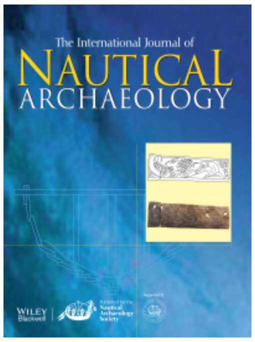

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Windward Sailing Capabilities of Ancient Vessels

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Weatherliness is widely considered to have been an important ability for ancient sailing vessels, yet little firm experimental or theoretical data on the matter is available. However, by drawing on a variety of sources of model-test data and trials of full-scale replicas, it is possible to establish a general picture of what might have been possible. It appears that while ancient sailing vessels may have been capable of modest windward performance in moderate conditions and with a freshly-cleaned hull, this capability quickly disappeared as the hull became fouled and/or the wind and sea conditions deteriorated.

Key words: ancient sailing, sailing performance, archaeological reconstructions.

The potential for windward sailing performance receives considerable attention in the discussion of ancient ships and seafaring (for example Gillmer, 1979; Hutchinson, 1994; Tilley, 1994; Casson, 1995: 273, 464; Greenhill, 1995; Roberts, 1995; Gifford and Gifford, 1996; Gifford, 1997; Wachsmann, 1998: 253; Weski, 1999; Greenhill, 2000; Whitewright, 2007). These authors all consider the effects of factors such as hull shape, rig-geometry, mast-position and the number of masts in order to explain how ancient boats were sailed, and what, if any, progress they could make to windward. This interest is said to be because 'It is not reasonable to go to sea without the ability to get to windward by any means' (Tilley, 1994: 309) and 'Being able to sail to windward at all was vital to being able to sail back to one's home port' (Roberts, 1995: 307).

This paper sets out to examine the windward sailing potential of ancient vessels in the light of technical data which is available from investigations of the performance of yachts and sail-assisted ships, and sailing trials on replicas of ancient vessels. It suggests that the ability to sail to windward was much less widespread than is commonly assumed.

Windward performance

The windward performance of a sailing vessel (as defined by its ability to make progress towards the wind over an extended period, so as to 'keep in deep water when the wind blows towards the shore' (Tilley, 1994: 309) depends upon the hydrodynamic efficiency of the hull and the aerodynamic efficiency of the sails. These factors are separate in that hull and sail efficiencies can be analysed in isolation, and it is only when they come together on a complete vessel, with the addition of some form of rudder for control, that their combined potential is realised.

When a sailing vessel proceeds on a close-hauled course, the sails have to be sheeted fore-and-aft, and thus most of the force they produce is actually directed athwartships (generally referred to as side-force), not in the fore-and-aft direction required to provide propulsive force. These aerodynamic forces have to be balanced by equal and opposite forces produced by the hull, which results in the hull adopting an angle to the incident flow in order to produce side-forces. This angle is the leeway angle. The balance of forces is illustrated in Fig. 1. Under steady conditions, the resultant hull and rig forces must be equal and opposite. For the rig they can be resolved relative to the apparent wind-angle and thus represent the lift and drag forces of conventional aerodynamic analysis. The angle between the lift and resultant forces is known as the drag-angle—it is the ratio of the lift to the drag and thus a measure of the aerodynamic efficiency of the rig.

The hull forces are resolved relative to the course made good (not the centreline of the vessel) and the angle between the hull side-force and the

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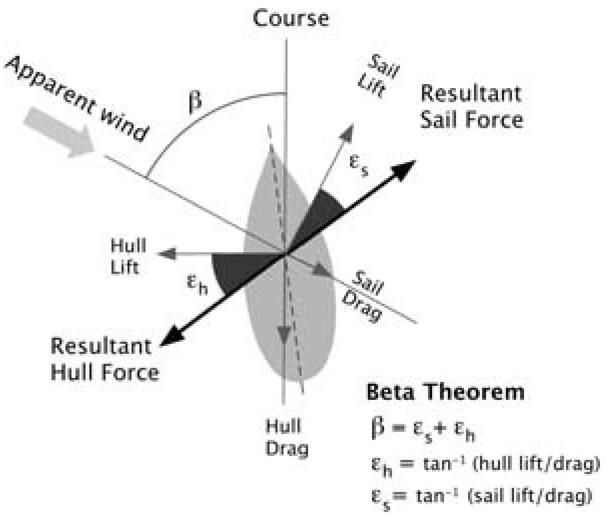

Figure 1. Forces acting on a sailing vessel when sailing close-hauled. The total forces produced by the hull and the rig are equal and opposite and resolved relative to the respective incident flow directions. The sum of the 'drag-angles' of these forces is equal to the angle between the course and the apparent wind—the 'beta theorem'. (C. Palmer)

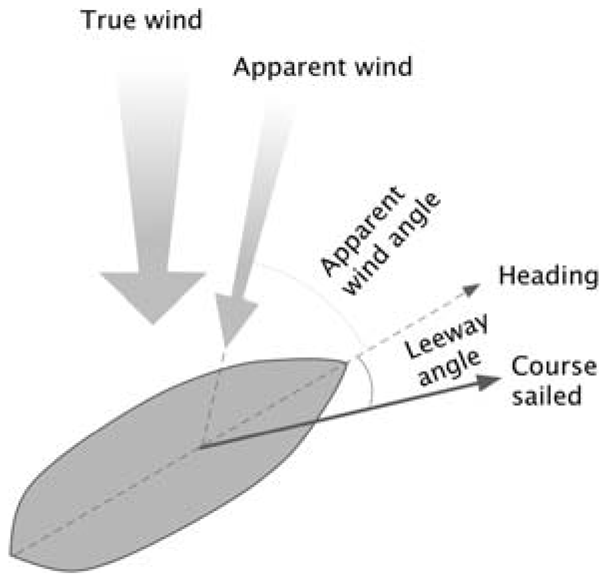

Figure 2. Relationships between true and apparent wind-angle—showing that apparent wind appears further forward due to forward speed of the vessel. (C. Palmer)

resultant is the hull drag-angle. It can be shown by geometry that the apparent wind-angle relative to the course made good is the sum of the drag-angles of the rig and hull.

Beta theorem

This deceptively simple relationship (which is commonly called the beta theorem since the Greek symbol beta (β) is conventionally used to indicate the apparent wind-angle) implies that knowledge of the minimum drag-angles for hull and rig is all that is needed to predict the sailing-angle to the apparent wind. In fact the conditions at which the resultant forces are equal and opposite are not always those at which the drag-angles are minimised. In practice, this balance generally occurs when the sails are operated at a lift condition which is higher than when the lift-angle is minimised (Garrett, 1987: 68). This means that windward ability (as measured by angle to the apparent wind) will always be less than that predicted by the calculation of apparent wind-angle from the addition of the lowest drag-angles of the hull and rig. Consequently any analysis based on this relationship will err on the optimistic side. This paper will use this relationship with that *caveat* in mind, since the determination of the actual sailing point is very complex. It can only be undertaken using computer models, which require detailed definitions of the characteristics of the hull and rig over a wide range of speeds and angles to the incident flow. Such information is not available for traditional sailing vessels and, even if it were, the analysis involved is extensive and the additional accuracy of doubtful value to the overall conclusions of this analysis.

The drag-angle theorem can be used to study the relationship between the hull- and rig-efficiency and the angle to the apparent wind, but actual windward ability is of course relative to the true wind direction. The relationship between the apparent and true wind (Fig. 2) is a function of the true wind-speed and the vessel-speed, and can vary substantially depending on that ratio. However, the difference between the two becomes less as the ratio of true wind speed to vessel speed increases, so in the case of traditional sailing vessels, which seldom sail faster than 33% of the true wind speed when close-hauled, the variation with small changes in vessel:true wind speed is in fact quite small. Accordingly, for this paper an analysis has been undertaken at a vessel-to-wind-speed ratio of 0.33, but the conclusions will change little over the range of 0.25 to 0.5, the band within which almost all traditional vessels fall (Brandt and Hochkirch, 1995; Harries *et al.*, 2000; Nomoto *et al.*, 2003).

