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The Most Sophisticated and Successful High-Speed Ships for Their Time.

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ABSTRACT

The foundation of modern Scandinavia was laid in the Viking age (AD 800-1066). Never before had so many decisive changes taken place in such a short time and never have Scandinavians played so great a role abroad. High performance sailing ships and formidable seamanship allowed the Scandinavians to travel vast distances and assured much of their military success, based on surprise attack and mobility. The ship-builders succeeded to develop unique sailing ships by combining semi-displacement hydrodynamic hull design with hull lightness, hull strength and flexibility, and a surprisingly effective and safe square rig and sail system.

MARINTEK has taken part in and sponsors the recent research to expand the knowledge and understanding of the Viking ship technology, sailing, and sea going performance. The ongoing building in Tønsberg, Norway of a full-scale replica of the world's best preserved Viking ship, the Oseberg, buried in 834 and excavated in 1904, is based on new scientific interpretation of the hull-lines and comprehensive model tests at MARINTEK to document calm water sailing performance. Speeds of up to 20 knots were tested. Seakeeping tests in the Ocean Basin in rough seas are planned for autumn 2011. In 1991 the explorer Ragnar Thorseth sailed a replica of the long-ship Gokstad across the North Atlantic. Model tests in waves and wind indicated that the ship would survive the 99.5% percentile summer sea conditions - and so she did. In 2008 the world's largest Viking long-ship replica, Sea Stallion (Skuldelev 2) successfully sailed the 1000 nautical mile voyage from Roskilde in Denmark to Dublin.

This paper summarizes the development of Viking ships from coastal rowing ships to superb sea going sailing ships. Major findings from MARINTEK model tests with Viking ships are documented and speed performance, seakeeping performance, steering balance, steering board effectiveness, and importance of hull flexibility, rig, sail and reef systems are discussed.

KEY WORDS

Viking, Sailing Ship, High-Speed, Dynamic Stability, Construction, Flexible Hull, Calm Water Performance, Sea Keeping, Hydrodynamics

1.0 INTRODUCTION

In the year 793 some Norse sea-raiders attacked the monastery of Lindisfarne on the north-east coast of England. This event is generally considered to be the beginning of the Viking age. From the end of the 8th century and up to the middle of the 11th century, Scandinavian peoples played a leading role in European history for the first time. During this period Swedes, Danes and Norwegians set out on sea voyages to distant lands and coasts. Their expeditions reached the steppes of Russia in the east, the Mediterranean, the Black sea and the Caspian Sea in the south, the Barents Sea in the north and America in the west.

At the start of the Viking period it appears that Scandinavians sailed to foreign lands purely on trading missions. During these journeys they must have realised that their ships were superior, that coastal defences were poor and that conditions were rife for plunder. The chief destinations for the Norwegian Vikings were the British Isles. In the second half of the 9th century Iceland was discovered by a party of Vikings who had been blown off course on their way to the British Isles. The sagas relate that the first Vikings settled in Greenland around 980. The colonisation was led by Eirik the Red. Around the year 1000, Eirik's son Leiv led an expedition along the coast of North America and he wintered on the tip of Newfoundland at a place which is now called L'Anse aux Meadows.

If one date has to be chosen to mark the end of the Viking age it has to be 1066. The last major Viking expeditions, which took place in 1066, decided the fate of England and England's relationship with Scandinavia; in two great battles Vikings and Viking descendants from completely different regions and backgrounds met and fought in the battle of Stamford Bridge on 25 September and at the battle of Hastings 14 October. On Christmas Day 1066 William the Conqueror, a Viking descendant, was crowned king of England.

2.0 THE VIKING SHIP DEVELOPMENT

The long-ship is the very symbol of the Viking age. It represents the pinnacle of the Vikings' technical achievements. The seagoing ship had a solid keel, flexible hull and efficient sails, enabling the Vikings to make long open sea voyages under the most extreme weather conditions. Despite being open ships with low freeboard, the ships could weather high wind and seas. Their draft was very low and they could enter shallow waters, beach easily and be rowed up rivers. Ships with such attributes gave the Vikings great scope of actions. They could move rapidly, attack unexpectedly and withdraw quickly. The Viking achievements were only accomplished as a result of centuries of systematic transfer of knowledge, fine seamanship and skilful shipbuilding. The great ships Oseberg and Gokstad preserved in Oslo (Norway) and the 5 Skuldelev ships in Roskilde (Denmark) are amongst the most impressive remains of the Viking Age.

