Module 3

Small craft structure, strength, stability and corrosion control strategies

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Contents

Module 3: Small Craft Structure Strength, stability… etc.

1. Introduction

This module covers important aspects of small vessels, but with an emphasis on sailing yachts. Considerably descriptive effort centers on vessel stability, structural detail of hull appendages, flow around sails, interference caused by masts, streamlining and, finally, corrosion prevention; the latter topic is elaborated further in slide section 3. All these themes are huge areas of study and consequently, not every aspect can be given the full attention they merit, but the expectation is that the most important underlying principles and details are discussed to a good level and will further the understanding of those not familiar with the technical details. The ideas covered are further complemented in the slide sections and in some cases, these provide more specific information.

The module opens with the definitions for yacht/boat terminology and this is expanded further in the first slide section. An appreciation of yacht/boat terminology is considered an important foundation for appreciating yacht/boat stability, both statical – response in still water and dynamical – response in waves. Stability is a prerequisite to understanding the movements that occur in yachts and other small vessels too. Further, knowledge of the response of boats and in particular the forces that impact movement is critical to appreciating how yacht/boat architecture and designs have evolved.

2. Hull Geometry

The hull of a yacht is a complex three-dimensional shape, which cannot be defined by any simple mathematical expression. Gross features of the hull can be described by dimensional quantities such as length, beam and draft, or non-dimensional ones like prismatic coefficient or slenderness (length/displacement) ratio. For an accurate definition of the hull the traditional lines drawing is still in use, although most yacht designers now take advantage of the rapid developments in computer aided design (CAD) technology.

2.1 Geometric Parameters[1]

In is useful to start with a number of quantities that define the form of a yacht hull and indeed any sea going vessels, these are frequently referred to in yachting literature and relate to basic dimensional properties.

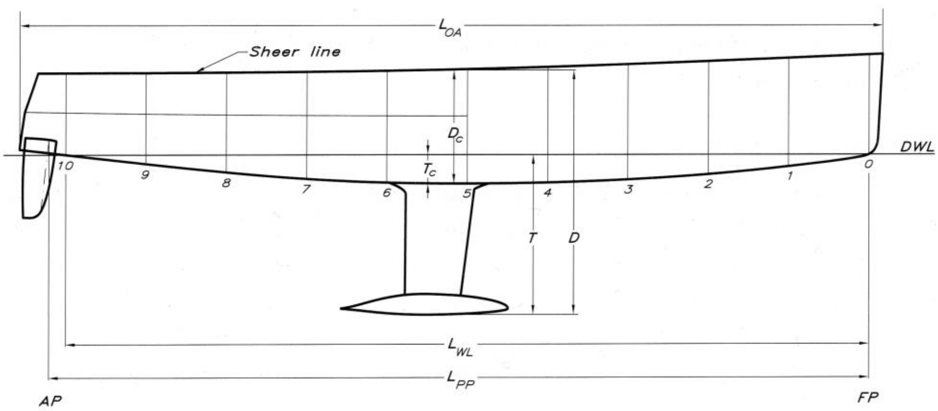


Figure 1. Definitions of Important Yacht (Boat) Dimensions

- Length overall (L_{OA})

The maximum length of the hull from the forwardmost point on the stem to the extreme after end, see Figure 1. According to common practice, spars or fittings, like bowsprits, pulpits, etc. are not included and neither is the rudder.

- Length of waterline (L_{wl})

The length of the designed waterline (often referred to as the DWL).

- Length between perpendiculars (L_{pp})

This length is not much used in yachting but is quite important for ships. The forward perpendicular (FP) is the forward end of the designed waterline, while the aft perpendicular (AP) is the centre of the rudder stock.

- Rated length

A very important parameter in traditional rating rules. Usually L is obtained by considering the fullness of the bow and stern sections in a more or less complex way.

- Beam (B or B_{MAX})

The maximum beam of the hull excluding fittings, like rubbing strakes.

- Beam of waterline (B_{WL})

The maximum beam at the designed waterline.

- Draft (T)

The maximum draft of the yacht when floating on the designed waterline. T_c is the draft of the hull without the keel (the 'canoe' body).

- Depth (D)

The vertical distance from the deepest point of the keel to the sheer line (see below). D_c is without the keel.

- Displacement

Could be either mass displacement (m) i.e. the mass of the yacht, or volume displacement (V or ∇), the volume of the immersed part of the yacht. m_c, V_c and ∇_c are the corresponding notations without the keel.

- Midship section

For ships, this section is located midway between the fore and aft perpendiculars. For yachts it is more common to put it midway between the fore and aft ends of the waterline. The area of the midship section (submerged part) is denoted A_M, with an index 'c' indicating that the keel is not included. C_{Mc} is the midship sectional area coefficient defined for the canoe body as $C_{Mc} = A_{Mc}/(B_{Wl} \times T_c$.

For yachts the maximum area section is usually located behind the midship section. Its area is denoted A_X (A_{Xc}).

- Prismatic coefficient (C_P)

This is the ratio of the volume displacement and the maximum section area multiplied by the waterline length, i.e. $C_P = \nabla/(A_X \times L_{WL})$. This value is very much influenced by the keel and in most yacht applications only the canoe body is considered: $C_{Pc} = \nabla_c /(A_X \times L_{WL})$, see Figure 2. The prismatic coefficient is representative of the fullness of the yacht. The fuller the ends, the larger the C_{pc}. Its optimum value depends on the speed. Note that the index c is often dropped, even if the coefficient refers to the canoe body.

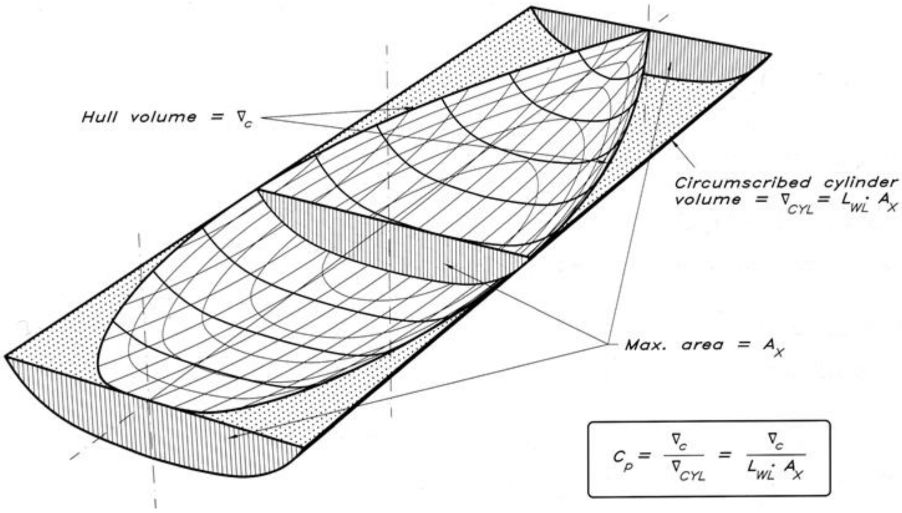


Figure 2. Prismatic Coefficient[1]

- Block coefficient (C_B)

Although quite important in general ship hydrodynamics this coefficient is not so commonly used in yacht design. The volume displacement is now divided by the volume of a circumscribed block (only the canoe body value is of any relevance) $C_{Bc} = \nabla_c /(L_{WL} \times B_{WL} \times T_c)$. See Figure 3.

