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SQUARE-RIG SAILING

Intended Readership

Recreational and professional sailors with a basic knowledge of nautical terminology intending to serve as voyage crew on square-rig vessels.

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City and Guilds Examinations 536-1

Technical Communication Techniques

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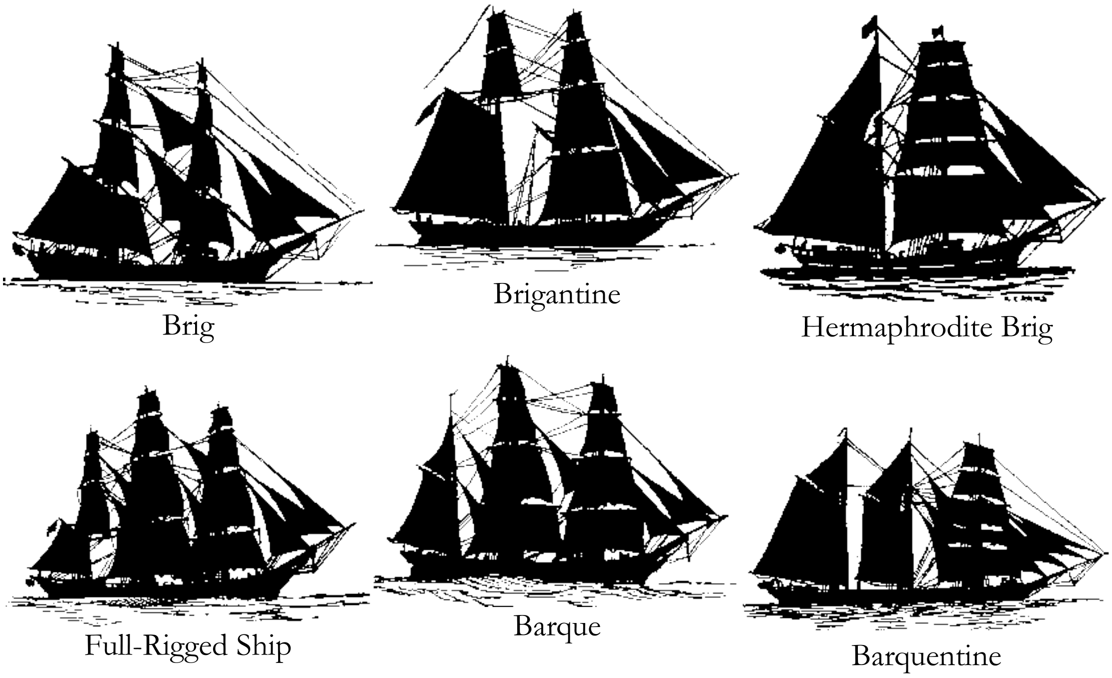
INTRODUCTION

1. Square-rig vessels (Fig. 1) are sailing ships where the driving force is generated primarily by square-sails set on yards attached at right-angles to the mast. Vessels of this type remained in use as commercial cargo vessels until the outbreak of the Second World War. After 1945 a few vessels remained in the grain and nitrate trade but by 1960 these had all been replaced by propeller driven vessels.

2. After the war, most of the remaining square-rig vessels still in service were those in use as sail-training vessels by the navies of countries including the USA, USSR, and Brazil. In 1956 five square-rig vessels took part in an informal race from from England to Portugal. What was intended to be a final tribute to the age of sail immediately became an annual event that is still held today.

3. Crews were initially restricted to naval cadets, but today people of all ages and from all walks of life take part in the race. The number of vessels has grown from five in 1956 to more than 100 today. In addition to the historic vessels, many newly built vessels now take part.

4. Many of these new vessels are maintained by non-profit organisations rather than governments. To reduce the burden on donations, they offer short voyages to paying members of the public who sign-on as crew but often have no previous sailing experience. This means that they must be given on-the-job training by members of the permanent crew.



Brig

Brigantine

Hermaphrodite Brig

Full-Rigged Ship

Barque

Barquentine

Figure 1. Square-Rig Vessels

5. Despite the increasing number of square-rig vessels at sea, there are limited opportunities for merchant sailors to gain experience with these vessels before joining as crew. It is not unheard of for captains to be appointed with no previous square-rig experience, although they would be expected to be experienced with powered vessels and fore-and-aft sailing vessels.

6. Many of the skills required on a square-rig vessel are identical to those required on powered and fore-and-aft sailing vessels. There are plenty of books and training courses that address these skills. But there does not appear to be a single document that addresses the unique aspects of square-rig sailing for a general reader or sailor with experience of powered or fore-and-aft vessels.

7. It is the aim of this report to describe the unique underlying principles behind square-rig sailing, to explain some of the main terminology involved, and to offer an insight into the resulting practical considerations for sailing square-rig vessels.