Fig.1. The Oseberg ship. Vikingship Museum, Oslo.

2.1 Seagoing Rowing Vessels

The evolution of the Scandinavian rowing vessel is seen in the late 4^{th} century AD. The Nydam ship (AD 350) from Schleswig is a true clinker, built with its oak planks edge-joined with iron rivets. Framing is secured by means of cleats and frames consisting of shaped pieces of timber rather than bent branches. The Nydam ship was 23m long and only 3.75m wide. The ship was extremely slender and the instability was compensated for by using ballast stones. The most vital new development was to strengthen the ship longitudinally. The ship was rowed by 30 men and the first known type of larger seagoing vessel. It was with ships like the Nydam vessel that the Anglo-Saxons invaded Britain in the 5^{th} century. The famous find from Sutton Hoo in East ship England (AD 650) is of same principal design.

Three hundred years later, the Kvalsund ship (AD 700) was built with oak planks and pine ribs, a rudimentary keel and wide hull. The ship shows another important development; an efficient steering oar combined with a strong and efficient rudder mounting to the starboard quarter of the stern, with the tiller projecting transversely. Cleats continued to be used for some of the fastening of the planks to the frames, but the keel itself is not attached to the frames, and the upper planks are secured with wooden pegs. These features show a sophisticated understanding of the stresses involved, and of how strength could be obtained by combining lightness with flexibility. A vessel of this type could have been rigged for sailing, but the Kvalsund ship shows no sign of having carried a mast.

Fig.2. The Kvalsund seagoing rowing ship.

2.2 First known Sailing Vessel

The Oseberg ship (AD 800) is the earliest Viking ship known to have carried a mast and sail. The mast could be easily lowered and raised thanks to the design of the mast partner which supported the mast at deck level and the mast step in the keelson. The combination of a sailing and rowing vessel also gave unique manoeuvrability. The Oseberg ship with its low freeboard (height 0.65m) was certainly a coastal travel and "royal" ship rather than warship proper. The high prow and stern are embellished with complicated animal ornaments of particularly handsome craftsmanship. The Oseberg ship construction is also comparatively weak compared to later built ocean sailing ships, like the Gokstad ship. For instance cracks in the mast partner supporting the mast which was repaired with iron bands gives clear evidence that it was too slender for heavy weather sailing. Since the Oseberg is the earliest example yet discovered of a Viking sailing vessel, this may possibly indicate that some of the complex problems of setting and working such a rig had not as yet been solved, due to lack of experience.

2.3 A superb Ocean Sailing Vessel

Excavated in 1880, the "Gokstad" has been called the most beautiful ship ever built. The Gokstad ship (AD 850), being slightly larger than the Oseberg ship, has a fully developed keel and strongly supported mast. Built in oak throughout, the Gokstad ship was an excellent ocean-sailing ship. The 18m T-shaped single- piece keel was tapered towards the ends so that the deepest draft was amidships. The effect was to greatly strengthen the ship longitudinally, increase her buoyancy, and make her easier to turn. Directly over the amidships part of the keel, and spanning the four central frames, was a massive block of oak into which the heel of the mast was stepped. Above this, supported by six cross beams, was the mast partner, an elegant and functional fish-shaped component designed to transmit to the hull the forward and side forces delivered through the mast from the sail. The ship, with its shallow draught (0.85m fully loaded), could be beached and launched with ease, thus it was supremely well adapted for raiding and also to penetrate deep into estuaries and up rivers.

Fig.3. GAIA built 1990 (Gokstad ship replica).

The Gokstad ship's hybrid construction of clinker planking, cleat lashing (11 lower planks), and wooden nails (upper 5 planks) gave it a lightness and flexibility which made it a superb sailing vessel. Essential for seaworthiness is the height of the gunwale above the sea surface. The height of the gunwale still remarkable low at about 1.10m, which is two planks higher than the Oseberg.