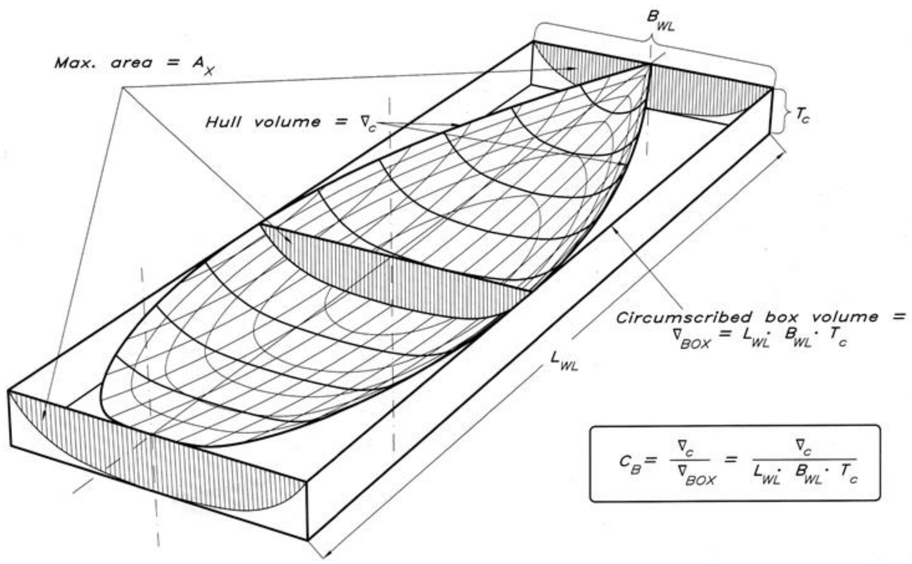


Figure 3. Block Coefficient[1]

- Centre of buoyancy (B)

The centre of gravity of the displaced volume of water. Its longitudinal and vertical positions are denoted by LCB and VCB respectively.

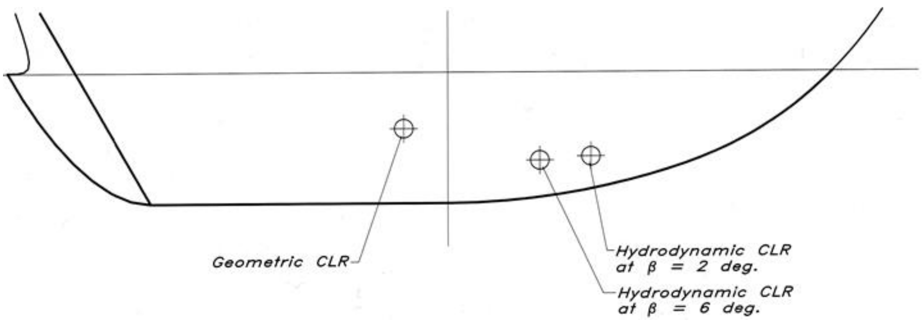


Figure 4. Geometric Centre of Lateral Resistance (G)

- Centre of gravity (G)

The centre of gravity of the yacht must be on the same vertical line as the centre of buoyancy. In drawings G is often marked with a special symbol created by a circle and a cross. This is used also for marking geometric centre of gravity. See, for instance, Figure 4.

- Sheer line

The intersection between the deck and the topside. Traditionally, the projection of this line on the symmetry plane is concave, the 'sheer' is positive. Zero and negative sheer may be found on some extreme racing yachts and powerboats.

- Freeboard

The vertical distance between the sheer line and the waterline.

- Tumble home

When the maximum beam is below the sheer line the upper part of the topsides will bend inwards as in Figure 5. To some extent this reduces the weight at deck level, but it also reduces the righting moment of the crew on the windward rail. Further, the hull becomes more vulnerable to outer skin damage in harbours.

- Flare

The opposite of tumble home. On the forebody in particular, the sections may bend outwards to reduce excessive pitching of the yacht and to keep it drier when beating to windward.

- Scale factor (a)

This is not a geometrical parameter of the hull, but it is very important when designing a yacht. The scale factor is simply the ratio of a length (for instance the L_{WL}) at full scale to the corresponding length at model scale. Note that the ratio of corresponding areas (like the wetted area) is α^2 and of corresponding volumes (like displacement) α^3.

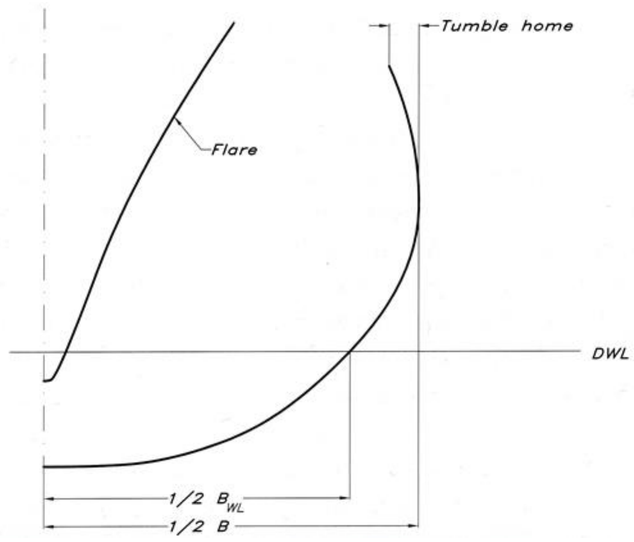


Figure 5. Definition of Tumble Home and Flair[1]

2.2 Lines Drawing

A typical full lines drawing for a yacht is shown in Figure 6. The hull is shown in three views: the profile plan (top left), the body plan (top right) and half breadth plan (bottom). Note that the bow is to the right.

In principle, the hull can be defined by its intersection with two different families of planes, and these are usually taken as horizontal ones (waterlines) and vertical ones at right angles to the longitudinal axis of the hull (sections). While the number of water lines is chosen rather arbitrarily, there are standard rules for the positioning of the sections. In yacht architecture the designed waterline is usually divided into ten equal parts and the corresponding sections are numbered from the forward perpendicular (section 0) backwards. At the ends, other equidistant sections, like #11 and # -1 may be added, and to define rapid changes in the geometry, half or quarter sections may be introduced as well. In Figure 6 half sections are shown in dotted lines.

The profile is very important for the appearance of the yacht, showing the shapes of the bow and stern and the sheer line. When drawing the waterlines, displayed in the half breadth plan, it is most helpful if the lines end in a geometrically well-defined way. Therefore a ghost' stem and a ghost' transom may be added. The ghost stem is the imagined sharp leading edge of the hull, which in practice often has a rounded stem, and the ghost transom is introduced because the real transom is often curved and inclined. If an imagined vertical transom is put near the real one at some convenient station, it will facilitate the fairing of the lines.

In the body plan, the cross sections of the hull are displayed. Since the hull is usually symmetrical port and starboard, only one half needs to be shown, and this makes it possible to present the forebody to the right and the afterbody to the left. In this way mixing of the lines is avoided and the picture is clearer. Note that in the figure the half stations are drawn with a different line type.