FLUID DYNAMICS

8. A sailing ship, the water it floats on, and the air that drives it are all composed of molecules. The sailing ship is a solid; it has densely spaced molecules with large intermolecular cohesive forces that allow it to maintain its shape, and not to be easily deformed. The water is a liquid; its molecules are spaced further apart, the intermolecular forces are smaller than for solids, and the molecules have more freedom of movement. Therefore it can be easily deformed, but not easily compressed. The air is a gas; it has an even greater molecular spacing and freedom of motion with negligible cohesive intermolecular forces. Therefore it can be easily deformed and easily compressed.

9. In fluid dynamics, the branch of fluid mechanics that is concerned with the behaviour of liquids and gases in motion, a fluid is defined as a substance that deforms continuously when acted on by a shearing stress of any magnitude. A shearing stress (force per unit area) is created whenever a tangential force acts on a surface, for example when air flows over a sail or when water flows over a hull, keel or rudder.

10. In 1738 the Italian scientist Daniel Bernoulli (1700-1782) published *Hydrodynamics* containing the now celebrated *Bernoulli equation* which can be expressed as $p + \frac{1}{2}\rho V^2 + \gamma z =$ **constant along streamline**. This is a mathematical statement of the principle that as the fluid particle moves, both gravity and pressure forces do work on the particle (the work done by a force is equal to the product of the distance the particle travels times the component of force in the direction of travel). As a consequence, any fluid flowing through a constriction will speed up and pressure will drop (Fig. 2). Once clear of this restriction the fluid will slow down and pressure will rise. Aerofoils, such as aircraft wings and sails, and hydrofoils such as keels and rudders, use this effect to produce lift.

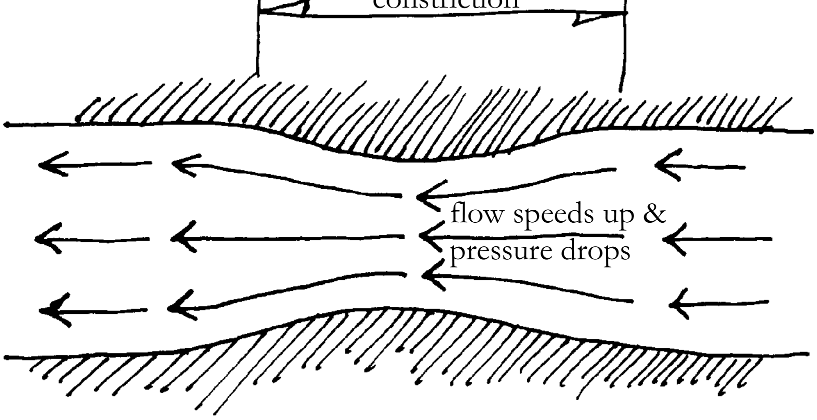


Figure 2. The Bernoulli Effect

11. A useful concept for examining the effect of a foil is the parallelogram of forces and movement (Fig. 3). The parallelogram can be thought of as a rectangle for our purposes. It consists of three forces, acting in the directions DA, DB and DC, with magnitudes equal to their length. DB can be resolved into the two forces DA and DC at right angles to each other. DA and DC can be combined into the 'resultant' force DB.

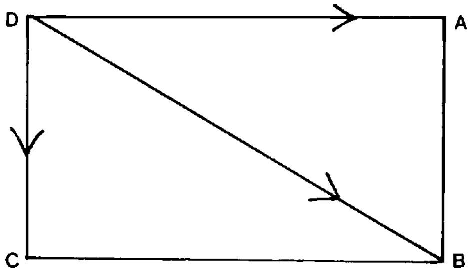


Figure 3. The Parallelogram of Forces and Movement

12. The lift generated by a sail (DB) can be determined by combining the two component forces of heeling force (DA) and drive (DC). This is shown in Fig. 4 where the line 'L' represents lift acting at right-angles (90 degrees) from the sail surface, the line 'H' represents heeling force (pushing the ship over) acting at right-angles to the centreline (CL) of the ship, and line 'D' acting parallel to the centreline represents drive or motive force (propelling the ship forward). From this simple graphic representation it is clear that more than two thirds of the energy extracted from the wind by the sail is expended in heeling the vessel and driving it downwind (leeway). Only a small part of the wind's force acts to drive the ship forwards.