Figure 3 shows the results of calculations which use the drag-angle theorem to produce contours of the relationship between hull and rig lift/drag

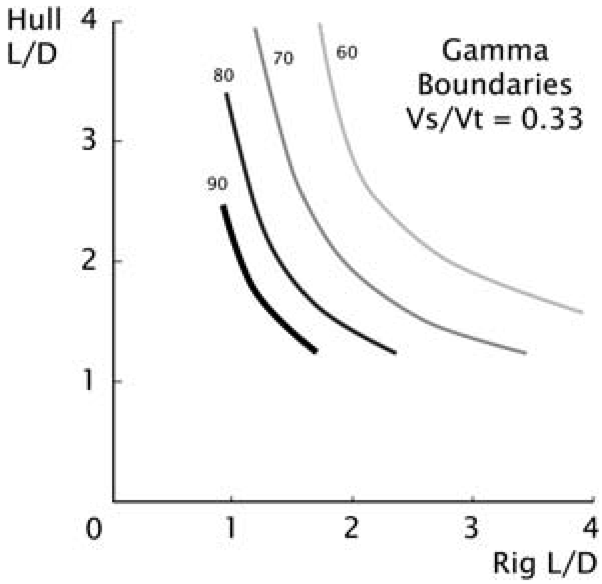

Figure 3. Contour curves of relationship between hull and rig efficiencies (lift/drag ratios) and the sailing angle to the true wind (calculated using the beta theorem.) The result is valid for a case where the vessel speed is 33% of the true wind speed—a typical value for traditional sailing vessels. (C. Palmer)

ratio (the drag-angle) and angle sailed to the true wind. It shows the combinations of hull and rig efficiency that are required to achieve different sailing angles to the true wind. For example, if the hull and rig efficiency are both around 2, the vessel will be able to sail at up to 70° to the wind. However, the same hull fitted with a rig which can only achieve a lift-to-drag ratio of 1 will only be able to sail at 90° to the wind. By way of comparison, the most efficient of modern sailing yachts can achieve an angle of better than 35° (Marchaj, 1996: 23). This graph therefore provides a theoretical background against which the efficiency of different rigs and hulls may be evaluated. What are now needed are typical efficiency values so that real boats can be plotted against these boundary curves.

Hull drag-angle

The ability of a hull to produce the lateral forces required for windward sailing is a function of the depth of the hull and the shape of the hull sections. In order to produce these lateral forces, the hull must operate at an angle to the incoming water-flow, called the leeway angle. The amount of leeway is thus a consequence of the efficiency of the hull and a high leeway-angle is a result of poor hull efficiency, not its cause.

The published literature does not contain a large number of sources of information on the hydrodynamic efficiency of the types of hulls used by traditional vessels. Such information is best obtained from tank-tests and few of these have been conducted on traditional hull forms. It is not possible to obtain this information directly from full-scale trials, but it can be deduced from the results of measurements of rig-forces, though this requires knowledge of the leeway-angle, a variable that is notoriously difficult to measure with any accuracy (Grant and Stephens, 1997).

Towing-tank tests conducted to support the development of sailing fishing-boats (Palmer, 1987; 1990) provide some insights, particularly on the effect of different appendage configurations. Harries *et al.* (2000) tested models of the 18th-century sailing vessels *Bellona* and *Hebe*, from which it is possible to derive hull-efficiency parameters. This is also possible with results presented by Nomoto *et al.* (2003), reporting tests on a model of the *Bezai*, a traditional Japanese sail-trading vessel. The tests on a proposed fishing-boat for Sudan (Palmer, 1987) used one hull form to which were fitted a range of different appendages. These are illustrated in Fig. 4. Configuration 1 is the bare hull—a round-bilged hull of moderate fullness, which is not dissimilar to many traditional sailing vessels. It was fitted with three different types of appendages—bilge keels, skeg and rudder (two versions), a bar stem and a deep forefoot, as was used on the sailing fishing-boats of north-west India, and adopted for racing 'dhows' built by members of the Royal Bombay Yacht Club (Kemp, 1895: 439).

The tests were conducted at a speed equivalent to 5 knots full-scale, a likely sailing-speed for this type of boat in a 15-knot wind. In fact, as the results of the *Bezai* tests (which will be discussed later) demonstrate, the hull efficiency is not very sensitive to sailing speed, so the results from one typical speed are sufficient to characterise a hull. Each hull profile shown in Fig. 4 is annotated with two numbers—the highest value of hull efficiency achieved (that is, the ratio of hull side-force to hull resistance as measured by the towing-tank dynamometer, and consequently relative to the course sailed, not the hull centreline) and the associated leeway-angle. The bare hull achieves an efficiency ratio of 1.4, whereas the hulls with the deep bow or deep skeg (configurations 5 to 8) achieve ratios of 2.8 to 3.0. The leeway-angle associated with these maximum ratios shows

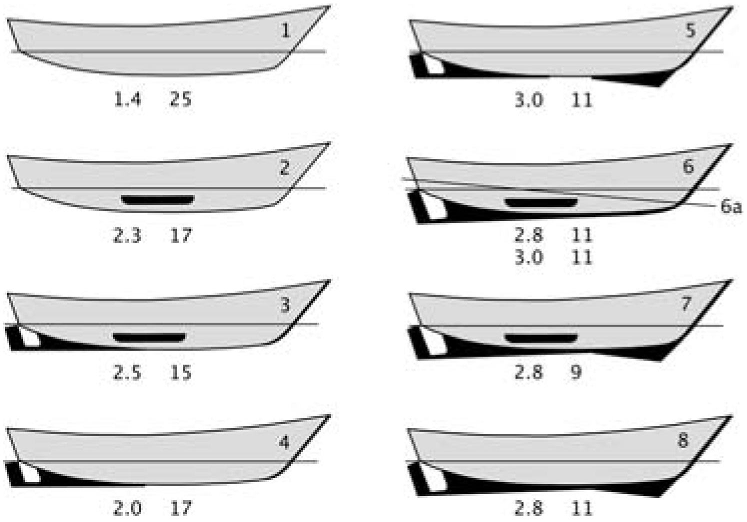

Figure 4. Profiles showing the range of appendages tested on a towing tank model of a fishing boat hull. Configuration 1, bare hull. Bilge keels are fitted to 2, 3, 6 and 7. Bar keel and shallow skeg and rudder, 3 to 5. Bar keel and deep skeg and rudder, 6 to 8. Deep forefoot, 5, 7 and 8. Trim by the stern 6a. (C. Palmer)

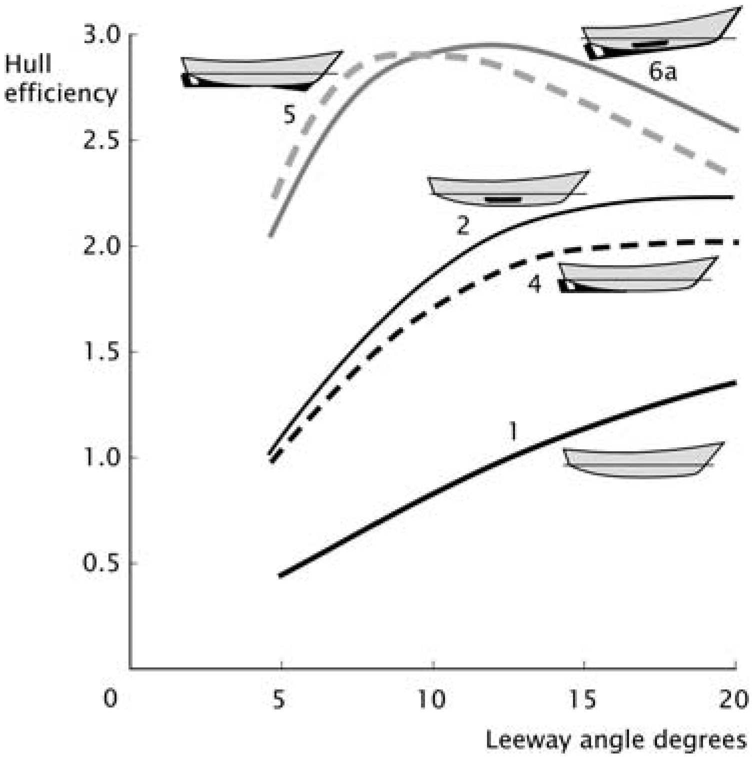

Figure 5. Selection of configurations from fishing-boat tests, showing the variation of leeway-angle with hull efficiency. Configurations as in Figure 4. (C. Palmer)

that the more efficient hulls operate at lower leeway-angles (around 10 to 11° as compared to more than 15 for the less-effective configurations). Figure 5 shows how the efficiency ratio varied with leeway-angle for a selection of the hull forms. Broadly, these results show that the most significant feature associated with high efficiency is draft. The forms with the deep skeg and those with the deep bow have very similar efficiency, although they had very different centre of lateral resistance locations, so would require different rig locations in order to give acceptable helm balance.