2.4 The Skuldelev Finds

Other remarkable finds include five ships of different types from around AD 959-1050, which were scuttled during late half of the 11th century at Skuldelev to blockade Roskilde fjord on the north coast of the Danish island Zeeland. In summer of 1962 a major archaeological excavation was set up. In all some 50 000 pieces of wood were recovered. The builders of the blockade could scarcely have chosen five better ships as a sample of contemporary types.

The finds tell us that within Scandinavia ships varied according to local environmental conditions, and there is evidence that the Skuldelev ships originated from both Norway and Denmark. Main particulars for the Skuldelev ships and other ship finds are given in Table 1, below:

Table 1. Particulars of Viking ship finds.

Ship	Loa (m)	Boa (m)	Displ. (tons)	Sail (m2)	Built AD
Nydam-Row	23.0	3.75	8.8		300
Kvalsund-Row	18.0	3.20			700
Oseberg	21.5	5.2	16	90	800
Gokstad	23.4	5.2	24	110	850
Klåstad	21.0	4.5			998
Skuldelev 1	15.9	4.8	20-26	96	
Skuldelev 2	29.4	3.8	26	112	>950
Skuldelev 3	14.0	3.3	9.6	45	>1000
Skuldelev 5	17.5	2.5	7.8	46	>950
Skuldelev 6	11.2	2.5	3	26	

3.0 SWAN OF THE SEA GODS

Ships lay at the root of Viking achievement. Indeed, Viking expansion was only possible because of the expertise in seafaring and shipbuilding for which Vikings are famed. High performance open deck sailing ships and formidable seamanship allowed them to travel vast distances and assured much of their military success, based on surprise attack and mobility. The ship-builders succeeded to develop unique sailing ships by combining hull design with hull lightness, hull strength and flexibility and utilization of surprisingly effective and safe rig and sail systems, and use of ballast for final trim of sailing balance.

The main features of any fast ship are a hull form capable of generating dynamic lift, light operational weight, effective powering, adequate dynamic stability, steering balance at high speed, and adequate strength. These features as related to Viking ships will be discussed in the following.

3.1 Speed Performance

The sailing ships built in Scandinavia more than 1000 years ago were predominantly high performance semi-displacement (light displacement) ships.

When comparing the speed performance of different types of boat designs or boats of different sizes, it is not speed alone which counts, but speed in relation to hull length L or relative speed ratio $V_s/\sqrt{L}$ (Vs in knots, L in feet). This refers to the well known fact that mere increase of size, with no change of other design features, will increase sailing speeds roughly in proportion to the square root of the increase of ship length. In practice, heavy-displacement yachts can only attain Vs about $1.5\sqrt{L}$ in the most favourable reaching conditions. In the same conditions a light-displacement yacht of the same waterline length may reach a speed ratio of 2.0. Planing sailing dinghies and modern catamarans may attain a speed ratio well above 4.0.

In 1893 a copy of the Gokstad ship (VIKING) made the Atlantic crossing from Norway to New York and on to the World's Columbian Exposition in Chicago. In heavy weather and storms, sailing speeds in excess of 10 knots were reported. Helmsmen sailing the Gokstad replica (GAIA) have confirmed measured speeds of 12 knots in reaching conditions and 10.5 knots in a square reach, which equals to speed ratios 1.50 and 1.30. The Norwegian adventurer Ragnar Thorseth sailed GAIA from Norway to New York in 1991 (the 500 year anniversary for Columbus' discovery of the continent). GAIA experienced great sailing with measured maximum speeds up to 17 knots, which equals a speed ratio of 2.20 (Froude number Fn=0.62). In 1984-86 Ragnar sailed around the world with "Saga Siglar" a replica of a larger 15.9m merchant ship (Skuldelev 1) built more for strength rather than lightness and speed. During the most dramatic event, with a full reef in the sail, downwind surfing speed of 14 knots in 40m/s hurricane were measured, yielding an astonishing speed ratio of 3.5. During a 4 hour period mean speed of 8.4 knots was measured giving a speed ratio of 2.12.

