paddles are wider than the Hjortspring paddles. The modern ones were found to be slightly more efficient, which is due to their larger blade area. But it should be noticed that they are made of plywood. This gives the possibility of having a large area without the penalty of an added weight, which would be the case if the paddles were made of solid wood. This problem is discussed in the section: Efficiency of paddling.

It was the opinion of the dragon boat team that the edges of the blades of the replica paddles should be more sharp in order to give the paddles a better grip in the water.

The cross section of the handle should not be circular but elliptical with the major axis in the direction of sailing. This has ergonometrical reasons, but it also gives a smaller weight/strength ratio

Kinematics of Paddling with Tests.

The paddling process was recorded by means of a video camera from a following boat. A single paddler with his paddle was studied. In order to record horizontal coordinates the gunwale of the replica was marked with read tape for every 10 cm over a distance of one metre in front of and one metre behind the paddler. His paddle was also marked with read tape for each 10 cm. The time was recorded by means of a special clock with a pointer rotating two revolutions per second. This clock was raised on a pole in order to keep it visible. The figure below shows the arrangement of the experiment.

Figure 18. Paddling Experiment.

From the video records one single paddle stroke was selected for further analysis. A series of exposures from this stroke was printed on paper. The position of the paddle versus time could then be measured. The results are shown in figure 19.

The best paddling technique was to keep the paddle as vertical as possible, when it was in the water. The diagram shows that the blade of the paddle is almost vertical, when it is set into the water and remains so for some time. This ideal position can unfortunately not be kept. Before the paddle is withdrawn from the water it makes an angle of about 45 degrees to the vertical direction, and this part of the stroke is therefore less efficient. The effective length of the stroke is estimated to be one metre as indicated in the figure, and time required for this is about ¼ of the time of a full stroke.

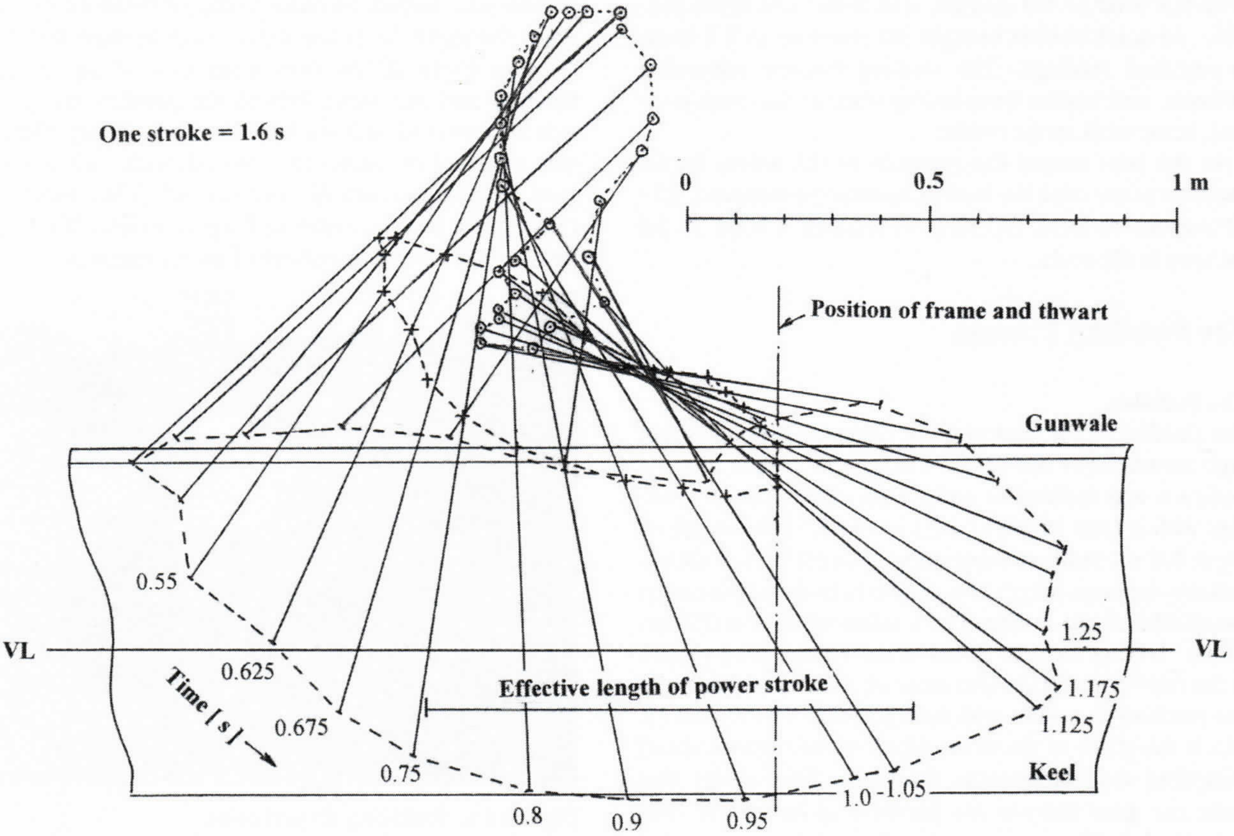


Figure 19. Position of Paddle During a Full Stroke.