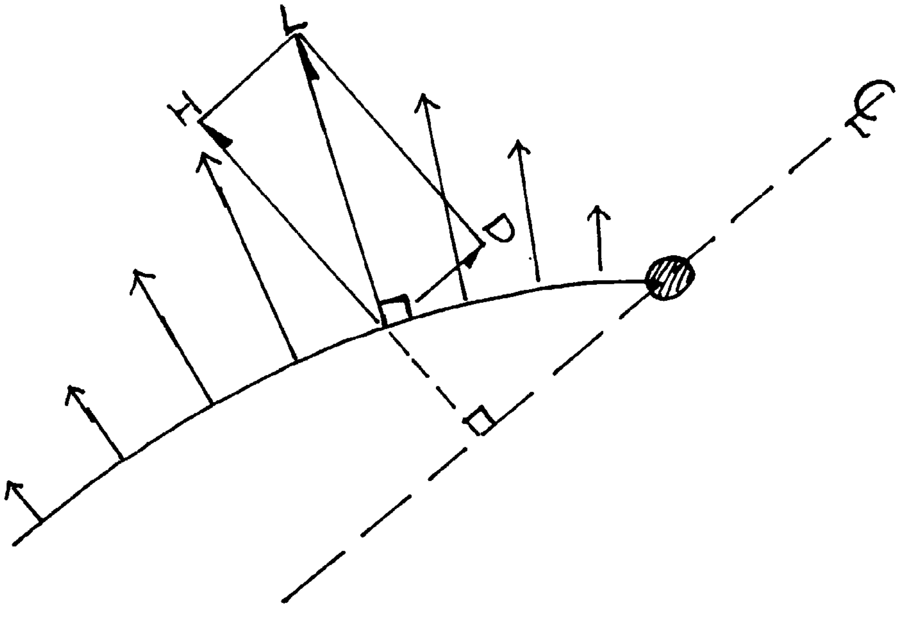


Figure 4. The Parallelogram of Forces and Movement as Applied to a Sail

13. Bernoulli's Theorem demonstrates that air flow on the leeward, forward aspect of the sail, generates a negative pressure, which draws the canvas ahead, 'sucking' the ship forward, as it were.

14. The flow of a fluid, such air over a sail or water over a keel, can be described as *laminar* (steady), or *turbulent* (unsteady). In laminar flow the imaginary 'layers' of a fluid move parallel and in unison. Turbulence results from some obstruction in a laminar flow, that causes chaotic eddies and back currents in the fluid downstream from the obstruction. Even a highly streamlined body will only experience laminar flow over the 'entry' or first part (Fig. 5). As a fluid is thrust aside pressure waves build up which produce turbulence (Fig. 6). It must be understood that the definition of steady or unsteady flow pertains to the behaviour of a fluid property as observed at a fixed point in space. For laminar flow the values of all fluid properties (velocity, temperature, density, etc.) at any fixed point are independent of time.