The worlds largest Viking long-ship replica, the 29.4m and 3.8m wide Sea Stallion from Glendalough (Skuldelev 2) was launched by the Vikingship Museum in Roskilde in 2004. During initial trials the ship appeared to be very sensitive to small changes in ballast weight, longitudinal center of gravity, and trimming of sail. Total ship weight was 25 tons, including 9 tons of ballast weight and about 5 tons of crew weight. The experiences after sailing the ship for half a year were that; the Sea Stallion should be sailed with ballast stone weight close to the ship centre, i.e. with smallest possible longitudinal radius of gyration. This load condition gave the least pitch motions in a seaway and made it possible for the crew to trim weight forward, as proved necessary for effective tacking. In 2008 the ship was making the 1000 nautical mile voyage from Roskilde in Denmark to Dublin. Mean speeds up to 15 knots were measured over a period of several minutes, which equals a speed ratio of 1.5, in rough weather.

3.2 Light Weight and Speed Capacity

The Viking sailing ships were predominantly semi-displacement (light displacement) ships with most of the vessels weight supported through buoyancy, however with hull forms capable of developing dynamic lift in extreme wind and wave conditions.

Fully loaded weight and vessel waterline length is often applied for comparison of ship speed capacity. The figure below gives Length Displacement Ratios of Viking ships and modern yachts. It is remarkable that Viking long-ships have a lightness ratio even better than modern yachts and with only extreme designs such as Volvo Ocean racers coming close.

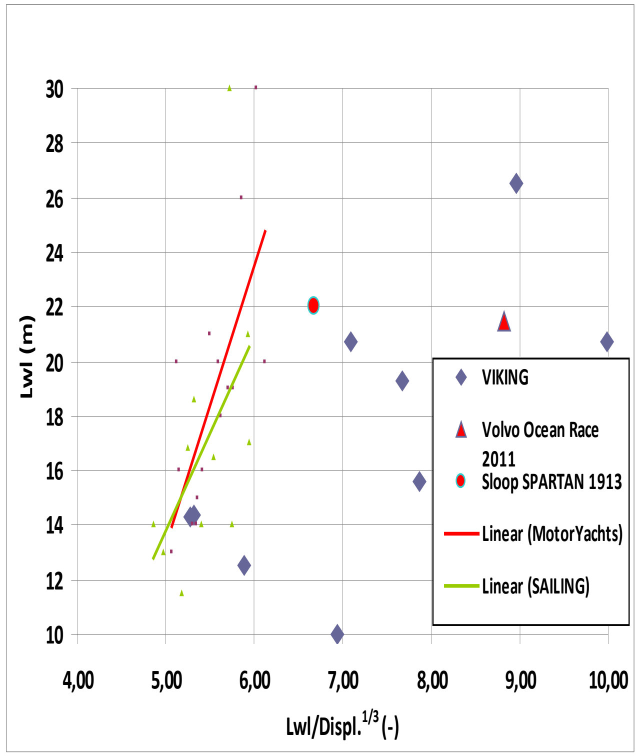

Fig.4. Comparison Length Displacement Ratio.

3.3 Seakeeping and Ship Flexibility

Unlike modern vessels, in which the structural design aim is maximum stiffness in the construction and materials chosen, Viking Age ships were very light and flexible. Sailing with Sea Stallion confirms that it is of major importance that flexibility is evenly spread through the whole construction. The stiffest part of the construction would be the first part to break. A simple torsion stiffness test of the Gokstad ship replica GAIA was performed by moving a ballast weight of 1.5 ton +- 1.8m transverse at a distance of 10m from LCG. The stems flexed +/- 8cm, measured at height 2m above midship deck level.

In 2008 the world's largest Viking long-ship replica, the Sea Stallion (Skuldelev 2) was making the 1000 nautical mile voyage from Roskilde in Denmark to Dublin. During heavy seas sailing with Sea Stallion it is reported that; "Through the many miles we have sailed, we have become accustomed to the fact that Sea Stallion is a very flexible ship. When the ship sails out of a wave and immediately knocks down the next, the whole bow moves 20 to 30cm back and forth, ship sides are pushed in and out, beams move diagonally in relation to each other, braces move in and out, thwarts move from and to the ship sides, the mast fish moves from side to side every time a swell hits the ship, the rigging changes from being completely tightened to hanging loose the next moment, etc".