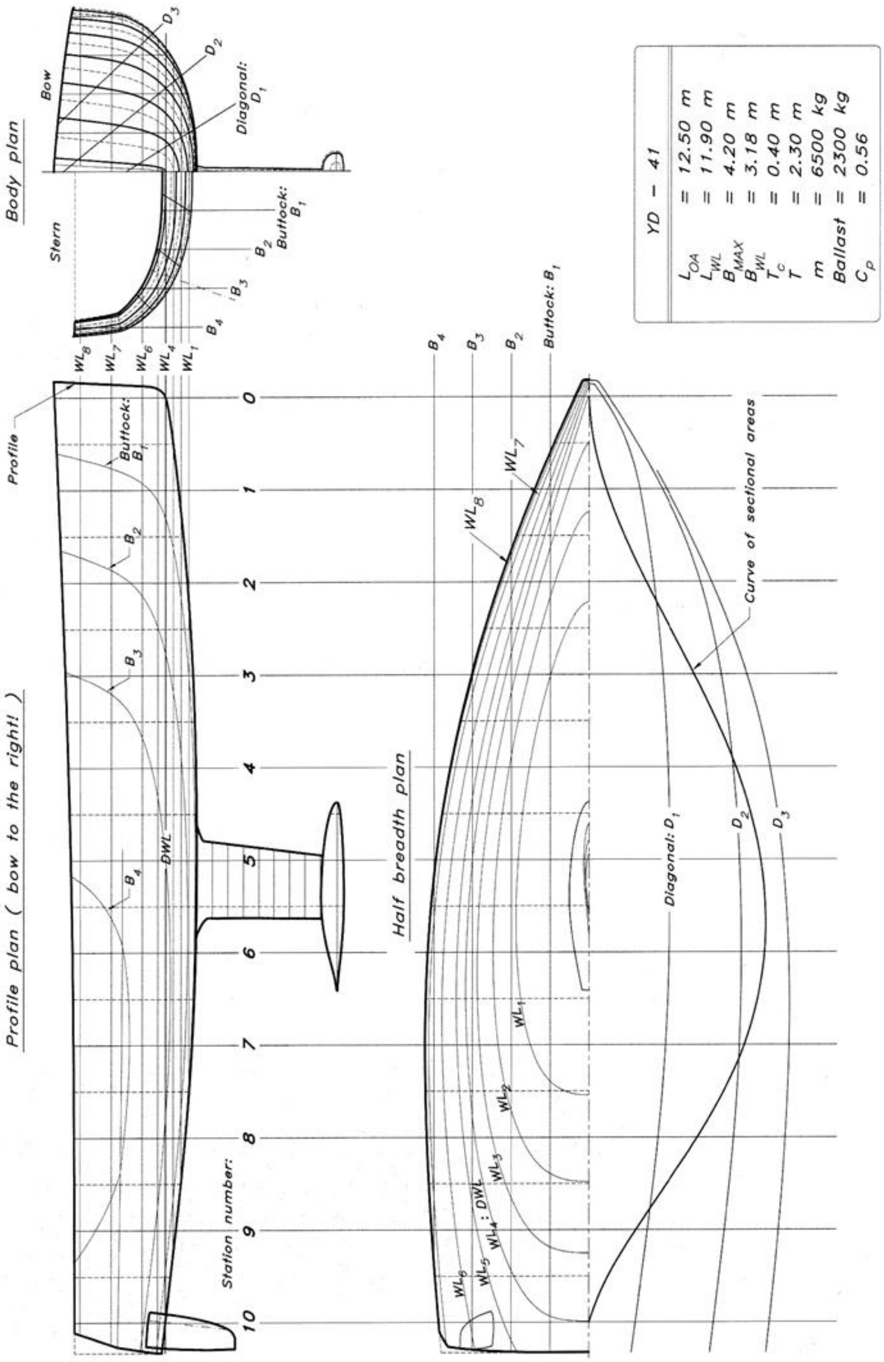


Figure 6. Typical Yacht Lines Drawing[1]

The above cuts through the hull are sufficient for defining the shape, but another two families of cuts are usually added, to aid in the visual perception of the body. Buttock lines are introduced in the profile plan, showing vertical, longitudinal cuts through the hull at positions indicated in the half breadth plan. The diagonals in the lower part of the half breadth plan are also quite important. They are obtained by cutting the hull longitudinally in different inclined planes, as indicated in the body plan. The planes should be, as much as possible, at right angles to the surface of the hull, thus representing its longitudinal smoothness. In practice, the flow tends to follow the diagonals, at least approximately, so that they are representative of the hull shape as seen by the water. Special attention should be paid to the after end of the diagonals, where knuckles, not noticed in the other cuts, may be found, particularly on yachts designed under the International Offshore Rule (IOR) in the 1970s and 1980s. Almost certainly, such unevenness increases the resistance and reduces the speed of the yacht.

The other line in the lower part of the half breadth plan is the curve of sectional areas, representing the longitudinal distribution of the submerged volume of the yacht. The value at each section is proportional to the submerged area of that section, while the total area under the curve represents the displacement (volume).

If the drawing is produced manually, a table of offsets is usually provided by the designer. This is to enable the builder to lay out the lines at full size and produce his templates. Offsets are always provided for the waterlines, but the same information may be given for diagonals and/or buttocks, too. Note that all measurements are to the outside of the shell. For drawings produced by a CAD system the geometry information can be transferred directly to a numerically controlled cutting machine. Usually the international IGES (Initial Graphics Exchange Specification) standard is then used as the file format.

3. Yacht Hydrodynamics

The motion of a boat through the water may at first sight seem quite simple and natural, but it is in reality a very complex phenomenon. When a boat moves through the water, it creates turbulence in the fluid surrounding it, which produces resistance to its motion and also develops forces that assist that motion, through very different mechanisms.

Consider for example the dissipation of energy in the boundary layer, a relatively stagnant water layer adjacent the hull, or the energy used to create waves, or the turbulence the boat leaves behind in its wake. All these different forms of energy can only come from the system (engine or sails) that drives the boat along, and thus represent energy subtracted from the energy resource available for propelling the boat.

When a boat is moving at a constant speed, for reasons of dynamic equilibrium the driving force is equal and opposite to the total resistance. If we consider this in terms of energy, we can say that the thrust horse power is equal to the horse power developed by the resistance forces.

In the case of a sailing boat, the thrust horse power comes from the wind and is thus intrinsically quite modest and it therefore becomes particularly important to reduce to a minimum any form of resistance to motion.

Given the large number of factors involved and the complexity of the mechanisms of interaction between the boat and the water surrounding it (the free surface effects), it would be very arduous and difficult in practical terms to calculate the hydrodynamic forces on the basis of geometrical hull data unless one had access to considerable computing resources.

In fact there is currently no simple mathematical method capable of producing reliable results for the resistance and lift developed by a boat under way, and even if a numerical solution for the fluid dynamic problem was developed, several problems still remain to be solved.

Experimental measurement of the hydrodynamic forces using scale models in a towing tank is still the most frequently used method, though computational fluid dynamics is proving increasingly useful.

The widespread use of the experimental approach is also due to the fact that it can be used to advantage in methods that break down the complex mechanism of interaction between a boat and the water surrounding it and analyse the effects separately, bringing them together later to build up an overall picture.

Each of these elementary mechanisms, into which the distinctly complex problem of the interaction of the boat with the water is broken down, can be dealt with using fairly simple formulae. These are based on data obtained from experiments (in tanks or wind tunnels) on the individual components that make up the submerged part of the hull (the hull itself, the keel, the rudder and so on).

This approach, though it undeniably involves a series of approximations that are sometimes quite rough, is very practical and produces a series of results that are easy to use in designing a boat and are also a valid tool for analysing and interpreting a design.

Consider the submerged part of the boat as a whole in hydrodynamic terms. From a quite general point of view the dynamic action that develops in the interaction between a fluid and a solid in relative motion can be broken down into two components: one in the direction of the relative speed of the incident flow and one in a direction perpendicular to it. These are, respectively, resistance or drag and lift.

It is now consolidated practice in scientific and technical literature to distinguish conceptually between the submerged part of the bare hull and the appendages, that is the combination of keel, bulb and rudder.

This is linked above all to the fact that the hull is generally the part of the boat that prevalently encounters resistance to motion, while the appendages, though they also encounter resistance forces, are able to develop lift which, together with the action of the sails, enables the boat to follow a course through the water.

It is known from experience which is the best way to move a plate so as to minimise resistance: when the plate is moved end on, see Figure 7, it does not disturb the flow and the pressure is virtually equal on all points of its surface, except on the leading and trailing edges. The pressure difference here does produce a resistance force, but since the areas on which the pressure acts are very small the pressure resistance will be almost zero.

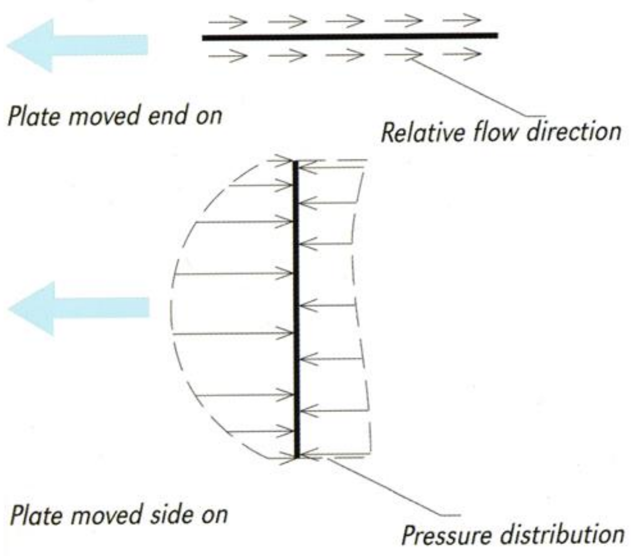


Figure 7. Hydrodynamic Resistance on a Flat Plate[2]

All the resistance developed by the plate comes from the tangential forces parallel to the plate, which are caused by frictional effects inside the boundary layer. To sum up, when the plate is moved end-on all the resistance comes from frictional resistance.