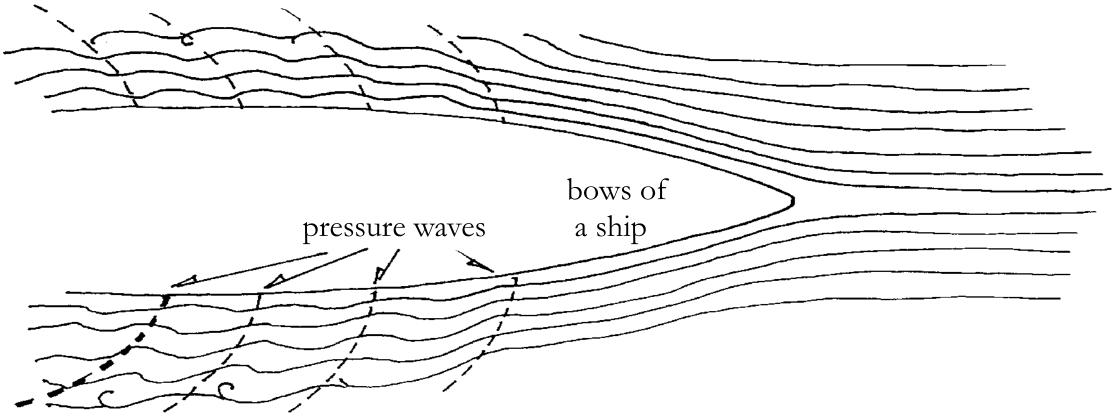


Figure 5. Laminar Flow Decay

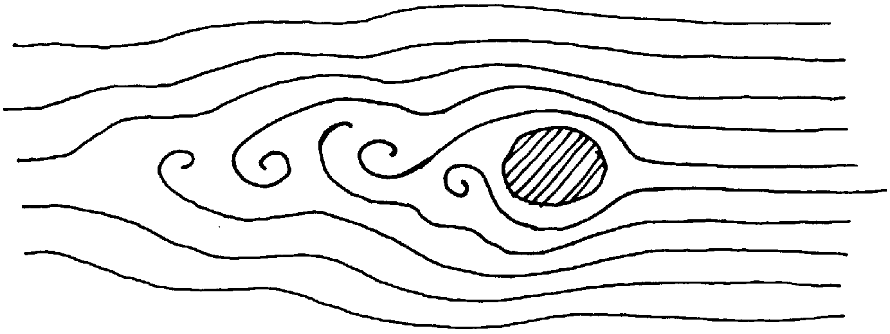


Figure 6. Laminar and Turbulent Flows

SAIL THEORY

15. Square-rig ships use three types of sails; square-sails set from a yards that cross the centreline, 'fore-and-aft' sails set on a boom, and 'fore-and-aft' sails set from stays (stays'ls). Fore-and-aft sails can be set on either side of the centreline. Figure 7.1 shows the airflow pattern over a typical fore-and-aft sail when sailing upwind. The area of maximum lift is produced by laminar flow over the first part of the sail. Further downstream the lift diminishes as the turbulence increases.

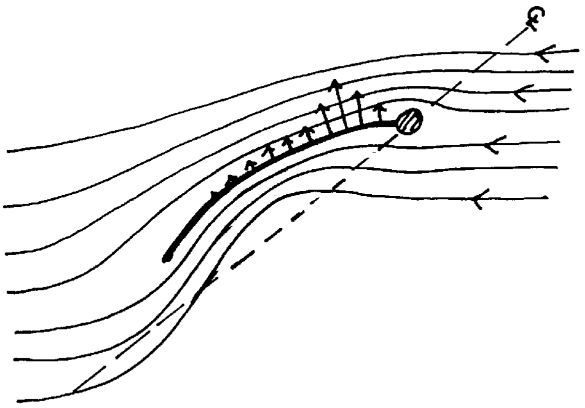


Figure 7.1. Airflow Over A Correctly Sheeted Sail Produces Lift

16. The position of the fore-and-aft sail is determined by the position of the boom it is attached to or, in the case of a stay'sl, how hard the sheet (a line attached to lower corner of the free part of the sail) is hauled in. Using the same example but with the sail 'over-sheeted' as in Figure 7.2, the airflow is so turbulent as to produce little or no lift but an opposite force called 'drag'. Delamination (detached airflow) produces massive turbulence, which persists downstream for a considerable distance. This will produce great heeling force on the rig and consequent leeway. Lift and drag are always acting together. Even when a sail is correctly trimmed the mast, spars and rigging are creating wind resistance (drag), which diminishes the lift acting to drive the ship.

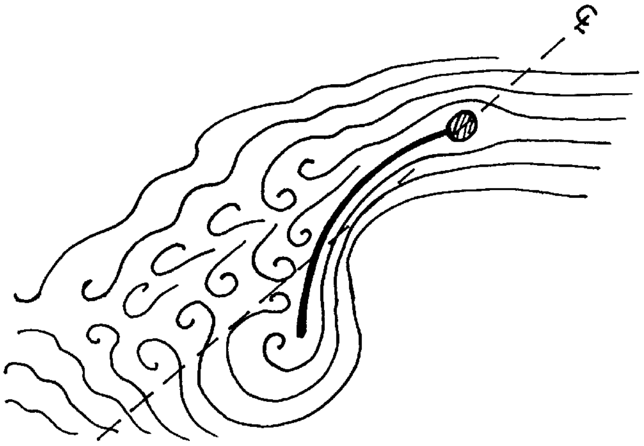


Figure 7.2. Detached Flow Over A Sheeted Sail Produces Drag

17.However, drag only acts negatively when sailing into the wind. Its effects become progressively less as a ship sails off the wind, being negligible when the wind is at right-angles to the centreline, and actually acting positively as the wind comes from further aft. When sailing downwind a ship is largely propelled by its wind resistance (drag).

18.Ships which do not have square sails can point high into the wind, using lift to drive them. But a square-rig ship cannot usually point higher than about 70 degrees off the wind due to the greater wind resistance produced by setting the square-sails. It is not possible to point higher by only using the fore-and-aft sails as they do not produce enough lift by themselves to drive the ship forward. However, this disadvantage when sailing upwind becomes an advantage sailing downwind where the square-sails, which are equally balanced across the centreline, will generally perform better than a fore-and-aft vessel with its sails all set to one side.

19.Aspect ratio is another important factor in the function of aerofoils such as the sails and hydrofoils such as the keel. As shown previously, a laminar flow quickly decays into chaotic turbulence regardless how streamlined or smooth a foil may be. Therefore, a hull with a long but shallow keel will have more resistance than one with a short but deep keel. Modem racing yachts have extremely narrow but deep keels in an attempt to utilize the laminar flows and eliminate turbulence. Similarly, a narrow but tall sail will create more lift than a shallow but wide sail.