Fig.5. "Sea Stallion" Rough Sea Sailing.

It is a matter of discussion as to whether the Vikings deliberately built their ships to be flexible or whether it is a result of their sailing ship technological development. The author would agree with sailors of Viking ship replicas and traditional Norwegian clinker built open square-rig boats who claim that a flexible hull gives good seaworthiness. In particular, the spreading of bow impact forces and forces from the mast and rig would reduce local loads in the structural triangles formed by the deck and two sides of the hull bottom, holding the ship together. No doubt, the hull construction utilizing extreme hull lightness combined with hull flexibility and hull strength was essential for the Viking ships' outstanding sailing and seakeeping capabilities. It might also be postulated that hull flexibility would increase rough weather sail performance. A sail is most efficient when the aerofoil is stable and not sharply moving or fluttering. The flexibility of the hull would be of importance in dampening and stabilizing mast movements and fluctuations in sail forces.

3.4 Dynamic Stability

High-speed vessel dynamic instability might occur with abrupt changes of hydrodynamic pressure along the hull. It is essential for safe operation of any high speed vessel that consistent stability forces are generated at increasing speed (and increasing heel for sailing boats). Model tests in calm water with the Oseberg Viking ship show that combined static and dynamic roll moments increase nearly linearly with increasing speed at relevant heel angles. However, 10% to 8% reductions of static GZ are measured at 10 knots and 5° and 10° of heel, respectively. One should also note that ventilation and cavitation phenomena would influence the dynamic stability of high-speed vessels. For Viking ships buoyancy based stability and the dynamic stability effects in heel and yaw must be in perfect balance with the controllable sail and rudder forces.

Sailing with traditional Norwegian clinker built, open square rig boats (Loa 10 to 15m) have confirmed that small variations of hull design (and load and ballast condition) could have decisive importance on sailing and handling performance. Experience shows that water flow ideally should follow the plank chines from water entry to stern, without transverse flow separation. As Viking ships are sailed with heel and drift angles up to above 15 degrees, the transverse separation from the keel might also contribute to increased risk of dynamic instability.

Fig.6. Traditional Norwegian (50ft.) square rig boat.

4.0 MODEL TESTS CALM WATER PERFORMANCE

In March 2008, model tests were carried out at MARINTEK in support of hydrodynamic evaluation of two hull variants of the Oseberg Viking ship. The tests were carried out to assess the ships' performance under sail, with particular interest in the change of longitudinal Centre of Lateral Resistance (CLR) with speed and heel in regard to helm balance, and also to provide accurate hydrodynamic performance data.

4.1 Calm Water sailing Performance (VPP Plots)

The Wolfson Unit WinDesign velocity performance prediction program has been used to estimate the Oseberg ship speeds across a range of true wind speed and heading angle conditions. This program combines the hydrodynamic properties as derived from the tank test data with aerodynamic information for the rig and the ship stability characteristics to estimate the ship sailing performance.

Aerodynamic coefficients for the Oseberg square rig sail were derived from a range of data sources based on experimental wind tunnel tests carried out by the Wolfson Unit on similar single square rigged configurations, which were then implemented into the VPP (Velocity Prediction Program).

The Oseberg ship polar speed plot shows a comparison of the 14 and 16 ton load conditions, both with and without the effect of crew transverse movement which increases the stability of the vessel. For each of these plots the circular axis represents the true wind direction in degrees (0° is head to wind, and 180° is dead downwind) and the radial axis represents the boat speed in knots. Each plotted curve of boat speed versus true wind angles characterises a different true wind speed and/or load condition.