If, however, the plate is moved through the water sideways, the resistance is entirely due to the lack of symmetry in the pressure developed around it. Even if there are flow components along its surface that create friction, these do not contribute to the resistance, which is entirely due to the fact that the sum of the pressures on the left-hand side of the plate is greater than that on the right-hand side. When the plate is moved sideways on, all the resistance is from form or viscous pressure drag.

In the case of a boat, in addition to the steel plate the wave system created by the boat must be taken into account. Creating this system of waves requires energy, and this energy is subtracted from the energy of the moving boat. In other words, the production of the system of waves creates a resistance force which is called 'wave resistance' or 'wave-making resistance.

Thus viscous resistance and wave resistance describe what happens when a boat moves upright through the water, as in downwind sailing.

When sailing between a beam reach and close- hauled, the boat heels under the effect of the thrust of the wind on the sails and, it must develop hydrodynamic lift to balance the lateral aerodynamic force. As a result, the boat makes 'leeway' (sideways movement).

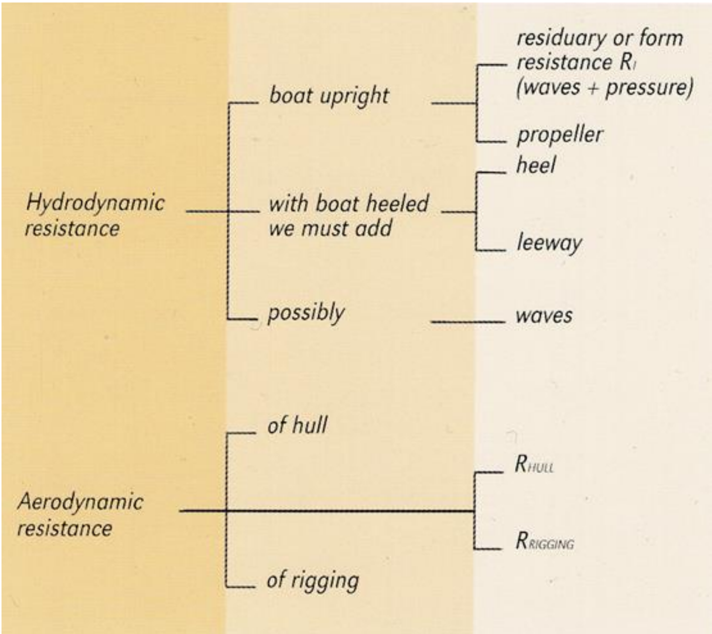


Figure 8. Resistive Components Acting on a Sailing Boat[2]

In these conditions resistance generally increases, and this increase is due to two new factors:

- Heeled resistance;
- Leeway resistance (also called induced resistance).

Historically, it was Davidson who in 1936 first illustrated a complete theory of the propulsion of a sailing boat, giving a full interpretation of heel and leeway resistance

Much more recently, further mechanisms of resistance creation have been described. These are related to the influence of the waves the boat encounters as it sails along and also to forms of aerodynamic resistance on the part of the hull above the waterline and on its equipment (mast, shrouds and stays), which in strong wind are far from negligible, see Figure 8.

3.1 Stability at Small Heel Angles

The transverse stability of a yacht may be explained with reference to Figure 9 and Table 1. When the yacht is heeled, the centre of buoyancy moves to leeward from B to $B^/$ The buoyancy force, upwards, then creates a couple with the equally large gravity force acting downwards at G. The lever arm is usually called GZ and the righting moment is m × g × GZ, since the gravity force is the mass, m, multiplied by the acceleration of gravity, g (9.81 m/s^2).

There is another important point marked in the figure: the transverse metacentre, M. This is the intersection between the vertical line through $B^/$ and the symmetry plane of the yacht. For small angles of heel this point may be assumed fixed, which simplifies the calculations considerably. The distance between the centre of gravity G and M, GM, is called the metacentric height and BM is the metacentric radius. A fundamental stability formula (which will not be proven here) says that the metacentric radius is equal to the ratio of the transverse moment of inertia I_T and the volume displacement ∇. Using this formula and some simple geometric relations the righting moment may be obtained as shown in Table 1.

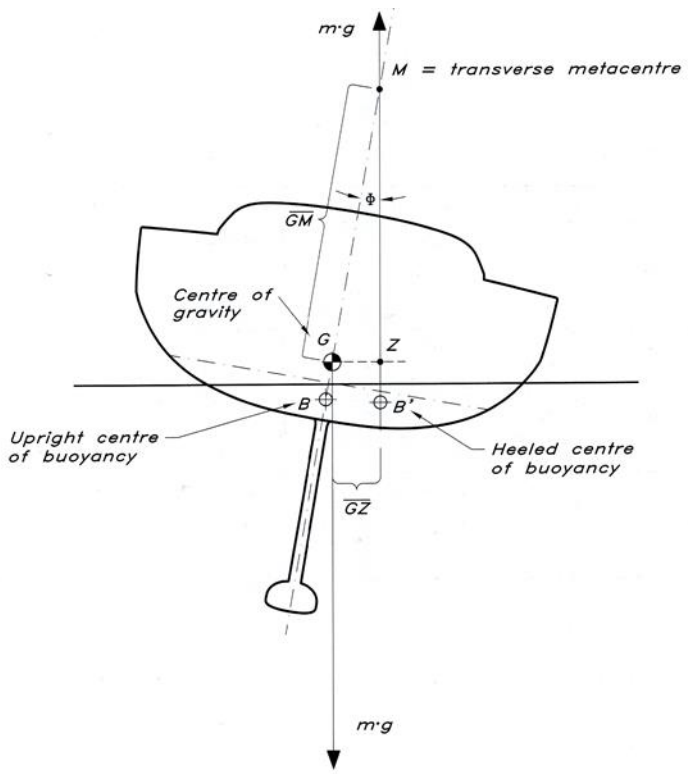


Figure 9. Transverse Stability at Small Heel Angles (<10^o) [1]

Since the stability of the yacht is proportional to GM there are two principal ways of increasing it. Either G may be lowered or M may be raised. A low G is found on narrow, heavy yachts with a large ballast ratio, like 12 m and other R yachts (sports yacht); such yachts have weight stability. Modern racing yachts, on the other hand, are wide and shallow, which raises M; they have form stability.

Table 1. Longitudinal Stability Relationships at Small Heel Angles

Transverse stability relations:

$\overline{BM} = \frac{I_T}{\nabla}$ (*Fundamental stability formula*) [2.55 m]

$\overline{GM} = \overline{BM} - \overline{BG}$ (*G above B*) [2.52 m]

$\overline{GZ} = \overline{GM} \cdot \sin\Phi$ (Φ = *heel angle*)

[$\overline{BG} = 0.03$ m]

[$\nabla = 6.3$ m^3]

Transverse righting moment: [Nm]

$$RM = m \cdot g \cdot \overline{GZ}$$

The method of calculating the longitudinal stability corresponds exactly to that of the transverse stability, see Figure 10. Thus, the restoring moment when the hull gets a trim angle may be computed from the formulae in Table 2, which correspond to those in the previous figure. A formula is also available for computing the trim angle obtained when moving a weight longitudinally on board the yacht.