Three closed curves are shown in figure 19. The upper one is the trajectory of the top of the handle of the paddle where the inner hand of the paddler is placed. The lower one is the trajectory of the blade tip, and the middle curve is the outer hand of the paddler placed approximately at the middle of the paddle. This position is rather close to the centre of gravity of the paddle, subsequently giving information about the work required for lifting the paddle against gravity in each stroke.

Theoretical Considerations.

A theoretical model of paddling has been developed. A paddle can only apply a propulsive force, when it is moved backwards relative to the surrounding water. Each stroke is assumed to consist of a working stroke, where a constant force is applied. After the power stroke the paddle is immediately lifted up and moved forwards with a constant velocity. This is called the return stroke. After this stroke the paddle is instantly plunged into the water at boat velocity, and a new power stroke commences. The paddle is assumed to be kept vertical. The kinematics of this model is illustrated below.

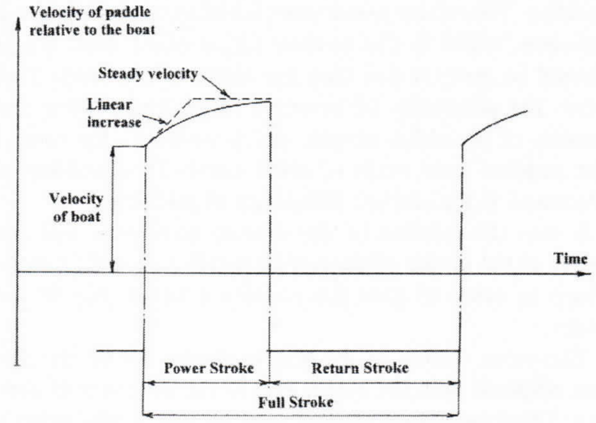


Figure 20. Kinematics of the Theoretical Model

The velocities of this diagram are relative to the boat and positive, when the paddle moves backwards. During the power stroke the area under the velocity curve is equal to the length of the stroke. The same holds for the return stroke. As a consequence the two areas are equal. If the paddle in each stroke reaches a steady velocity relative to the water, there is a simple relation between the velocity and the force. Other parameters are the area of the paddle, the density of water and a coefficient, which can be found in handbooks of fluid mechanics.

Assuming that a constant force is applied continuously during the power stroke, it is obvious that the steady velocity will be reached after a certain time. The acceleration of water at the beginning can therefore not be neglected. At the very beginning of the stroke the boundary layer has not yet been developed, and the whole force is used for accelerating the water, which moves around the paddle. Therefore the velocity increases linearly with time at the very beginning of the power stroke. It is not known, how the transition between this linear increase and the constant velocity of the steady flow occurs. Here it is assumed that this transition can be described by an exponential function as indicated in the figure.

An important parameter for describing the kinematics is the ratio of the time, used for the power stroke and the time for the full stroke. This ratio is called the intermittence factor.

Efficiency of paddling

The propulsion force for moving the boat with a given velocity is determined by measurements. If the intermittence factor is known, the force by which each paddle acts on the water can be determined. As this force is assumed to be constant, and the length of the power stroke is equal to the area under the velocity curve of figure 20, the work done by each paddler can be computed. The work required for propelling the boat during a full stroke can also be computed. The ratio of these two quantities is the hydrodynamic efficiency.

In the studied sequence the active length of a power stroke is approximately one metre, and the intermittence factor is 0.25. Each paddle has a width of 90 mm and a blade length of 400 mm. With this input the theoretical model can compute the time for a stroke and hence the paddling frequency as a function of boat speed.

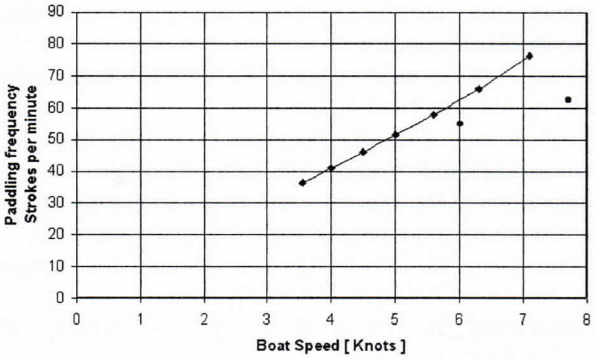


Figure 21. Paddling Frequency Versus Boat Speed.

The two single points are measured mean values from tests in 2000.

It is seen that the paddling frequency varies almost linearly with boat speed. During tests in 1999 it was found that the number of strokes per minute is approximately 10 times the speed in knots, when there was not too much head wind. This shows that the rather crude theoretical model is in a reasonable accordance with the physical reality.

With the input data the model gives a hydraulic efficiency about 0.75, decreasing slightly with boat speed, as seen in the below figure.