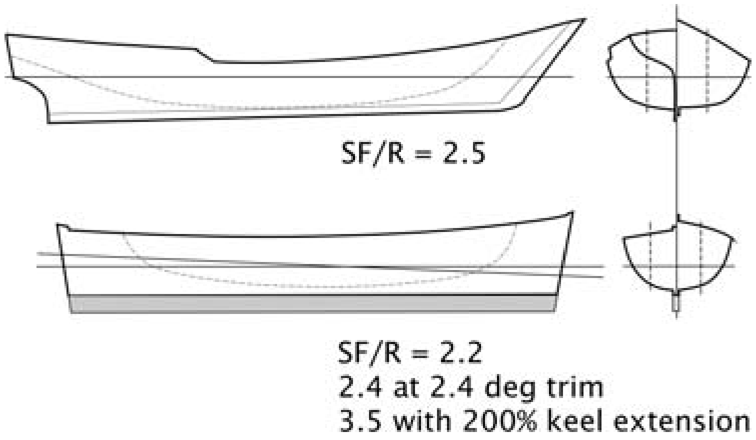

Figure 6. Traditional Indian fishing-boats of 'Satpati' (top) and 'Tuticorin' types, tested in a towing tank to determine hull efficiency. The Tuticorin hull was tested at level and 2.4° trim by the stern and with a deep keel extension. (C. Palmer)

Bradbury (1985) conducted wind-tunnel tests on models of a modern *Mariner* merchant-ship hull form. While the absolute results are unreliable due to the absence of wave-making resistance and the presence of a free surface, the trends demonstrated are of some assistance in explaining the differences described above. Bradbury's results showed that increasing draught and trim by the stern improved the hull efficiency. However, trim by the bow reduced it, which helps to explain why trim by the stern (Fig. 4, no. 6a) was more effective than achieving the same draught with a 'bow keel' (Fig. 4, no. 5). Since the use of aft trim has other practical advantages of greater directional stability and aft position of CLR, it is perhaps no wonder that the deep bow configuration has not become widespread. (Bradbury's results indicated that when trimmed 1 in 20 by the stern, the centre of lateral resistance moved aft by 25% of the waterline length.) Bradbury's results also show another interesting trend. When the beam of the model was reduced, the hull efficiency increased significantly, which has implications for the windward ability of long slender hulls such as the Viking longships.

Similar tests to those on the Sudan boat were conducted on two different traditional Indian fishing-boat forms (Fig. 6)—a boat from Satpati near modern-day Mumbai, and one from near Tuticorin in south-east India (Palmer, 1990). The lines were obtained from Zeiner (1958). The Satpati hull had a firm bilge and raking keel that faired into a skeg. No rudder was fitted for the tests. The Tuticorin boat was double-ended with a vestigial keel. The maximum efficiency was 2.5 for the Satpati form and 2.2 for the Tuticorin hull. When the Tuticorin hull was trimmed by the stern by 2.4°, the efficiency increased to 2.4. This hull was also fitted with a deep keel-extension, which increased the efficiency to 3.5. Here again, the results show that draft (achieved by trim or an extended keel) is the key to hull efficiency.

Effect of hull roughness

These model tests were conducted on hydrodynamically smooth model hulls and scaled assuming fair, clean, full-scale hulls such as would be the case for new fibreglass construction. In practice, the real hulls of traditional vessels are made of wood and roughly finished. They quickly become further roughened in use and, if they are not hauled out frequently, they accumulate biological fouling. All these factors cause a significant increase in resistance, and the magnitude of the increase depends upon the degree of roughness and the proportion of the total resistance that is due to surface friction. Typically the frictional resistance of even a smooth hull will be at least half of the total at close-hauled sailing speeds (Nomoto *et al.*, 2003).

Consequently, an increase in frictional resistance can have a significant effect upon total resistance and thus upon the hull efficiency (because side-force is unaffected by surface roughness and thus remains constant so long as leeway-angle and speed do not change). The results from the tank-tests were re-analysed to incorporate the influence of hull roughness, and the effect on hull efficiency for the Sudan vessel is shown in Fig. 7. It shows that for a configuration that achieves an efficiency of 3.1 when perfectly

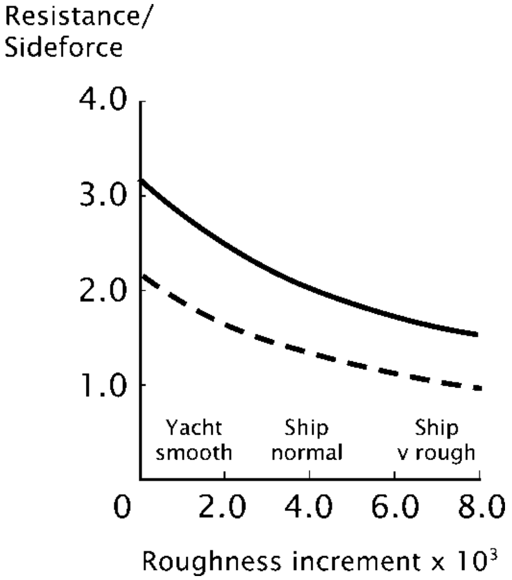

Figure 7. Effect of hull roughness on the hull efficiency of the fishing-boat hull shown in Figures 4 and 5. Roughness ranges from a smooth, fibreglass yacht hull to a very rough bottom with around 10 mm of marine fouling. (C. Palmer)

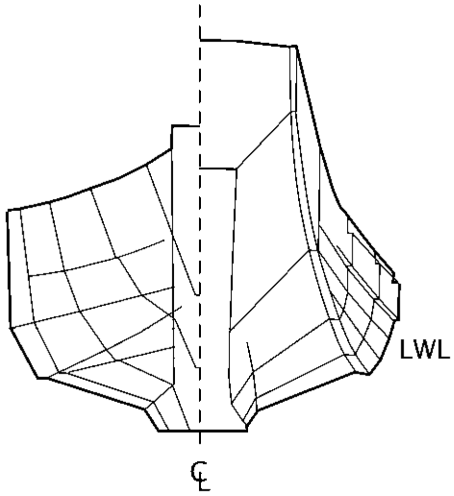

Figure 8. Body plan of *Bezai*-ship. (C. Palmer, redrawn from Nomoto *et al.*, 2003)

smooth, the efficiency can be reduced to less than 2 when the hull is heavily fouled. Similarly a configuration that has a smooth hull efficiency of 2.1 reduces to little more than 1 when foul.

Nomoto *et al.* (2003) report the result of towing-tank tests on a *Bezai*-ship, the lines of which are shown in Fig. 8. The variation of side-force-to-resistance ratio is shown in Fig. 9, plotted for three different leeway-angles, and hull-surface roughness ranging from smooth to very rough.

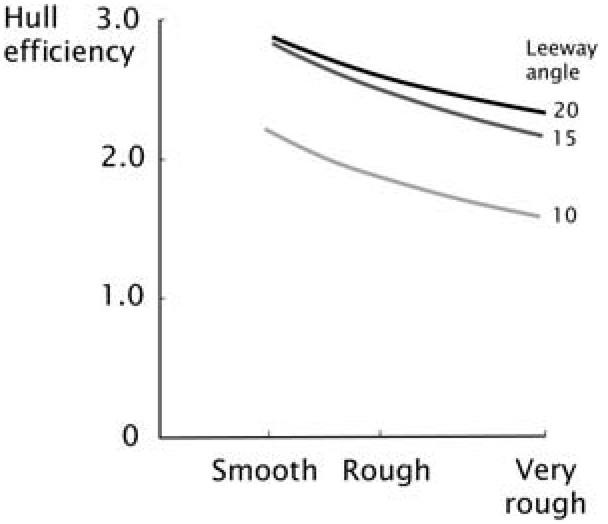

Figure 9. Effect of hull roughness on hull efficiency of *Bezai*-ship, for three different values of leeway-angle. (C. Palmer)

The smooth hull achieves a maximum efficiency of 2.8, but when it is very rough this drops to 2.3. The towing-tank tests on models of *Bellona* and *Hebe* reported by Harries *et al.* (2000) provide sufficient information on the resistance and hydrodynamic-lift characteristics for the hull efficiency to be calculated. As before, the hull efficiency reduces with increasing levels of fouling, from 3.5 down to 2.3 at 5.4 knots and 3.05 down to 2.15 at 6.4 knots. Taken together, these results suggest that for most traditional long-keel hull forms, the very best hull efficiency for new, smooth hulls is unlikely to exceed 3.0, and that under more usual operating conditions the efficiency will drop to 2.5 or less.

Rig drag-angle

The three main factors which influence the efficiency of a sailing rig are: sail geometry—in particular aspect-ratio or slenderness in a vertical direction; sail section—the amount of camber or ‘belly’ in the sail; and windage—the resistance produced by wind passing over masts, rigging and the hull.