20.A sail assumes a curved configuration when properly set, but it would be most efficient if it were flat. The pressure of the wind is most effective when it strikes the sail at right angles. To the extent that it hits the canvas obliquely, its effect is by so much diminished. If we compare an imaginary flat sail AB with one shaped like a half-cylinder ADB, one would expect their effectiveness to be about the same, although the former is two-thirds the size of the latter. Put another way, if the sail ADB were flattened out as CDE, it would be one and a half times as effective as AB (Fig. 8).

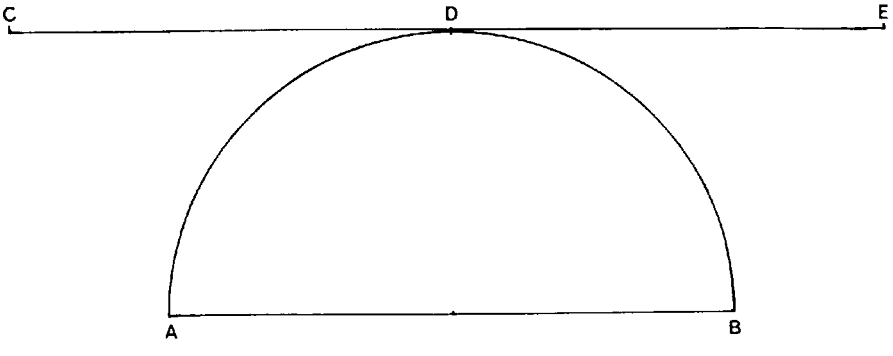
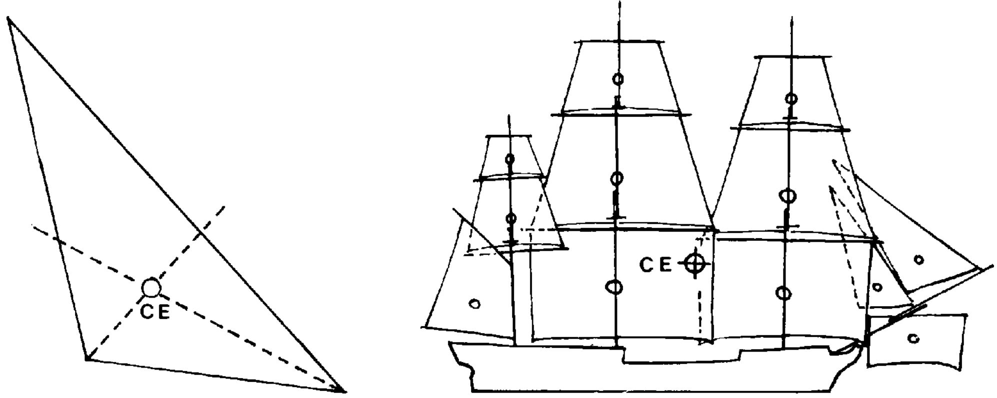


Figure 8. Sail as a Curved Surface

SAILING CHARACTERISTICS

21.The sailing characteristics of a square-rig vessel are determined by the *centre of effort* (CE) of wind on the sail and the *centre of lateral resistance* (CLR). Particles of air striking the sail act at every point of its surface. But it is simpler to consider the force as concentrated at a point in the geometric centre of the sail, the CE. Using simple geometric constructions, the theoretical CE of the total sail plan can also be pinpointed (Fig. 9).



The CE of a triangular sail is established by bisecting the angles. The CE of a ship's sail plan is established from the collective CEs of all the individual sails.

Figure 9. Centre of Effort

22.When the submerged part of the hull moves through the water, its progress is resisted by the particles of water which it forces aside. A dish shaped under-body, like a coracle, presents no resistance to cross-flow and can therefore be moved in any direction with equal ease. A deep keeled or long hulled/keeled ship has a high lateral resistance and will move easily only forwards or backwards.

23.As previously noted the lift generated by a sail is approximately two-thirds sideways force and one-third forward drive. The lateral resistance of the hull largely opposes any tendency for it to be driven sideways beyond modest leeway and therefore this energy is absorbed in heeling the vessel. The forward drive is only opposed by the actual water resistance of the hull cross-section, usually modest and therefore the hull moves forward. The resistance may be considered to be concentrated at a theoretical point in the middle of the submerged part of the hull, the CLR.

24.This water resistance of a hull to forward motion is termed hull co-efficiency (Ce) or 'block co-efficient' (BCe). Stated simply, a block of wood with just its corners rounded off to resemble a barge has a high BCe. The same block of wood pared down to resemble a racing yacht has lost a huge amount of its original volume and such a hull therefore has a low BCe.