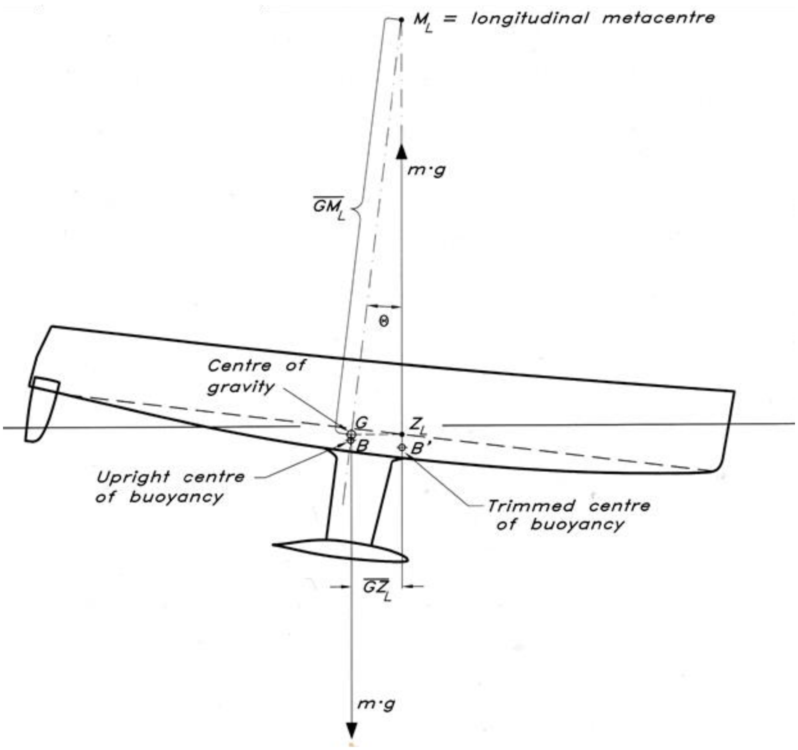


Figure 10. Longitudinal Stability at Small Heel Angles (<10^0) [1]

Table 2. Longitudinal Stability Relationships at Small Heel Angles

Longitudinal stability relation:

$\overline{BM}_L = \frac{I_L}{\nabla}$ (*Fundamental stability formula*) [33.06 m]

$\overline{GM}_L = \overline{BM}_L - \overline{BG}$ (*G above B*) [33.03 m]

$\overline{GZ}_L = \overline{GM}_L \cdot \sin\Theta$ (Θ = *trim angle*)

[$\overline{BG} = 0.03$ m]

[$\nabla = 6.3$ m^3]

Longitudinal righting moment:

$$RM_L = m \cdot g \cdot \overline{GZ}_L$$

3.2 Stability at Large Heel Angles

The calculation of the righting moment at large heel angles is considerably more complicated than that for small angles. One difficulty arises from the fact that the positioning of the heeled hull with respect to the water surface is not known. If the hull is just rotated about the centreline (at the level of the DWL), the displacement will generally become too large and a trimming moment will develop. The only way to overcome this difficulty is by trial and error, i.e. by trying several attitudes, varying the sinkage and trim systematically, in order to find a position where the displacement and LCB correspond to the original ones.

After finding the right attitude a considerable amount of calculation is needed to find the righting moment, since no simple formulae, like those for small heel angles, are available. In practice, these calculations have seldom been carried out manually even for ships, because before the computer era naval architects made use of a special instrument, called an integrator, a development of the planimeter. Such an instrument is, however, rarely available to the yacht designer, so we will propose a slightly more approximate method, which is often accurate enough.

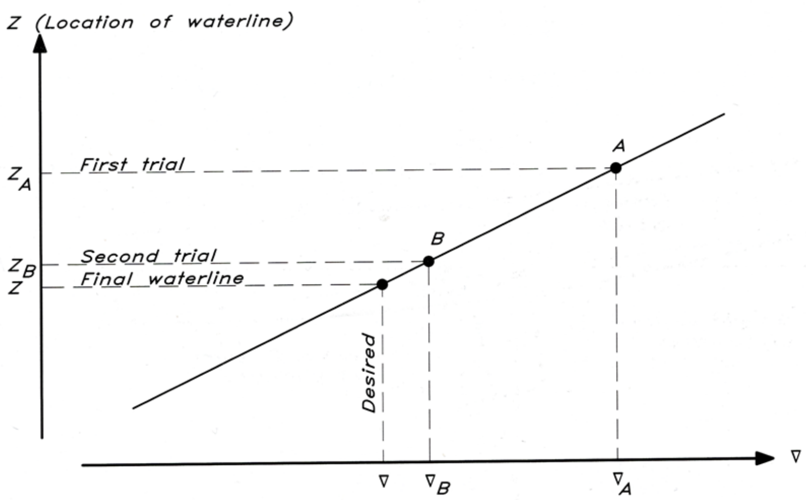


Figure 11. Method to Find the Heeled Waterline[1]

The method is illustrated in Figure 11. Special care must be taken, however, with very beamy yachts with large fore and aft asymmetry. Such hulls will develop a considerable trim when heeling, and this effect is not considered here.

To find the attitude of the hull, rotate it first around the centreline at DWL (designed waterline) to the desired angle. Then calculate the displacement ∇_A up to this waterline located at Z_A. This cannot be done, however, without knowing the shape of the sections on both sides of the symmetry plane, so the body plan has first to be completed to include both sides of the hull.

The displacement ∇_A is bound to be too large, so a new waterline at Z_B has to be found. A first estimate of this line can be made by dividing the excess displacement by the area of the original DWL. This gives the approximate distance to the new waterline at Z_B, for which the displacement ∇_B is also computed. Not even this is likely to be very accurate, but the final position Z of the waterline can be found by interpolation or extrapolation to the right, as explained in the figure. In this way the displacement will be quite accurate, although all effects of trim are neglected.

Having found the waterline, the cardboard method' is used to find the transverse position of the centre of buoyancy, $B^/$ in Figure. All heeled sections below the waterline are cut out in cardboard and glued together in their correct positions. The centre of gravity of the cardboard body (corresponding to the centre of buoyancy of the real hull) can then be found from the intersection of two lines, obtained using a plumb bob, as explained above.

Knowing $B^/$, the location of the point where the vertical through B' hits the centre plane can be found, see Figure 12. BM may then be measured from the figure and the remaining formulae for small angles applied.

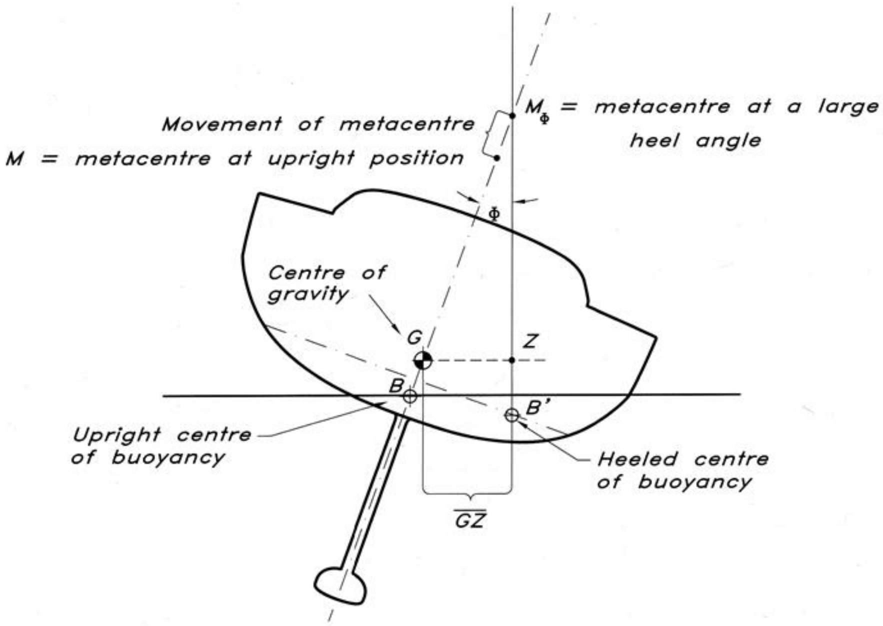


Figure 12. Stability at Large Heel Angles[1]

3.2.1 Static Stability Curve

The curve of static stability represents the righting moment at varying angles of heel. Since the moment differs from the lever arm only with respect to the constant m×g, the vertical scale could equally well represent GZ. In Figure 13 a GZ-curve is shown.

For small angles GM is constant and Sin Φ (in radians), so GZ is proportional to the heel angle, i.e. GZ = GM Sin Φ. The slope of the GZ curve at the origin may thus be obtained by noting that the tangent should pass through the point GZ = GM for Φ = 1 radian, i.e. at 57.3°.