Theoretically, the optimum sail shape for windward ability is a very high aspect-ratio (that is, tall and narrow) tapering square sail, not the triangle of modern racing yachts, which are dominated by racing rules and available technology (Marchaj, 1996: 152). However, in practice the theoretical shape advantage of the square rig is severely compromised by the difficulty of making a square sail set without excessive ‘belly’ or

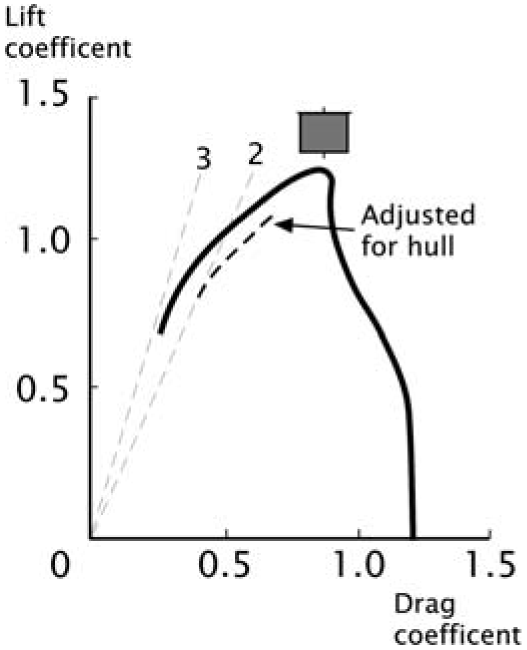

Figure 10. Polar plot of lift and drag for single squaresail, using data from tests on the *Bezai*-ship, with correction for the presence of the hull. (C. Palmer)

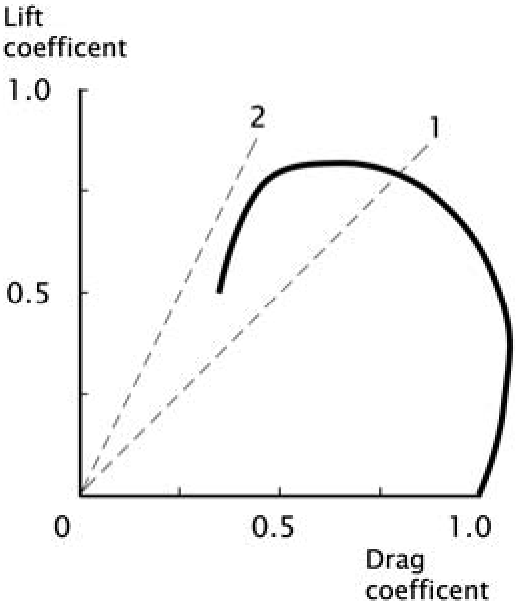

Figure 11. Polar plot of lift and drag for 3-masted barque rig, including the presence of the hull. (C. Palmer, re-drawn in simplified format from Schenzle, 1980: 175)

camber, and sustaining tension in the luff. An increase in camber means that the sail cannot be set so close to the wind, and at the same time it reduces the lift-to-drag ratio that can be achieved (Marchaj, 1996: 144).

Results from squaresail rigs are very few, and even for traditional fore-and-aft rigs there is only sparse data. Nomoto *et al.* (2003) present the most comprehensive and reliable data for a single square sail, and their results are shown in Fig. 10. They are presented as a polar plot of lift-coefficient against drag-coefficient, and consequently tangential lines through the axis provide a way of determining the lift-to-drag ratio and thus the rig efficiency. Figure 10 demonstrates that for the sail alone the maximum efficiency was 2.8, but this reduced to 2.0 when the windage of the hull was taken into account.

Schenzle (1980) reports the results of wind-tunnel tests conducted on a model of a 3-masted barque, which are re-drawn in simplified format in Fig. 11. The maximum lift:drag ratio is 1.75. A similar result was reported by Olsson (2005: 15) who conducted wind-tunnel tests on a model of the East Indiaman *Gotheborg*. Figure 12 shows the polar performance of the model (which included the effects of the hull). The maximum lift:drag ratio is 1.5.

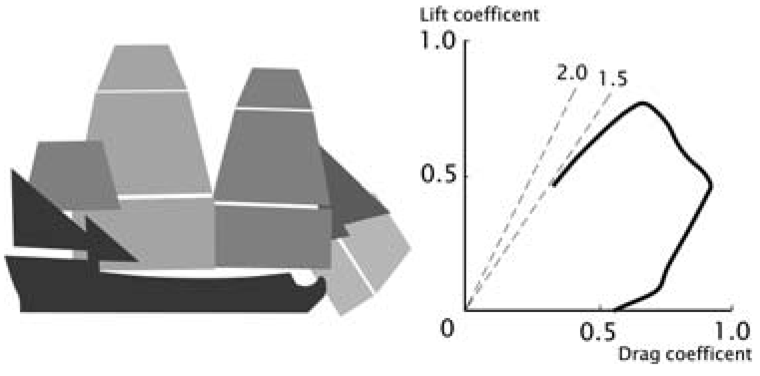

Figure 12. Polar plot of rig lift and drag for the Eastindiaman *Gotheborg*. (C. Palmer)

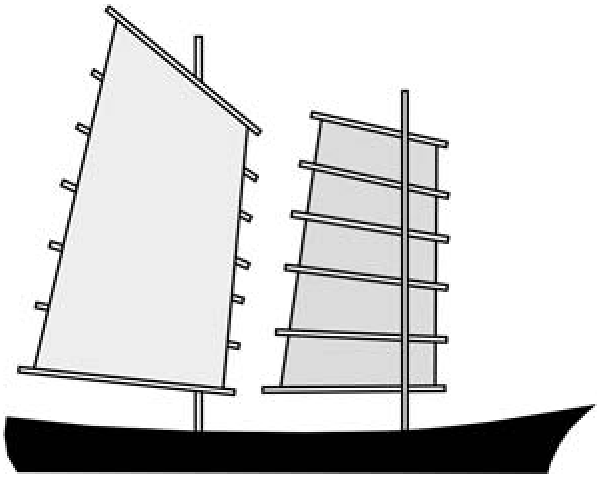

Figure 13. Schooner rigged Japanese *Shinshi-bo* fishing boat, fitted with two Chinese 'junk' sails. Sails are on opposite hands on the masts. (C. Palmer, re-drawn from Masuyama *et al.*, 2005)

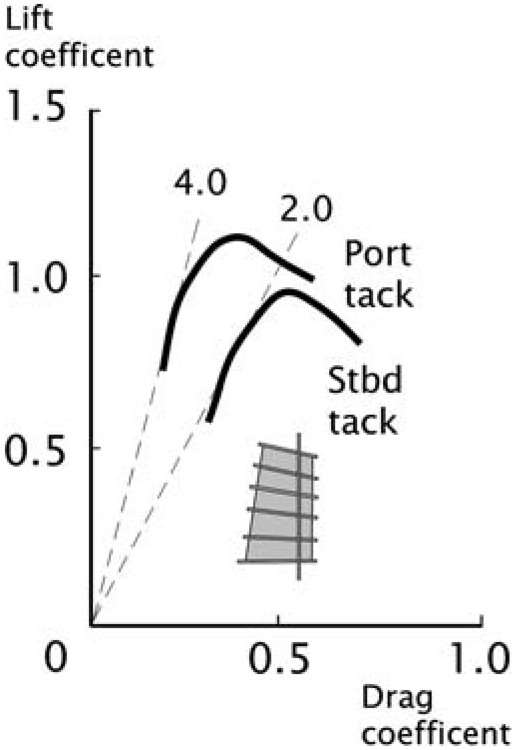

Figure 14. Lift and drag characteristics of a single *Shishi-bo* sail, showing marked differences from one tack to another due to flow interference from the mast. (C. Palmer, using data from Masuyama *et al.*, 2005)

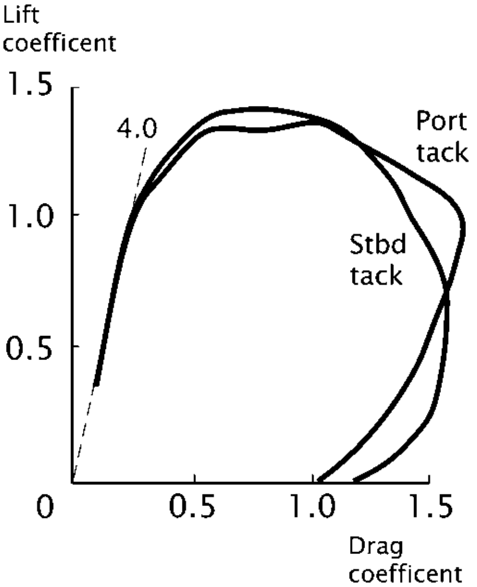

Figure 15. Polar plot of rig lift and drag for the *Shinshi-bo* schooner rig, including the effect of the hull. (C. Palmer, using data from Masuyama *et al.*, 2005)

In addition to the tests on a single square sail, Masuyama *et al.* (2005) also evaluated a fore-and-aft 'junk' rig. They conducted full-scale and model tests on a single sail, and wind-tunnel tests on a 2-masted fishing boat (Fig. 13). The results for the single sail (without modification for the presence of a hull) are shown in Fig. 14. An immediately striking feature is the substantial difference in performance from one tack to the other—which reflects the position of the mast relative to the sail. When it is on the windward side (port tack) the efficiency is much higher (4.0 as compared to 2.0), which shows the importance of the flow over the lee side of the sail. When the sail is fitted in a 2-masted configuration (with the sails on opposite sides of their respective masts) the difference between the two tacks is much less marked (Fig. 15). The combined rig achieves an efficiency of 4.2, which the authors attribute to the beneficial interaction between the two sails.