25.The hull, keel and rudder of any vessel with a medium to low BCe will function to a greater or lesser effect as a hydrofoil, experiencing lift and drag. This is because when sailing upwind a ship makes leeway – it is usually pointed higher than its true direction. In effect the keel is presented at a slight angle to the fluid flow and this invokes the same fluid dynamics as a fore-and-aft sail. The 'entry' of the hull, keel and rudder will also experience laminar flow, which deteriorates into turbulence further aft. The rudder, when attached to a stern-post at the end of a keel, acts much like the after side of a sail. When correctly adjusted it helps generate lift to windward. Angled too much it 'stalls', and simply generates drag.

26.Figure 10 demonstrates the relationship between CE and CLR. The force of the wind acting through the CE can be though of as trying to push the hull bodily to leeward, and also to heel the vessel over. In the first case the lateral movement is resisted by an equal and opposite force acting through the CLR. At least this is true in an idealised situation where there is no leeway.

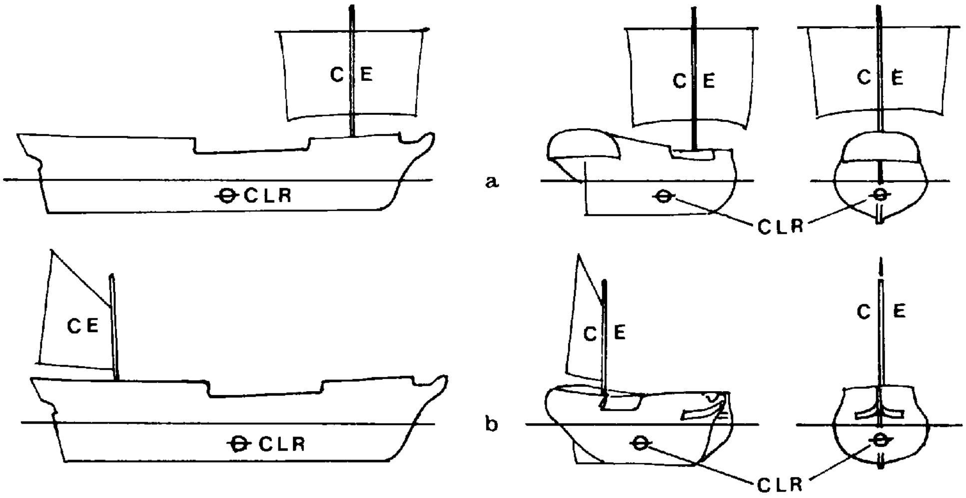


Figure 10. Relationship of the CE and CLR

27.If the CE and CLR are in the same vertical line, as seen from the side, the ship could be forced by the wind directly to leeward but keeping the wind at all times at right-angles to the hull.

28.If the CE moves ahead of the CLR (Fig. 10a), the bow will be pushed away from the wind. If the CE moves aft of the CLR, the bow will come up into the wind (Fig. 10b). In both cases, if unopposed, the ship will eventually come ahead or stern to wind, with the forces acting through the CE and CLR once more in line.

29.As can be seen in Figure 10, the CE of the ship is changed according to which sails are set. However, the designed centre of effort with all sails set must be ahead of the hull's CLR by about 7% of the waterline length. This difference is called 'lead'. The lead diminishes as speed increases because CLR effectively moves forward as a vessel sails, which explains why a sailing vessel becomes 'twitchy' as it approaches its 'hull speed'. On a square-rig ship it is therefore common practice to take in sail from aft as wind and speed increases, thereby moving the CE forward.

30. Hull speed is the theoretical maximum that a displacement hull can travel through the water. This is determined by resistance and wave-making. The faster a hull moves, the bigger the bow and stern wave it generates. This wave-making absorbs prodigious amounts of energy and there comes a point where the hull will simply not go faster regardless of how much power from sail or engine is applied. Hull speed can be calculated roughly as the square root of the waterline length x 1.25 for the medium BCe hull.

APPARENT WIND

31.Sail trim is further complicated by 'true wind' direction versus 'apparent wind' when sailing upwind. As the speed of the ship is added to the speed of the wind the bearing of the wind appears to draw forward (Fig. 11.1) and sails should be adjusted accordingly. The best guide is a streamer or pennant placed at the top of a mast which will always show 'apparent wind'.

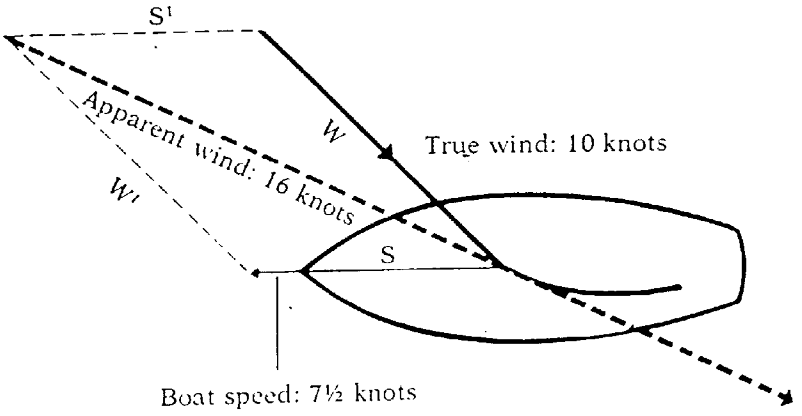


Figure 11.1. Apparent Wind Direction and Velocity

32.When the true wind is at right-angles to the hull, the combination of boat speed and true wind velocity produces an apparent wind that has a greater velocity than the true wind (Fig 11.2).