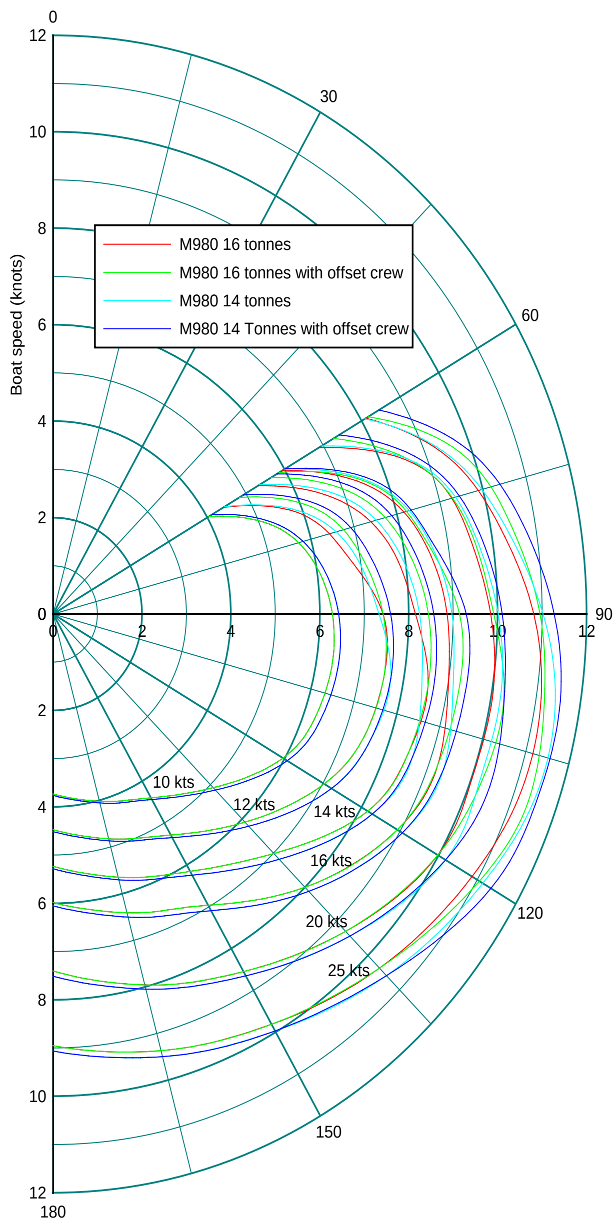

Fig.7. VPP polar plot comparing effectiveness of offset crew and displacement.

4.2 Balance of Hydro- and Aero-dynamic forces

As can be seen from the model test (Photos), with increasing leeway, the bow wave grows on the leeward side of the vessel, this result in a relative gain in buoyancy based stability. This is of high importance for Viking ship performance, as the roll moment does not increase significantly with increasing side-force, which is different from what one would see in a modern style sailing vessel. There is a noticeable, up to 10%, loss of total roll stability with speed. This is mainly a result of the change in volume distribution with the bow and stern wave immersing the ends, reducing the buoyancy in the midship region. At heel angles equal to and greater than 15°, the model shipped water over the deck edge at the tested freeboard. This is special for the Oseberg with its extremely low freeboard (midship height from bottom of the keel to the gunwale is 1.58m and freeboard 0.65m). This heel angle limit would be reduced when motions in waves are taken into consideration.

Tests were conducted at 16 ton load and 1° bow up trim to determine the effect of altering rudder angle on position of the hull CLR (longitudinal Centre of Lateral Resistance) were carried out at selected speed and heel conditions. Theses results are combined with the measured position of CLR, and calculated sail plan Centre of Effort (CE), to produce an estimate of the rudder angle required to hold a steady course. The calculated steady state rudder for each of the tested speed (up to 12 knots) and heel angle (up to 15°) combinations show that rudder angles below 1.7° are sufficient to maintain steering balance. These effectiveness tests were conducted on starboard tack where the rudder has less immersion than on port tack; as a result, one would expect the rudder effectiveness to be greater on port tack, shifting CLR by more than 0.5 metres. This is a reasonable shift in CLR in comparison to modern shallow draft sailing vessels.