Williams and Liljenberg (1983) tested a 2-masted spritsail rig (Fig. 16) as part of a study of the potential for wind-assisted ship propulsion. As in the case of the junk rig, there were differences in performance from one tack to the other, due to the presence of the sprit, although surprisingly the effect was insignificant when close-hauled, and only became apparent on reaching courses. This rig achieved a maximum lift-to-drag ratio of about 2.5. Almost all these tests were conducted on small-scale wind-tunnel models. The one exception was the tests on the single junk rig, which was fitted to a small sailing yacht. However, in all cases modern materials were used, which means that the porosity of natural-fibre sails was not reproduced, and the stiffness of the sailcloth, rigging and spars was

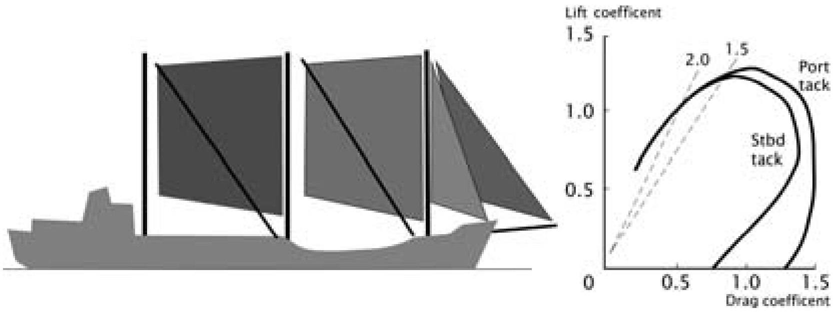

Figure 16. Polar plot of rig lift and drag for the proposed sprit rig to be fitted to provide sail assisted propulsion for the cargo ship *Stellan*. (C. Palmer)

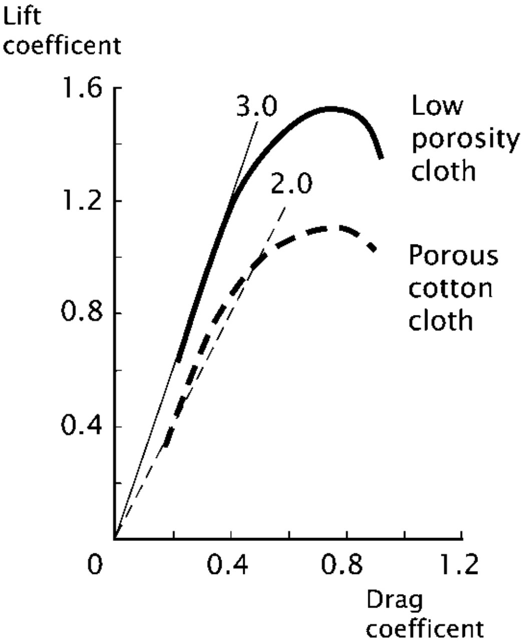

Figure 17. Lift and drag characteristics of a Bermudan sail to show effects of sail cloth porosity. The use of porous cloth results in a decrease in maximum lift and an increase in drag. (C. Palmer, re-drawn from Marchaj, 1996: 189)

greater than for traditional craft. All these practical factors will tend to reduce the efficiency of the rigs.

Porosity reduces the pressure difference that can be achieved and also appears to increase drag. Figure 17 shows the effect of porosity on a low aspect-ratio Bermudan sail. When the model was made from synthetic cloth, it achieved a maximum lift-coefficient of almost 1.6 and a lift:drag ratio of 3.0. When made from porous cotton cloth, the maximum lift-coefficient reduced to 1.1 and the lift:drag ratio to around 2.0. The drag had increased by approximately 50%. As sailcloth stretches under load, it increases the belly in the sail, which reduces lift:drag ratio when close-hauled. It will also tend to move the point of maximum camber towards the leach of the sail, with similarly negative effects. Stretch in the bolt-rope of a square sail will have a similar effect, as will deflection of the yard.

While it is true that the effects of cloth stretch and inadequate luff-tension can be partially offset by the use of bowlines to pull the luff forward against the forces of the wind in the belly of the sail, when traditional materials are used the effects of stretch in the sail material and rigging and the deflection of the spars are impossible to counteract in their entirety. The result is a negative spiral as wind strength increases—as the forces on the sail increase, so the sail camber increases, which is precisely the opposite change to that required to achieve good close-hauled performance. Unfortunately there are no experimental results to show the effect of the stiffness of the sailcloth, rigging and spars, but it is clear that results from stiff models will overstate the rig efficiency.

Full-scale trials

One technique for eliminating all these scale effects is to undertake full-scale trials. These are expensive, so are rare in the literature. Only two extensive series of experiments are known: Brandt and Hochkirch (1994) reported experimental results obtained from the full-scale sailing trials of the Hanse cog replica, the only example of technically-reliable trials on a traditional sailing vessel representative of an ancient type. Nomoto *et al.* (2003) conducted extensive trials on a replica of a more recent, but still traditional, square-rigged vessel, the Japanese *Bezai* Ho type.

Hanse cog

The Hanse cog trials used GPS to ascertain the ship's true position. These trials showed that

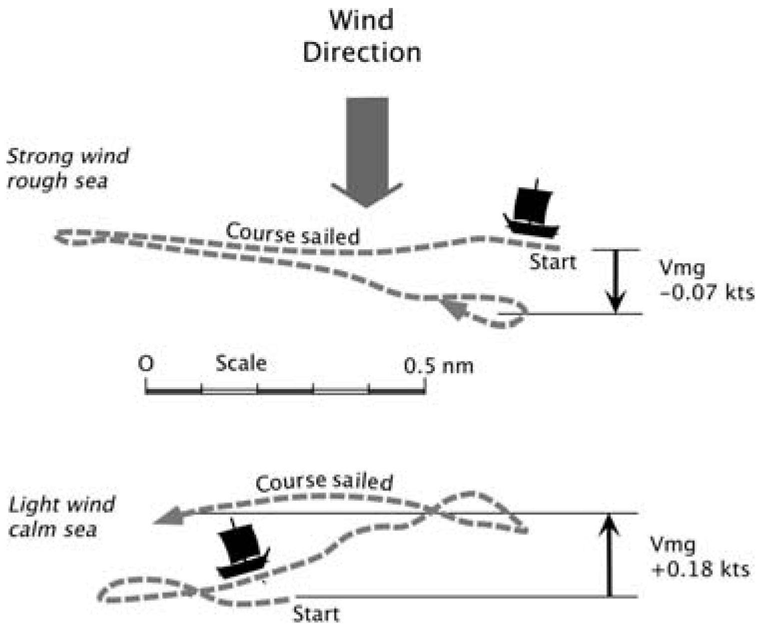

Figure 18. Windward sailing performance of Hanse cog replica in light and strong winds. (C. Palmer, using data presented in Brandt and Hochkirch (1995), re-oriented to a common wind-direction and drawn to a common scale)

while the vessel may have been able to maintain a course of up to 67° to the true wind for short periods in calm water, under 'real' conditions of sustained sailing and typical wave-conditions, the vessel could make no practical progress to windward. In addition to a polar plot derived from the results of short-term measurements, two plots were presented illustrating the longer-term (many minutes) performance in a light wind and calm sea, and strong wind plus associated sea conditions. These are reproduced here as Fig. 18. It is immediately apparent that the real performance of the Hanse cog is much worse than the figure of 67 to 75° to the true wind reported over short periods in ideal, calm-water conditions. It should also be noted that the Hanse cog replica was equipped with a new *Duradon* fabric sail which might well have provided a better performance than the sailcloth available to the owners of the original cogs (due to less porosity and stretch).