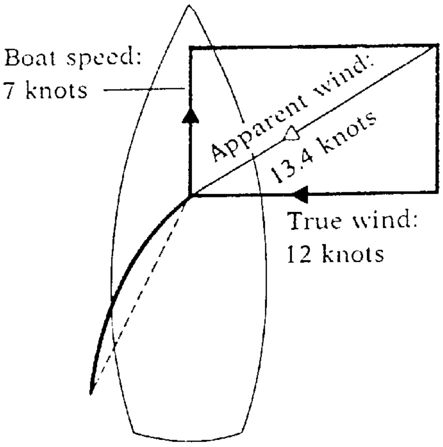


Figure 11.2. Apparent Wind Direction with True Wind at Right-Angles

33.As the true wind moves aft, the wind the boat 'feels' is decreased by the speed of the boat. Thus, the diagonal representing the apparent wind velocity is much smaller (Fig 11.3). This decrease in apparent wind is one reason why, under normal conditions, the boat speed of a fore-and-aft rigged vessel decreases downwind unless a great deal more sail is added.

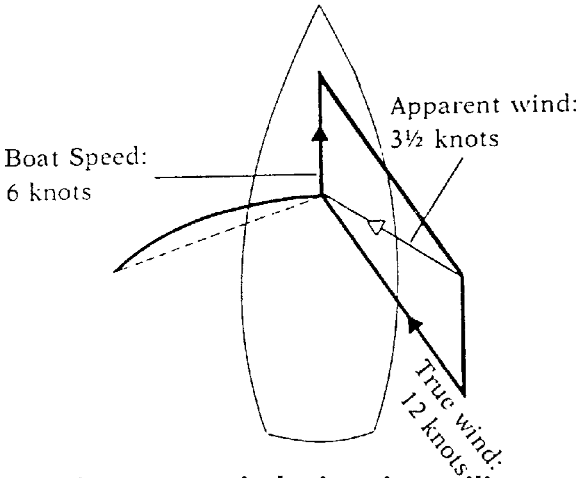


Figure 11.3. Apparent Wind Direction sailing Downwind

34.Square rigged vessels usually cannot brace their yards to more than about 30 degrees from the centreline of the vessel. At this stage the ship's yards will be hard against its backstays and the ship is said to be 'hard on the wind'. The leading edge of the square sail can be brought closer to the centreline with 'bowlines' (if rigged) which help eliminate 'luffing' or fluttering. Square sails in this situation act exactly like fore-and-aft sails but are less efficient due to insufficient luff tension, the increased windage of their gear, and turbulence from the masts and gear.

CONCLUSION

35. Having considered the theory behind square-rig ships it should be possible to draw some practical conclusions which will assist in sailing such a vessel.

36. It is immediately apparent when steering a sailing-ship for the first time that some rudder correction is needed in order to steer the desired course. This correction is called ‘weather helm’ because in the days of tiller steering (before the ship’s wheel was invented) the tiller was ‘hauled up to weather’. As shown in Figure 4, lift is generated in a narrow band from the leading edge (luff) of the sail to about one fifth of the way back. The forward drive is offset to leeward of the centreline. This acts in the same way as a tow-rope attached to a hull on one side rather than to its centreline. Left to its own devices under tow the hull will sheer off to one side. This is why a sailing ship tends to round up into the wind.

37. Weather helm becomes more pronounced with greater angles of heel as this increases the lever or offset from the centreline of the drive (force ‘D’) and immerses more of the lee bow which also pushes the head to windward. For this reason a sailing vessel will often sail faster and more comfortably if sheets are adjusted to reduce weather helm, centralize the rudder and therefore reduce drag. On a multi-masted vessel this is accomplished by over-sheeting the jibs slightly which pushes the bows away from the wind, and easing the spanker sheets slightly.

38. Whatever the hull form or sail plan, all sailing craft represent a compromise, excelling in certain points of sail and conditions and faring badly in others. Predominantly square-rigged vessels do well with the wind at 90 to 120 degrees (3 o'clock to 4 o'clock position) from the centreline, slightly less well with the wind at more than 120 degrees from the centreline and poorly with the wind at less than 90 degrees from the centreline. Predominantly fore-and-aft vessels can point higher and sail faster into the wind but do less well with the wind aft. The huge variety of rigs and hull forms that have developed through maritime history are all attempts to arrive at the best possible compromise for a particular function. It is therefore important to sail a vessel to its best advantage.