Another important aspect of the GZ curve is the maximum, which represents the largest possible righting moment of the hull. Obviously the yacht will capsize if the heeling moment exceeds this level.

Of great interest is the so-called stability range, which is the range of angles for which a positive righting moment is developed. For larger angles the hull is stable upside-down.

It is also of interest to note that the area under the RM curve up to a certain angle represents the work needed, by waves for instance, to heel the hull to this angle.

Large differences are found in the stability curves for modern fin-keel yachts and traditional V-shaped long keel ones. After the Fastnet Race disaster in 1979, a study was carried out at Southampton University in which two yachts of similar size were compared. Both raced in Class V. One was a cruiser-racer, the Contessa 32, while the other one was an extreme racer, Grimalkin, 30-foot L_{OA}.

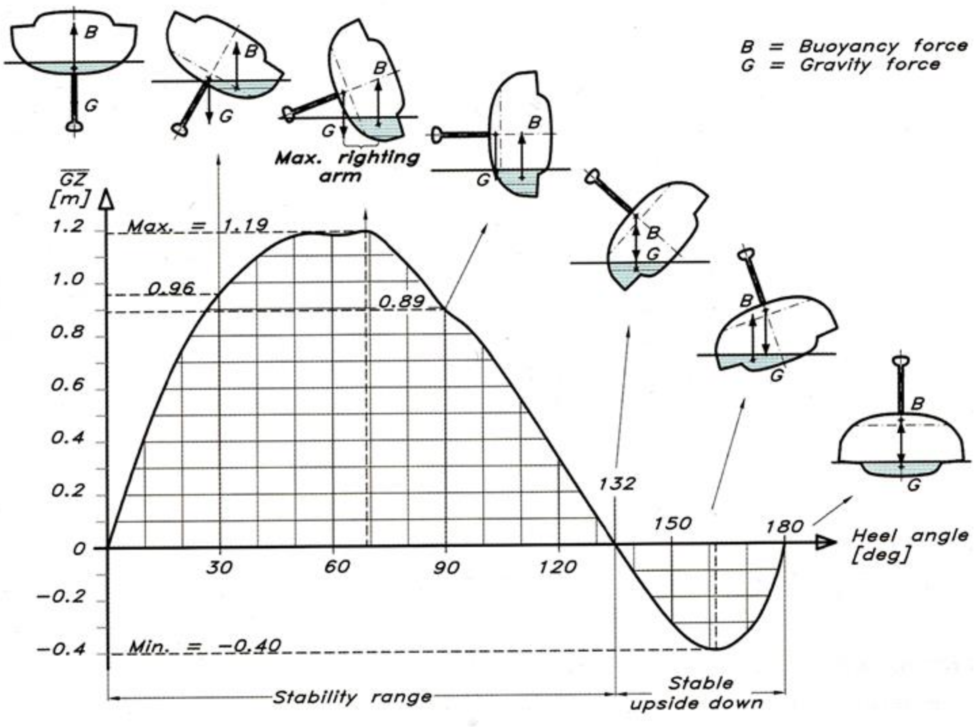


Figure 13. A Static Stability Curve[1]

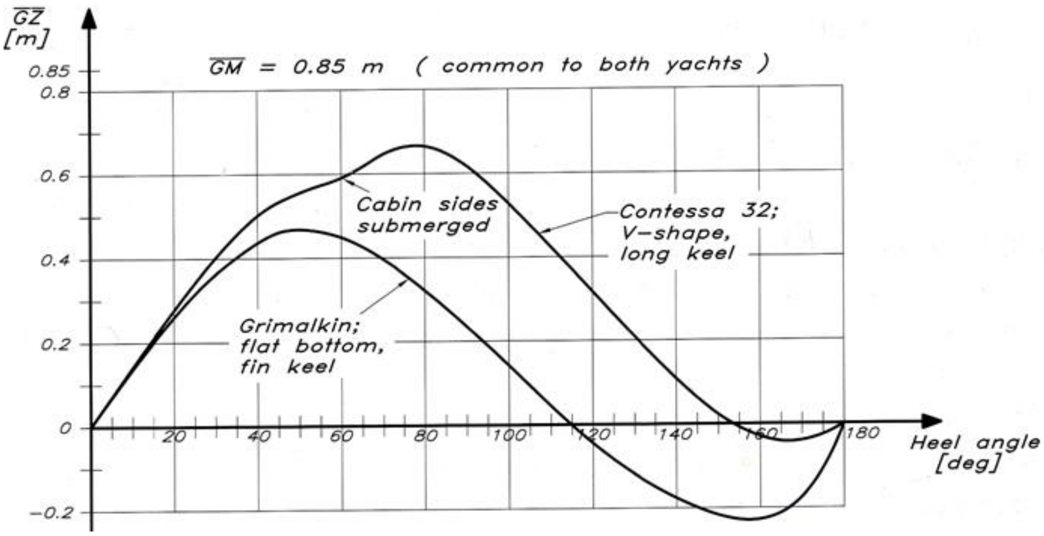


Figure 14. GZ Stability Curves for Grimalkin and Contessa 32[1]

Interestingly enough both yachts have the same GM = 0.85 m, see Figure 14, which shows the GZ-curves). This does not mean, however, that RM is exactly the same for small angles, since the mass differs: 4600 kg for the Contessa 32 and 3800 kg for Grimalkin. At 1° of heel RM is 670 Nm (Newton-metres) and 550 Nm, respectively. It should be noted that the sail area is almost exactly the same for both yachts.

A larger difference is found in the maximum GZ, which is about 40% higher for the Contessa 32. Converted into righting moment the difference is even larger. For the Contessa 32 RM_{max} occurs at about 80° and is equal to 30200 Nm, while for Grimalkin RM_{max} is only 17900 Nm at about 50°.

A more significant difference is also found in the stability range. The Contessa 32 is stable up to about 155°, while zero righting moment occurs already at about 115° for Grimalkin. There is thus a very small range of angles, 25°, where the Contessa 32 is stable upside down, and the area between the RM curve and the horizontal axis is very small in this range. For Grimalkin the corresponding range is about 65° and the area is significant. This means that it is considerably more difficult to put the latter yacht into the upright position once it has capsized. The amount of work required by wind and waves is large, so this yacht may be expected to stay upside down for some time, perhaps a few minutes, while the Contessa 32 would return to the upright position almost immediately after a knockdown.

In it is clear that the traditional yacht is safer under rough conditions than the more modern one.

3.2.2 Rolling

A sailing yacht in a seaway moves in all six degrees of freedom, i.e. surge, sway, heave, roll, pitch and yaw. The first three are linear motions in the longitudinal, transverse and vertical directions, while the remaining three are rotations around a longitudinal, transverse and vertical axis, respectively. From a safety point of view, rolling is the most important motion.

If a hull is given a heel angle in still water and is then suddenly released, the righting moment will immediately tend to put the hull upright. The hull starts rolling back to its upright position, but due to its inertia it will not stop when the heel angle is zero. Rather, it will continue to roll over to the other side, where an opposing righting moment develops. The hull then rolls back and forth, until the motion is damped out. In fact, for a sailing yacht, the damping is very large, so the motion dies rapidly.

This example contains many of the important features in connection with rolling excited by a seaway. Of great importance is the frequency with which the hull rolls in the still water test; the so-called natural frequency. The higher the stability, and the lower the inertia, the larger the natural frequency. It can easily be imagined that if the frequency of the waves hitting the hull in rough water is the same as the natural frequency (resonance), very large motions may result, at least if the damping is small.

This phenomenon is shown graphically in Figure 15. The horizontal scale is the frequency of encounter of the waves divided by the natural frequency of the hull, and the vertical scale is the roll angle divided by the wave slope. Several curves are shown in the diagram, each one with a constant damping. Note that the lowest curves represent the largest damping.