In a gentle breeze and calm sea, the Hanse cog made good a speed of 0.15 knots to windward when measured for a period of 52 minutes. The plot of the track (Fig. 18) shows that the cog was able to maintain a course that was up to 70° to the wind for short periods, but lost a lot of ground in the tacking process. This resulted in an overall performance that was significantly worse than might be expected from short-term measurements. In a stronger (but not exceptional) wind and the waves it produced, the Hanse cog made no progress at all, indeed she was driven downwind at a speed of 0.07 knots. The authors also reported that; 'In completely unloaded condition, sailing with one reef at ESE 5 to 6 [Beaufort wind strength] in the Strander Bay, the loss of closeness was higher—0.2 nm over distances of 1.8 and 2.4 nm. In such situations the leeway is quite considerable. It reaches 10 degrees to 15 degrees and can climb even higher when the sheet is hauled too close'. They go on to say 'Thus the Hanse cogs can hardly have beaten against the wind; they are suitable only for reaches' (Brandt and Hochkirch, 1994: 7). These results confirm that under most practical sea conditions the Hanse cog could not make progress to windward. In a storm this was certainly the case and in such conditions the cog would be quite incapable of escaping from a lee shore.

The performance of the cog has been discussed by Hutchinson (1994: 59–64) and in more recent papers (for example Weski, 1999; Greenhill, 2000). These authors have little that is positive to say about the potential windward sailing performance of the cog type, and this conclusion is used by Greenhill (2000: 17) to suggest that the cog was superseded by the hulc that 'could have handled better than the cog'. While there is indeed little reason to expect that the cog type was a good performer to windward, a conclusion supported by the trials of the reconstruction, there is in fact reason to believe that it may have been good by the standards of its time.

If we assess the cog hull form in the light of the tank-test results described earlier, it receives a mixed score. The sharply-V-shaped forward sections of many cogs might be expected to be a positive feature, as are the hard-bilged hull sections in the main body. The absence of all but a plank keel is a negative feature. The presence of a deadwood at the aft end is an additional positive feature. The use of a stern-hung rudder in some cogs would have an indirect positive benefit because it would produce less additional resistance than a side rudder and increase the effectiveness of the hull as a lift-generating body. This is because it is situated directly behind the main hull so will not produce its own wave-train and the associated resistance. A side-mounted rudder creates its own wave-train and also interference with the flow around the hull, which can result in substantial additional resistance. By contrast, the putative curved, almost 'banana'-shaped hulc hull (see for example Unger, 1994: 45; Greenhill, 2000: 17) scores badly by almost all these criteria, suggesting that it was potentially a backwards step in so far as close-hauled sailing ability was concerned.

Bezai Ho

Nomoto *et al.* (2003) conducted trials on a replica of a *Bezai*-ship—a Japanese sailing trader from the 18th to mid-19th century. This 30-m-long vessel had a single, 380 m^2 squaresail rig and a hard-chine hull with an unusually large and deep rudder. In calm water it was recorded sailing at up 75° to the true wind, but the hull was very foul (with 10 mm of marine growth) during the tests. The authors predict that with a clean hull the sailing angle might increase to just under 70° and the sailing speed increase by 50%. (Fig. 19). They concluded that 'it is fair to say that their [the *Bezai* ships'] best angle to windward is some 75° under a good sailing breeze with moderate sea-state and with the usual [clean] hull bottom condition' (Nomoto *et al.*, 2003). Under these conditions the vessel would have at least 10° of leeway and 5° of weather helm (Fig. 20). They also tracked the tacking manoeuvres and a typical result is shown in Fig. 21. Sailing at 5.0 knots close-hauled the *Bezai*-ship took about 15 minutes to re-cross its track, or measured another way, it lost 0.2 nautical miles to windward executing the wearing manoeuvre—a distance that would take about 10 minutes to make good at 15° to the wind.

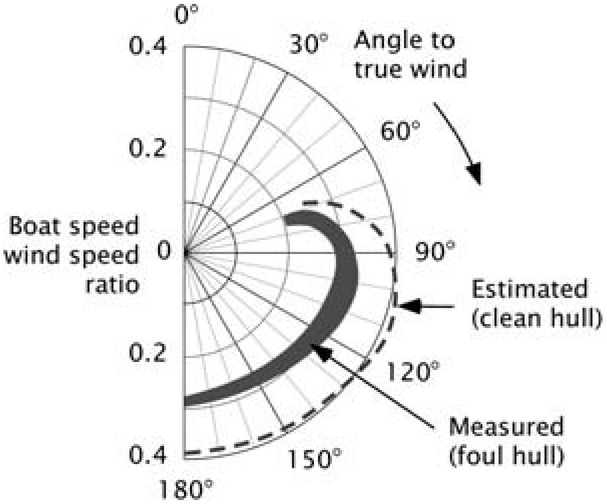

Figure 19. Polar performance plot of *Bezai*-ship as measured from short-term full-scale trials in calm water. (C. Palmer, re-drawn from Nomoto *et al.*, 2003).

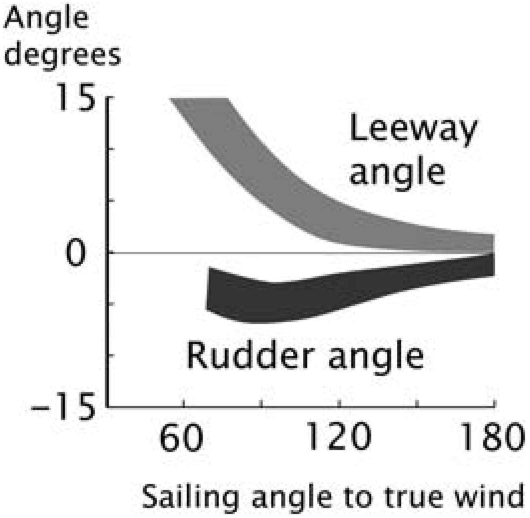

Figure 20. Variation of leeway and rudder angle with course relative to the true wind as measured from *Bezai*-ship trials. (C. Palmer)

Roskilde results

In 2004 the author attended a sailing course (An Introduction to Sailing Viking Ships) organised by the Vikingeskibsmuseet and held on Roskilde Fjord, an almost non-tidal inland waterway, ideal for sailing trials. I was able to track one small boat (an *Oselven* replica) and one larger one, *Roar Ege*, being sailed to windward. The *Oselven*

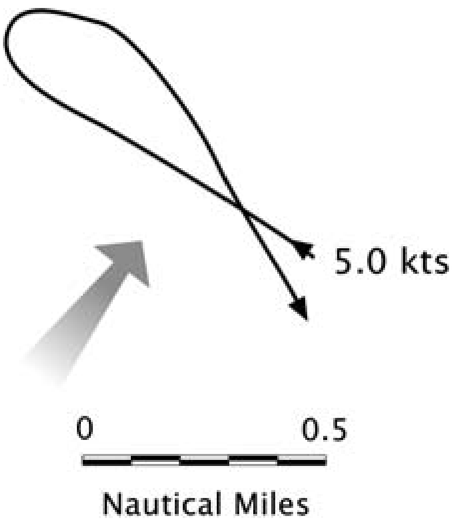

Figure 21. Track of *Bezai*-ship making a tacking manoeuvre by wearing ship. (C. Palmer, re-drawn from Nomoto *et al.*, 2003).

was sailed by an amateur crew, but I have considerable sailing experience so believe it was being sailed effectively. *Roar Ege* was helmed by one of the professional skippers from the Vikingeskibsmuseet. A GPS-based instrumentation system was used to record the tracks of these boats. The small *Oselven* was sailed in a force 4 breeze, close to the windward shore, so in very small waves. The tacking angles varied from 136° to 155°, giving an average of 146° and thus an angle to the true wind of 73° (Fig. 22). It is also clear from the traces just how much ground is lost by gybing through the wind (which is safer in a square-rigged boat) rather than tacking. Later in the day the wind increased to force 5 or more and the average tacking angle dropped to 151° (angle to the true wind of 75°).

Measurements on the larger *Roar Ege* where taken when working down Roskilde Fjord into winds touching force 7 at times (Fig. 23). For safety reasons the ship was gybed on most occasions and as the trace shows, when this manoeuvre was carried out in restricted water very little ground was made to windward. The average tacking angle for this Viking ship was 144°, or an angle to the true wind of 72°. No doubt if there had been waves to match the wind-speed, this angle would have been substantially greater.