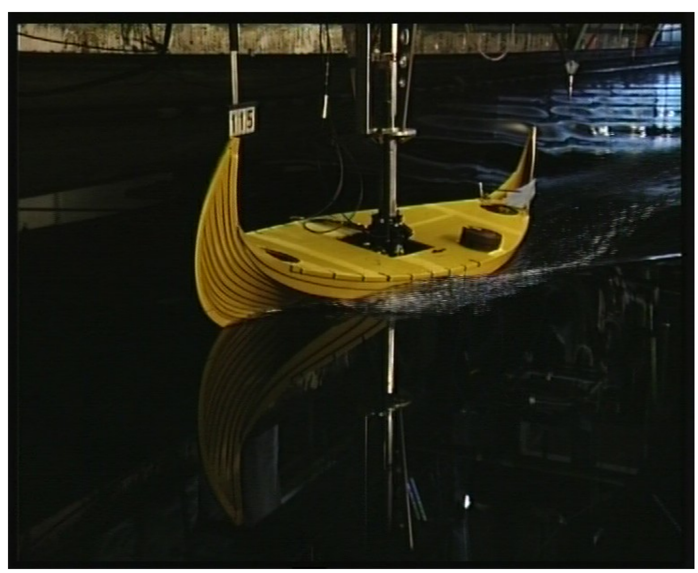

Fig.8. Oseberg (1:10 model) towed at 12 knots, heel 10deg. and yaw 10 deg.

As the ship is trimmed forward to level trim, so the CLR shifts forward. This shift in CLR would have a drastic 10° impact on rudder balance angle. Therefore it is likely that longitudinal ballast movements in general were made to ensure that the ship tracked well and responded well to the helm. It must be borne in mind that a fixed sail plan centre of effort position has been used in the calculation, whereas in reality the rig and sail plan would be adjusted with wind conditions to maintain balance in conjunction with the rudder.

5.0 THE DRAGON'S WING

Despite the fact that mathematics, computers and wind tunnel testing are playing an ever increasing part of the designing of sails, sail making as well as sail tuning are still based on a systematic trial and error process rather than pure science – as it surely also was 1200 years ago. Related to the proportions, size and positioning of the Viking ship square rig mast and sail, the optimal combination can hardly be found by modern advanced technical computations. Ancient basic design features must have been achieved by systematic gathering of quality sailing trials and experiences.

The rig would be the most important factor for the safe and successful sailing of Viking ships. What every sailor really needs is an adjustable sail, which can be trimmed and tuned effectively to cope with a great variety of wind speeds and angles of attack. This requires a different sail size and shape for light and gale conditions, different for close-hauled sailing and different still for reaching. The author would argue that the Viking ships' square sail and rig as developed during the 8th century seems to be close to optimal for these purposes. However, the Viking ship rig design is still debated as no normative finds of rig and sail are accessible.

5.1 Development of Viking ship Sail

Rectangular sails are used on all Viking ships. In principle low aspect ratio square sails are the best in downwind sailing and high aspect ratios are best for windward close-hauled sailing. A good compromise is the quadratic form. Higher aspect sails have an impact on mast dimensions and rigging. The yard is hoisted to just below the attachment point of the backstroked shrouds, so that the yard and side chords are kept forward of the shrouds in all sailing conditions. The forward and back stays are thus fastened close to the top of the mast, well above the yard.

The selection of width of the rectangular sail is mainly dependent on ship beam and length as the fastening point forward will be at the gunwale at a sheeting angle of about 20°. The position of the aft sheeting point is selected using a sheeting angle of about 45° from the resulting position at the gunwale. The quadratic sail area is then closely defined; however the ship stability and sailing stiffness can be adjusted by removing or adding stone ballast. More sail (higher) can be carried by increasing ballast. More ballast will also give the ship larger underwater area and thus less drift during windward sailing. Typical ballast ratios were up to about 0.25 for slender and fast long ships.

Final trimming of the steering balance during close-hauled sailing can be tested by adjustment of mast angle, trimmed forward to move the CE forward, and aft to move CE aft.

6.0 SEA-GOING CAPABILITIES

The most critical feature of Viking ships is the open boat concept with relatively low freeboard (Gokstad Loa 24.5m, Saga Siglar Loa 16.5m and Sea Stallion Loa 29.6m with freeboard of respectively 1.20m, 1.05m and 0.80m with added 0.22m in rough sea sailing).The low freeboard gives a very short range of positive hydrostatic stability and the ships have to be sailed skilfully by helmsman and crew. During tacking the low freeboard might be most critical at the windward side with risk of taking green water over gunwale and stern. Other decisive rough sea ship features are bow and hull capabilities to throw sea away from the low side during sailing and surely bow lift, hull dynamic lift and steering performance during extreme wave surfing conditions.