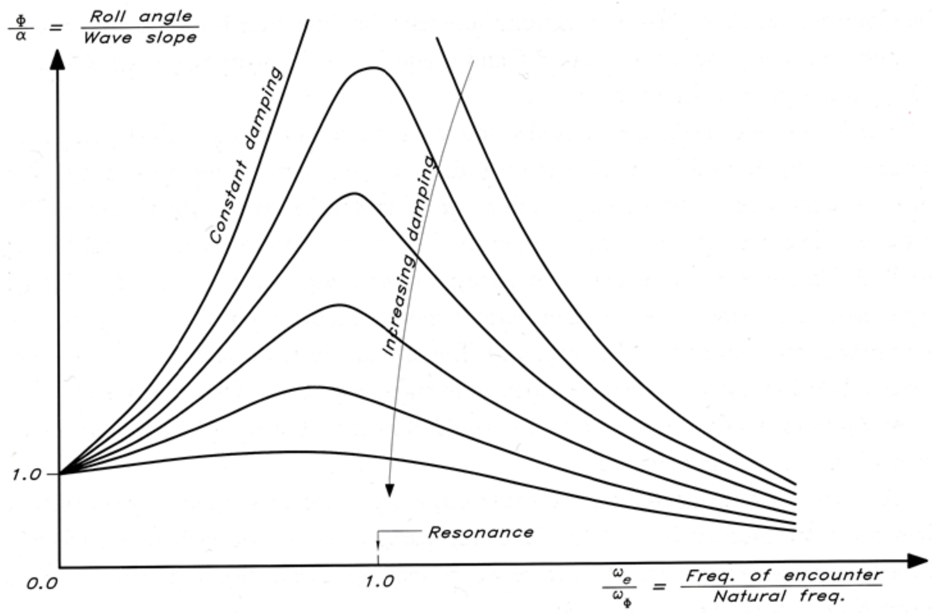


Figure 15. Roll Amplitude versus frequency for Different Damping Conditions[1]

If the frequency of encounter is low or the natural frequency high, small values are obtained on the horizontal axis. This is where all curves converge into a value of one on the vertical axis. The roll angle is then the same as the wave slope. This may happen for long ocean waves after a gale, where most hulls will follow the wave contour. A life raft, with a very small inertia, i.e. high natural frequency, will follow the wave contour for much shorter waves of higher frequency also, since the value on the horizontal scale is still very low. At the other end of the spectrum all curves tend to zero. This is where the waves hit the hull at such a high frequency that it does not have the time to react, an unlikely situation for waves of any significant height.

A dangerous condition is when the frequency of encounter is close to the natural frequency, i.e. close to resonance. As appears from Figure 15 the roll angle may then be several times larger than the wave slope and the yacht may capsize.

If the yacht approaches resonance, i.e. the frequency of encounter gets close to the natural frequency, one of these frequencies must be changed. The most straightforward way of doing this is to change the course. Since the frequency of encounter depends both on the wave speed (and length) and the speed component of the yacht in the direction of wave propagation, changing the course will change this frequency. If the yacht beats to windward many more waves are met per minute than if it runs downwind with the waves. This technique of avoiding excessive roll is also used on large ships under severe conditions. Speed reduction is also possible, of course.

From a theoretical point of view the natural frequency may be changed by increasing or reducing either the stability or the inertia (or more precisely, the mass moment of inertia around a longitudinal axis). To avoid the resonance situation the natural frequency can be either increased or reduced. However, in conditions where this problem occurs it is better to move to the left in Figure 15, either by increasing stability or reducing inertia. If weights located at a high position are moved down to the bottom of the hull (which is probably closer to the centre of gravity) both these effects are accomplished.

The technique of avoiding resonance is closely related to the operation of the yacht, while the other way to reduce roll - namely, to increase damping - is the designer's task. Damping may be caused by three things:

- Friction between the water and the yacht.
- Generation of waves on the water surface.
- Generation of vortices from the keel, rudder, sharp bilges and sails. This factor is by far the most important for sailing yachts.

Vortex generation depends partly on the shape of the sections Figure 16, but mainly on the size of the lateral area. Excessive rolling combined with low speed creates large angles of attack of the flow approaching the keel and rudder, which then get overloaded and stall. For the forces on the stalled surfaces the area is much more important than other geometrical properties, so a long keel yacht will have more damping than a fin-keel one. This is an important conclusion, which speaks in favour of traditional designs and against more modern ones with a small lateral area.

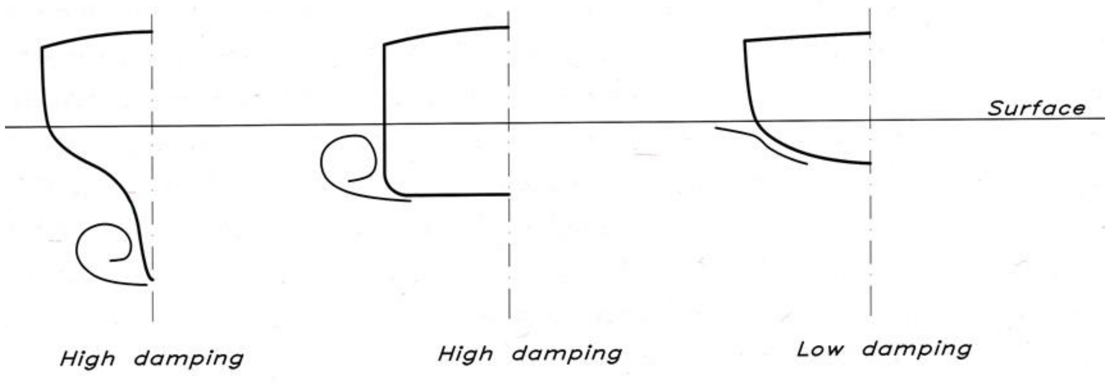


Figure 16. Influence of Section Shape on Damping

It should also be pointed out that forward speed increases damping considerably, particularly for fin-keel yachts. If the speed is high enough, the keel starts working properly and the forces get much larger. Figure 17 shows how the roll amplitude decays with time for Grimalkin in still water. At zero speed the decay is much smaller than at high speed, where the rolling is rapidly damped. It is therefore important, especially for fin-keel yachts, to keep the speed up under critical conditions.

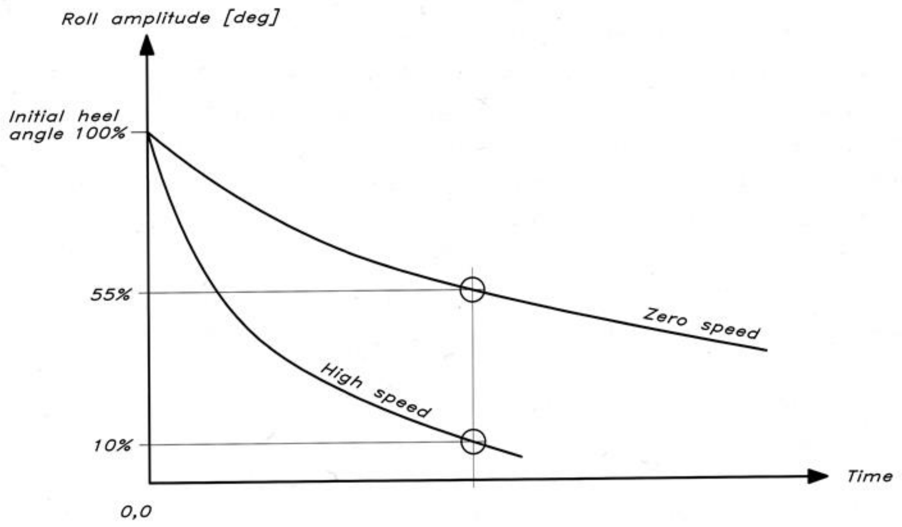


Figure 17. Influence of Speed on Roll Damping in a Fin-Keel Yacht

3.3 Keel and Rudder

In the design of keels and rudders, well-established principles from aircraft aerodynamics can be employed. Although most aircraft today fly at speeds at which the compressibility of the air is important (more than 100 m/s), much information can be gleaned also for the incompressible water flow, partly due to the early aerodynamic research carried out more than 50 years ago. Here a short introduction is given to the basic principles of the flow around a wing (keel or rudder) at an angle of attack, and the corresponding force generation.