Recently (2007) a team from Southampton University was able to measure the close-hauled sailing performance of a *kattumaram* sailing fishing boat of south India using similar GPS-based measurement equipment (Fig. 24). The boat was sailed by its experienced owners in a light wind and calm sea, in a location with very low tidal-stream rates. The track that they achieved when asked to sail against the wind is shown in Fig. 25. The result was that almost no progress was made, despite the *kattumaram* being fitted with lateen sails, which might be expected to be an efficient rig shape. While this was only a limited trial under just one set of conditions, it does suggest that impressions of ‘particularly good upwind performance’ of *kattumarams* reported by Pohl (2007: 393) should be treated with caution.

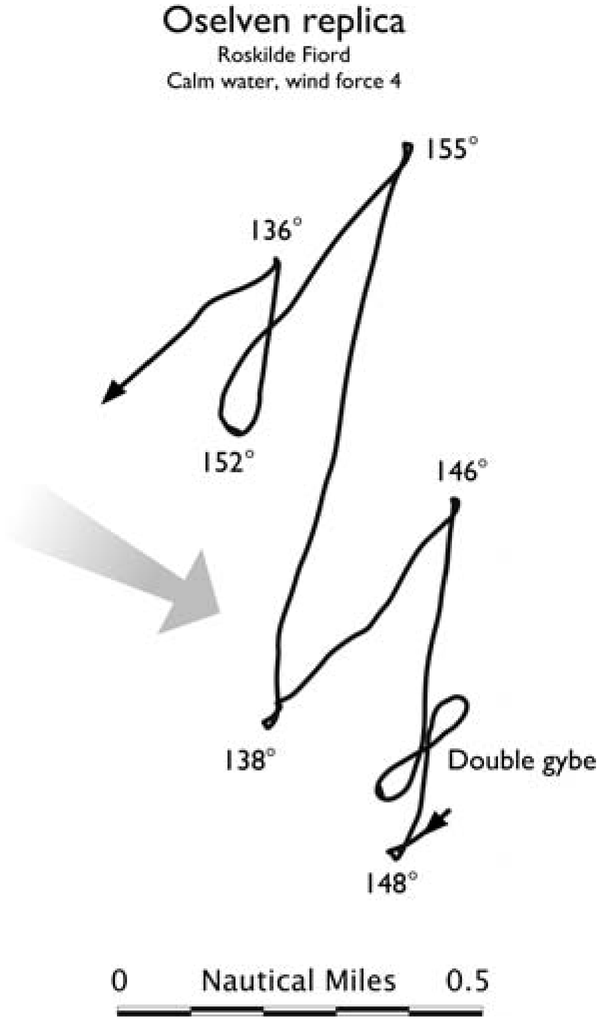

Figure 22. Track of Oselven replica working to windward in Roskilde fjord. Tacking angles shown for each tack. (C. Palmer)

Added resistance in waves

For seamen, the sailing performance of a vessel in calm water is of little interest. Such conditions

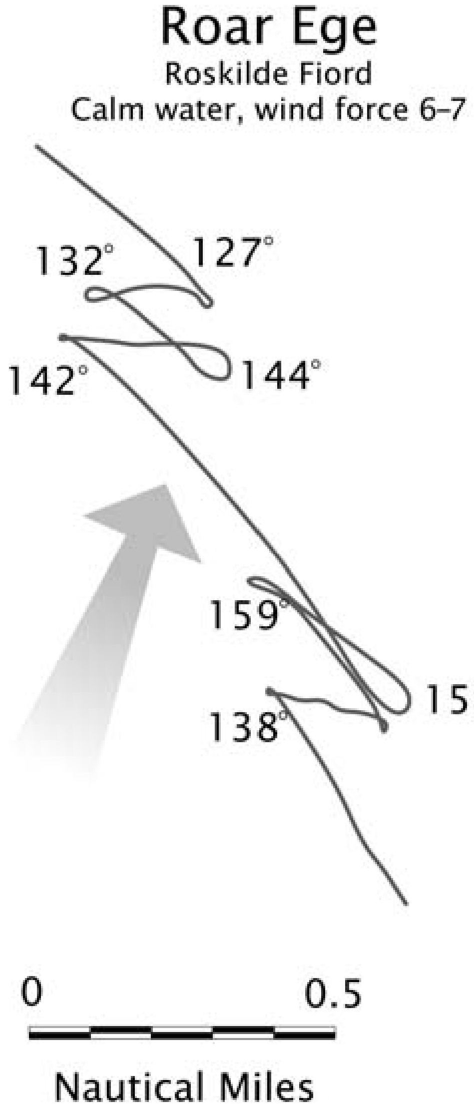

Figure 23. Track of Roar Ege replica working to windward in Roskilde Fjord. Strong winds (Beaufort 6–7 but calm water due to sheltered waters). Tacking angles shown for each tack. (C. Palmer)

are relatively rare at sea and certainly do not apply when a vessel is pinned to a lee shore by strong winds—a time when windward performance becomes a matter of life or death. What matters is performance in real conditions, which combine wind and waves. The resistance of a ship increases rapidly in head seas while motion reduces the effectiveness of the sails in producing drive and of the hull in resisting leeway. The overall effect is a further (and rapid) deterioration in windward capability.

The actual magnitude of the added resistance is a complex function of factors, which include the hull-shape and displacement, the ratio of the average wave length to the vessel length, the wave height, the longitudinal mass moment-of-inertia of the vessel and the heading to the waves (Gerritsma *et al.*, 1993: 239–44). It is quite possible for the added resistance in head sea to more than treble the total resistance at low forward speeds (see for example Fig. 26). However, the effect is very sensitive to heading angle to the waves, as shown by Fig. 27 (calculated from information in Gerritsma *et al.*, 1993: 242). This shows that the added resistance at 60 to 70° to the waves is only about 25% of that experienced when heading directly into the same seas. Thus it would not be unreasonable to expect that the resistance of a sailing vessel might increase by between 25% to 50% due to waves when close-hauled. This will have the effect of reducing the hull-efficiency by a somewhat lesser, but still significant, percentage. (The reduction is not *pro rata* because a proportion of the close-hauled resistance is due to induced drag, and this is unaffected by waves.) Analyses carried out for this paper show that at typical sailing points, the induced resistance is of similar magnitude to the unyawed resistance, which means that the effect on the hull-efficiency will be approximately half that of the added resistance.

Discussion

The foregoing has established a methodology for setting upper boundaries to the tacking-angle which can be achieved by sailing vessels, based upon the aerodynamic efficiency of the rig and the hydrodynamic efficiency of the hull. It has also presented data from model and full-scale tests that go some way to quantifying typical hull and rig efficiencies and showing how they are affected by real world phenomena such as marine fouling, sailcloth porosity and stretch, and added resistance in waves.

These results show that in practice the types of hull-shape used by traditional sailing vessels will achieve efficiencies within the range between 1.5 and 2.5 in calm water when suffering average levels of fouling. If added resistance in waves is taken into account these values will be lower, perhaps by as much as 25%. Severe fouling will decrease the efficiency by a further 10%, with the combined effects bringing the upper level down to 1.5 to 2.0. Multi-masted squaresail rigs fall in the range from 1.0 to 1.5 and a single square sail between 1.5 and 2.0, based upon the results of wind-tunnel tests. Since such tests use models

Figure 24. South Indian *kattumaram* showing double lateen rig. When sailing close-hauled, narrow vertical boards are pushed downwards between the logs and steering is provided by a paddle. (C. Palmer)

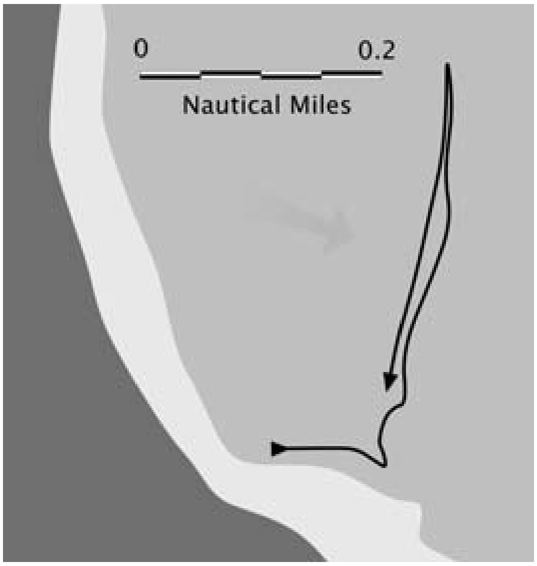

Figure 25. Track of south Indian *kattumaram* sailing close-hauled in a calm sea. The location was off the south-east coast of India, at Covelong, approximately 30 km south of Chennai. The measurements were taken on 4 October 2007. The sea was calm and the wind speed approximately 5 to 10 knots. (C. Palmer)