39. Performance is determined by sail shape. A baggy sail with a deep roach (cut with plenty of belly) can be advantageous when the wind comes from aft, because it is generating power through its wind resistance, but it is virtually useless when attempting to sail upwind where a much flatter sail is required. Sails can be flattened to some degree by increasing tension along each edge, and in the case of fore-and-aft sails by sheeting hard (not over-sheeting).

40. In a multi-masted square-rig vessel a situation called ‘back-winding’ can arise where the flow of air over one sail starts to adversely affect a nearby sail. This problem can sometimes be addressed by adjusting the sheets to open up a ‘slot’ between adjacent sails and allow a cleaner airflow.

41. When sailing downwind, ‘blanketing’ may be experienced, especially when the wind is directly aft. This is where a sail prevents wind reaching a sail in front of it. It is invariably faster for a square rigger to ‘tack’ down wind than try to sail a dead run for two reasons. First, sailing at an angle to the wind allows the maximum sail area to be presented to the wind and second, with steady wind pressure from one side rolling is reduced which, with the wind directly aft can become excessive.

GLOSSARY

AFT, at or towards the stern or after-part of a ship.
AFTER-SIDE, the side that is farthest aft.
BACKSTAY, a part of the standing rigging of a sailing vessel to support the strain on all upper masts.
BLOCK COEFFICIENT, the water resistance of a hull to forward motion.
BOOM, a spar used to extend the bottom of a sail.
BOW, the foremost end of a ship, the opposite of the stern.
BRACE, to, the operation of swinging round, by means of ropes, the yards of a square-rigged ship to present a more efficient sail surface to the direction of the wind.
DELAMINATION, separation into constituent layers.
FORE, at or towards the bows or forward part of a ship.
FORE-AND-AFT RIG, the arrangement of sails in a sailing vessel so that the luffs of the sails abut the masts or are attached to stays, the sails, except in certain cases, being extended by a boom.
HEEL, to, in relation to a ship, to lean over on one side.
HULL, the main body of a ship, excluding its masts, rigging and internal fittings.
KEEL, the lowest part of the hull of a ship.
LAMINAR FLOW, a steady pattern of motion of particles.
LEE, the side of a ship or sail which does not have the wind blowing on it.
LEEWARD, a term denoting direction at sea in relation to the wind, i.e. down wind as opposed to windward, up wind.
LEEWAY, the amount that a ship is blown down wind of the course that it is attempting to follow.
LUFF, the leading edge of a fore-and-aft sail.
MAST, a vertical spar set in a ship, primarily used for carrying sails.
RIGGING, the term which embraces all ropes, wires, or chains used in ships to support the masts and yards for hoisting, lowering or trimming sails to the wind.
ROACH, the curve in the side or foot of a sail.
SHEET, a single line used for trimming sail to the wind.
SPANKER, a sail hoisted on the aft-most mast to take advantage of a following wind.
SPAR, a general term for any support used in the rigging of a ship.
SQUARE-RIG, the arrangement of sails in a vessel where the main driving sails are laced to yards which lie square to the mast.
STAY, a part of the rigging of a sailing vessel which supports a mast along the centreline of the vessel.
STERN, the rear end of a vessel, the opposite of the bow.
TACK, to sail a zig-zag course so as to never sail directly into or directly away from the wind.
TURBULENT FLOW, an unsteady pattern of motion of particles.
WEATHER HELM, rudder correction required to steer the desired course.
WINDWARD, a term denoting direction at sea in relation to the wind, i.e. up wind as opposed to leeward, down wind.
YARD, a large wooden or metal spar crossing the masts of a ship horizontally or diagonally, from which a sail is set.

BIBLIOGRAPHY

Harland, John
Seamanship In The Age Of Sail
Conway Maritime Press, London 2000
ISBN 0-85177-179-3

Munson, Bruce R. et. al.
Fundamentals Of Fluid Mechanics
John Wiley & Sons, New York 1990
ISBN 0-471-85526-X

Kemp, Peter (ed.)
The Oxford Companion To Ships And The Sea
Oxford University Press, Oxford 1988
ISBN 0-19-282084-2

SQUARE-RIG SAILING

SUMMARY

This is a concise description of the principles involved in sailing a square-rigged ship. It deals only with the aspects of sailing that are relevant to square-rig sailing.

The background knowledge necessary to appreciate the concepts discussed in this report would be within the capabilities of anyone with GCSE Science. Some familiarity with nautical terminology or experience with other types of vessels would be useful, but is not essential.