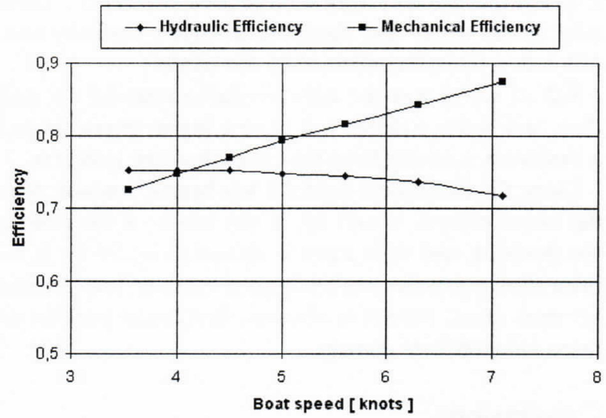


Figure 22. Hydraulic and Mechanical Efficiency Versus Boat Speed.

The hydraulic efficiency gives information about losses due to eddies around the paddles. But there are other losses, which should be taken into consideration. Each time a paddle is taken up from the water a work is done against gravity. This work is not regained, when the paddle is lowered and is consequently lost. This could be expressed as a mechanical efficiency. The mass of each paddle is approximately 1 kg, and from figure 2 it is seen that the paddle is lifted roughly 0.5 m. This gives a mechanical efficiency, which is roughly 0.8, increasing slightly with boat speed. It should be kept in mind that besides the work done against gravity, the paddles are also accelerated and decelerated during a stroke. This requires some work as well, and it is not regained and gives rise to extra mechanical losses. They are not taken into account at the time being.

The resistance of propulsion is shown in figure 13. Multiplied by the boat speed, we get the effective power for propulsion. Dividing this by the two efficiencies from figure 22, we get the power, which is equivalent to shaft horsepower of an engine driven ship.

This power is shown in the below figure.

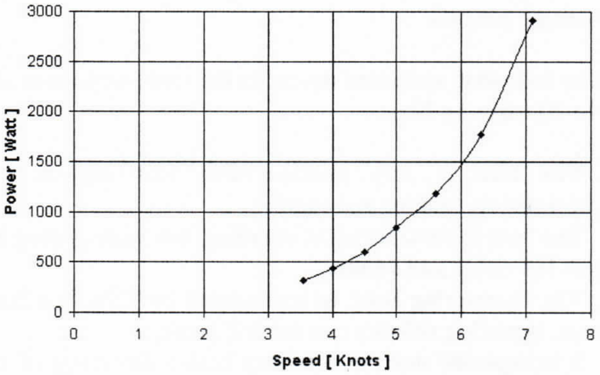


Figure 23. "Shaft Horse Power" Versus Speed.

The Width of the Paddles.

A question much discussed is the optimum width of the paddles. For an analysis of this question a theoretical model is useful, especially, if it has been verified. Intuitively it is felt that paddles with a large area will have a better grip in the water and therefore a higher hydrodynamic efficiency. This is confirmed by the model.

But as wood was the only available material for paddles, and wider paddles will have a higher mass, there is a limitation deriving from the strength of the paddlers.

Using the theoretical model it has been examined, what the consequences would be, if the width of the paddles are doubled, and their mass is increased by 50 %. It has been shown that the two tendencies more or less counteract each other. Also it is obvious, that broad paddles are more vulnerable to damage.

Conclusions.

It was the intention that the present paper should conclude the reporting of the reconstruction of the Hjortspring Boat and the testing of the replica.

Although many questions have been answered, the work of the testing has, however, produced new ones. A whole list of such additional testing is already present.

But let us stay with the present findings:

The construction of the Hjortspring Boat, as it is represented by Tilia, is flexible and sturdy.

The stresses of the sewing seams have not resulted in bursting of the strings.

The tightening of the sewing seams is adequate but not completely convincing.

The deck boards support the feet of the paddlers fairly well, but strength wise they are on the low side.

The hypothesis of the trussing rope remains a hypothesis.

A steering oar mounting was developed. The function was excellent, but it still remains a hypothesis.

The paddles should have different lengths according to their position in the boat.

The width of the paddle blades as used (9 cm) is evaluated as being well chosen for longer periods of paddling.

The paddles should be as light as the necessary strength permits.

The following statement describes the functional value of the Hjortspring Boat:

The boat is very manoeuvrable with regards to accelerating, braking and turning.

The boat is unstable when boarding, but when sailing it was felt stable and secure.

The Hjortspring Boat, as represented by Tilia, is a fast boat. Sprinting velocity can reach 8 knots.

It is expected that the boat may have a day range of at least 50 nautical miles.

The boat can negotiate waves up to 1 metre, shortly at least.

The boat is easy to launch by carrying it out into the water, and it is suitable for landing on a beach.

A paying load of 0.5 tons, excluding the mass of the crew, is quite acceptable.

The work until now advocates the following conclusions as to the production and use of the Hjortspring Boat:

The Hjortspring Boat was designed and built by skilled professionals in a line of still more refined boats.

Indication shows that the Hjortspring Boat was a formidable war tool for swift raids over distances that made it operative in the whole Baltic Sea area as well as in Danish waters including Kattegat and Skagerak, at least when employing "the Stepping Stone" strategy.

(The latter conclusion has yet to be confirmed by further tests.)

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