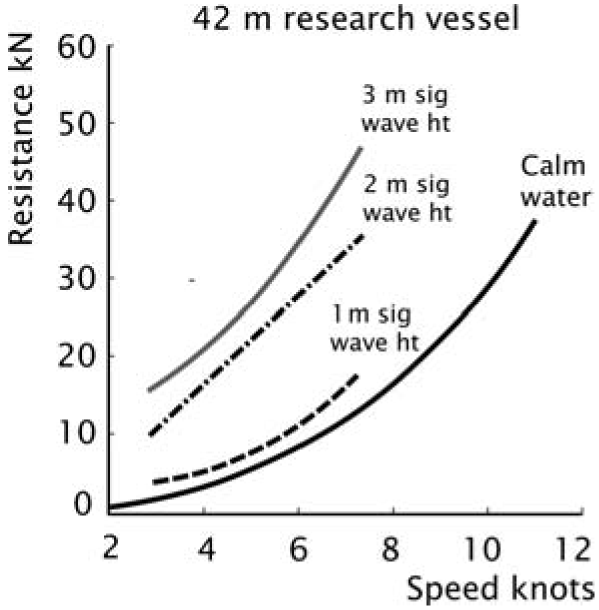

Figure 26. Results of resistance tests on a model of a modern 42-m research vessel, showing added resistance in head seas of varying height (and thus length). In 2-m waves (a moderate sea-state) the resistance at 6 knots is increased by a factor of three. (C. Palmer)

which are very stiff compared to the applied loading, and which use low-porosity synthetic sailcloth, the real efficiency will be less than this. It is very difficult to apply a reliable reduction ratio based on the available data, but one reported test on porosity showed a 50% increase in total drag, which has a directly proportional effect upon the efficiency.

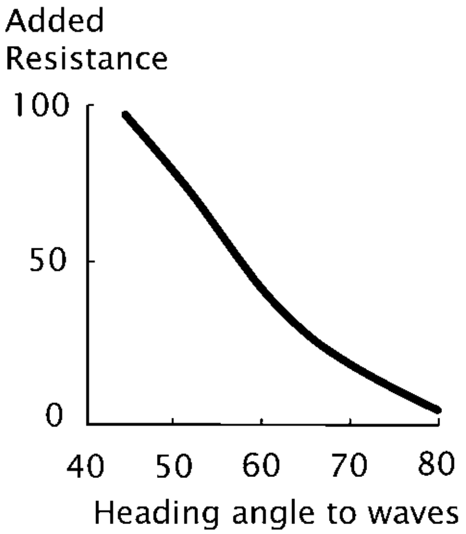

Figure 27. Added resistance in waves is sensitive to heading-angle relative to the waves. At 65° to the waves it is reduced to less than 25% of the head-sea value. (C. Palmer)

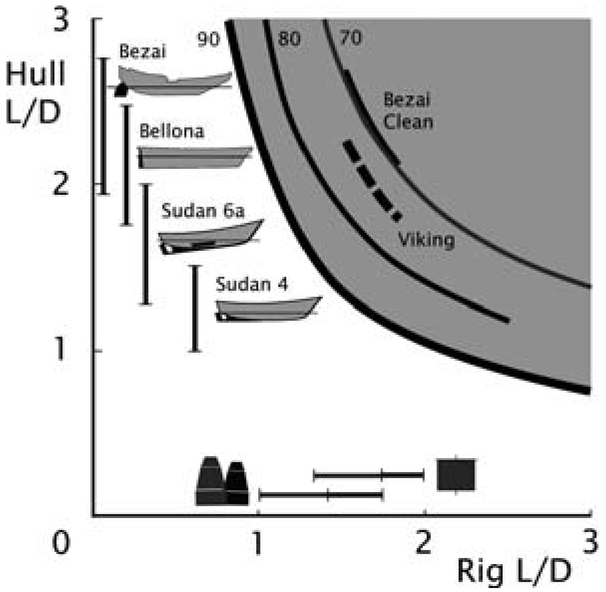

Figure 28. Summary plot using beta theorem contours to compare the performance of different rig and hull combinations, with efficiencies ranging from 'ideal' values predicted by model tests to possible actual values experienced by real ships in strong winds and rough seas. While the best of the ideal combinations appear to be capable of sailing closer than 70° to the wind, the more practical combinations fall into the 80 to 90° range. (C. Palmer)

Figure 28 uses the boundary-curve presentation discussed at the outset of this paper and overlays the above results as well as the actual performance recorded from sailing replicas. The *Bezai*-ship and Viking results imply hull efficiencies in the range from 2 to 2.8—which corresponds to the actual measured value for the *Bezai*-ship and thus provides support for the results and methodology. Four hulls are shown, with efficiency ranges corresponding to a normally rough hull in calm water as the upper limit and a very rough hull heading into waves as the lower limit. The most efficient is the *Bezai*-ship—probably because of its hard-chine hull form and large, deep rudder. Under the most adverse conditions its efficiency drops to 1.8. Next comes the warship *Bellona*, followed by two selected '*Sudan*' hulls—one that represents the most efficient configuration tested and another that is a simple hull with rudder and skeg configuration. Under the most severe conditions, this latter from only achieves an efficiency of 1.0. Two rigs are shown, a single square sail based on the *Bezai* result and a multi-masted rig based on the *Goteborg* and Schenzle data. The possible effects of porosity and stretch are illustrated by the faint lines extending to the left of each region derived from model tests.

What this figure shows is that the combination of the best *Bezai* hull-performance and the best single square sail is required to achieve a sailing angle of better than 70°. At the lowest end of the ranges for this combination, the angle drops to 80°. Similarly, the *Bellona*/multi-masted combination can perhaps achieve 75° under ideal conditions, but with a rough hull in waves and a strong wind (when the effect of sail-stretch will be most apparent) the angle increases to more than 90°. Even the best combinations of multi-masted rig and Sudan 4 hull-form cannot do better than 90°. Decenciere (2008: 282) reports the results of actual sailing trials conducted by the crew of the *Jean Bart*, an 80-gun French ship-of-the-line and notes that 'The lack of power in wooden sailing vessels in heavy weather is further shown up in her windward performance, for once the wind rose above force six she was able to point no closer than 110° to the true wind'.

Conclusions

The so-called beta theorem can be used as a basis for analysing the windward ability of sailing vessels, but with the *caveat* that it provides results which err on the optimistic (more close-winded) side. When this methodology is used with available data on the hull and rig efficiency of traditional (and ancient) vessels, it gives results that are broadly in line with those obtained from trials on full-scale replicas of traditional and ancient sailing vessels. Sailing trials on the Hanse cog, *Bezai*-ship and Viking-ship replicas show that these vessels can make modest progress to windward (as measured by their sailing angle to the true wind-direction) in moderate winds and calm water. During short test-runs of a few minutes in duration, angles of up to 70° to the wind can be achieved (which is twice the angle that can be sailed by the best modern yachts). When results from model tests in wind-tunnels and towing-tanks are used in the beta theorem analysis, similar results are predicted.

As wind-speed and the associated sea-state increases, progress to windward becomes more problematic. The Hanse cog replica was shown to be driven downwind by such conditions and the application of plausible efficiency reductions due to added resistance in waves, and the deformation of rigs and sails, predicts similar changes through beta theorem analysis. Since hull efficiency deteriorates significantly with hull-surface roughness, the combination of strong winds, rough seas and a foul hull almost guaranteed that working sailing vessels were unable to make progress to windward when it was most needed—when the ship needed to 'keep in deep water when the wind blows towards the shore' (Tilley, 1994: 309)

The *Bezai*-ship and Hanse cog are single squaresail vessels. When multiple square sails are set on multiple masts, as in many of the successors to the cog in northern Europe, the efficiency of the rig is further reduced due to interaction between the sails. This is apparent from a comparison of the polar curves of the multi-masted and single-masted rigs presented earlier. While the hulls of later sailing vessels appear to be more efficient than those of the cog, the result of the hull and rig combined suggests that a reliable windward sailing performance remained elusive.

Acknowledgements

This paper brings together many ideas I have developed since I was fortunate enough to obtain my introduction to sailing-boat design by working with Tony Marchaj and his yacht research colleagues at the University of Southampton. Much more recently I have greatly benefited from discussions with colleagues and MA students at the Centre for Maritime Archaeology at the same university. I am particularly grateful for the thoughtful comments that Dr Jon Adams and Julian Whitewright have made on a working draft.

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