As for any critical event at sea, experience and skill is most important, including the ability to evaluate safety limits and take corrective actions – in due time. The Viking ship rig and sail is extremely well arranged for easy reduction of sail forces by reducing sail area (reefing) and "instantly" reducing sail profile and thus sail forces. The capability to both reduce sail force and move sail force centre are extremely important Viking ship features – enabling safe sailing in extreme weather conditions.

Fig.9. "Sea Stallion" sailing with three reefs 50% sail area.

In the summer of 1992 the adventure Ragnar Thorseth crossed the North Atlantic with the Gokstad ship replica GAIA. Safety features of the ship were tested at Marintek Ocean Basin, using a 1:10 model in waves and wind. Performance during free-drift (without sails) was tested with alternative sea-anchor systems. Breaking waves up to 11m and wind up to 35m/s were generated. Critical performance factors were keeping the ship bow in close to downwind and following wave direction and to keep ship drift speed in balance with the wave speed. Green water over stern and gunwales were critical effects. With the best balance of sea anchor drag and ship drift speed the maximum generated Ocean Basin wind and wave conditions could be handled. We wished Ragnar good luck and advised him to avoid breaking waves above 12m!

The most dramatic event ever reported from a Viking ship sailing under extreme weather conditions, would probably be the "Saga Siglar" fighting a 40m/s Northwest hurricane along the coast of Labrador. The Skuldelev 1 (16m – 26 tons merchant and transport vessel) replica "Saga Siglar" was built in Norway by experienced and skilled boat builders. Adventurer Ragnar Thorseth with a crew of 6 men sailed the ship around the world in 1983-1986, experiencing several exciting events. During the sailing west from Greenland along the Labrador coast 10th August 1983, wind and waves increased dramatically during a 6 hour period. Wind increased to 22-25m/s and breaking waves of at least 10m developed. The sail was reefed two times from 96m2 to 40m2 and rescue organisations were alerted. During sun rise the wild ocean revealed itself and a wind speed of 40m/s was measured. Mean waves of 10m to 12m were observed (significant wave height above 10m). The ocean was a hell of breaking white water. The most critical operation was to keep the ship as close as possible to following weather with the spare steering oar. Ragnar reported in the ship log that "No fear of a possible visit to Valhalla was present – rather a divine feeling of steering an open Viking ship in gale conditions" at measured speeds of up to 14 knots (4 hours mean speed logged at an incredible 8.4 knots) in breaking waves above 15m height. The next morning the breeze was light, the waves kindly and the voyage proceeded with increased humility and respect for Viking ship capabilities.

In June 2008, the 29.4m long ship replica "Sea Stallion" sailed in the Irish Sea on a beam reach, in a strong breeze with winds 12m/s and waves up to 3.5m high. The sail had two reefs, out of a total of five. The ship was doing fantastically as it was being hit by waves and twisting in the sea. The reconstructed ship held on without problems in regard to structural issues, but it was also very worn out after such a trip where it constantly twists and is hit.

7.0 CONCLUSIONS

The long-ship is the very symbol of the Viking age. The many unique Viking ship features are detailed in this paper. The Viking achievements were only accomplished as a result of centuries of systematic transfer of knowledge, fine seamanship and skilful shipbuilding. Compared to today's regulative standards, shipbuilder specific designs and computer based development of modern high performance boats; the Viking development process must be admired. In particular, the use of available resources and materials are impressive; Oak used throughout, planks nailed by iron rivets, cleats using baleen whale plates to fasten lower planks to the frames, wooden pegs used for fastening the upper planks, ropes and stays made of basswood fibres and walrus skin, sails of goats wool, etc.

Featuring excellent helm balance, dynamic stability characteristics, and driven by an easily controllable square rig sail plan, the resulting lightweight and high speed vessel obtained a level of performance still to be challenged by most modern sailing yachts.

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