3.3.1 Flow around a Wing

When a wing works properly the flow on both sides is attached. No separation occurs, and the streamlines around a section of the wing resembles that in Figure 18. If we assume that the wing is infinitely long with a constant cross-section and that the flow is at right angles to the span, there is a stagnation point close to the leading edge (nose), where the flow is divided into two parts, following the upper and lower surfaces of the section, respectively. At the stagnation point itself there is no flow in either direction along the surface, and since the fluid does not penetrate the wing there is no velocity at right angles to the surface either. A similar point with zero velocity is found at the trailing edge (tail) of the section. This is the so-called two-dimensional case, where the properties at all cross-sections are the same. In practice this is accomplished by putting the wing between two walls at right angles to the span, for instance in a wind tunnel. Most of the wing sections of interest in sailing yacht design are symmetric, as in Figure 18, since they have to work equally well on both tacks. At zero angle of attack the pressure distribution along the section looks in principle like the one along a waterline (see Figure 19), i.e. there is high pressure at the nose and tail, and lower pressure in between. However, at non-zero angle of attack (Figure 18), the flow becomes highly asymmetric. In particular, there is a large difference between the flow that has to move from the stagnation point past the nose on to the upper side and the one moving backwards from the stagnation point. While the former passes a region of very large curvature, the latter moves more or less straight back. There is also a difference in speed between the two sides; the upper speed being higher than the undisturbed one, and the lower speed slower.

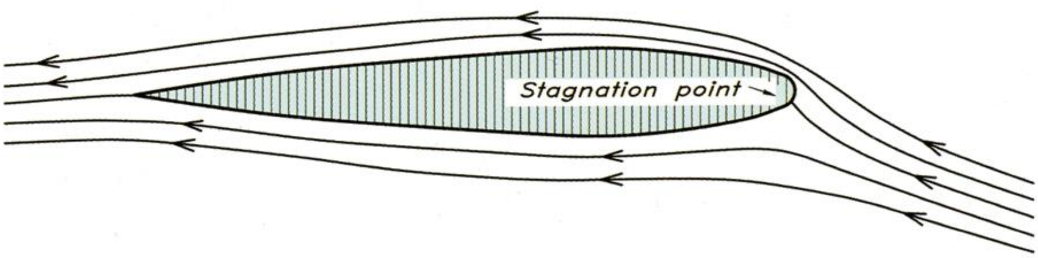


Figure 18. Flow Around a Wing Section (Keel or Rudder) [1]

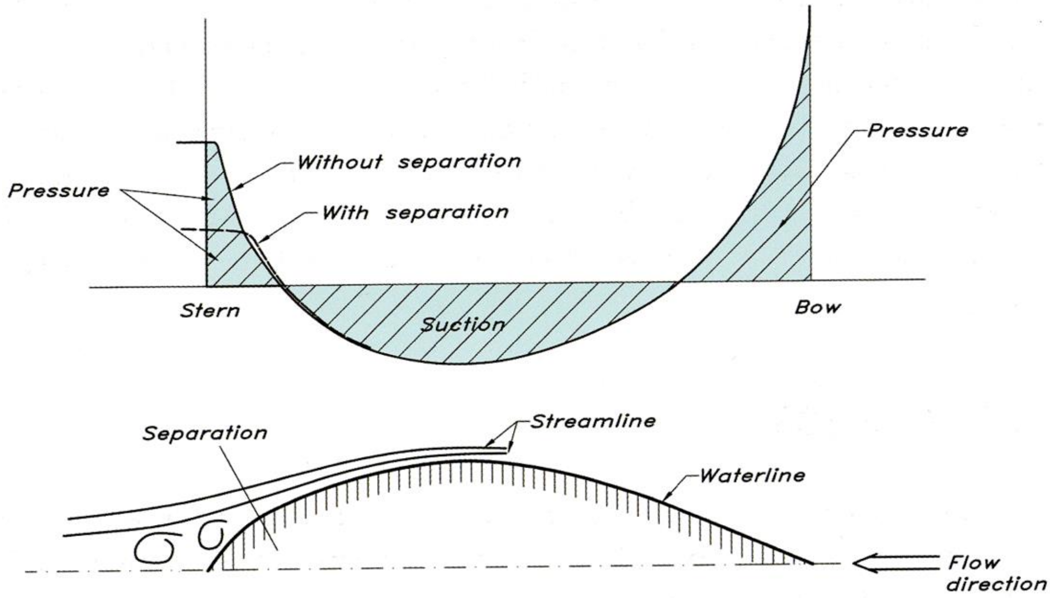


Figure 19. Pressure Distribution with and without Separation[1]

Quite different pressures are then created as shown in Figure 20, and it is particularly noteworthy that there is a large suction peak at the nose. Further back on the top side the suction is gradually reduced. On the lower side the pressure is positive, but its absolute value is lower than on the other side. If all the pressure forces on the section are added, a resulting force (shown as an arrow) is obtained. The angle between the undisturbed flow and the resulting force depends on the efficiency of the wing. For a two- dimensional case without friction the angle would be 90°. In a real situation it is always smaller than 90° (pointing more backwards).

Since the pressure and suction forces are much larger in the front part of the wing, the centre of effort of the resulting force is located in the forward part. In fact, it may be shown theoretically that the centre of effort is at one quarter of the distance from nose to tail for a symmetric section in a two-dimensional frictionless fluid. The lower part of Figure 20 shows a diagram, where the pressure is plotted in the more normal way, i.e. with the pressure on the vertical scale and the position along the section on the horizontal scale. Note, however, that negative pressures are plotted upwards. In this way the upper side of the wing corresponds to the upper part of the diagram, and conversely for the lower side. The distance between the upper and lower curves is representative of the vertical force being generated at that position, and the total vertical force is proportional to the area between the two curves.

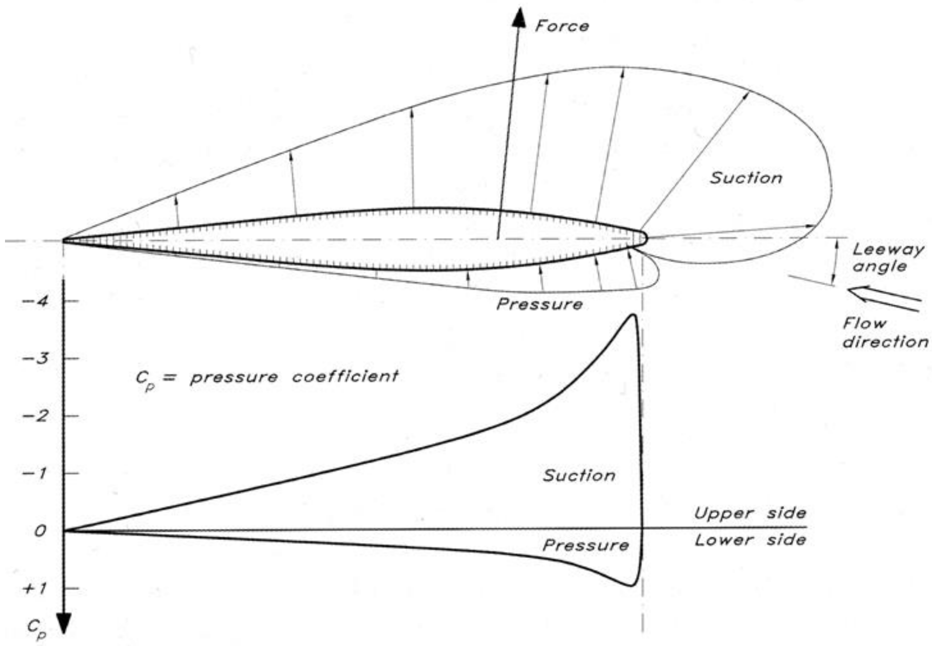


Figure 20. Pressure Distribution Around a Wing Section[1]

Real wings are not, of course, infinitely long, nor are they mounted between the walls of a tunnel. They therefore have free ends in the flow, and that creates some new phenomena. This is the three-dimensional case.

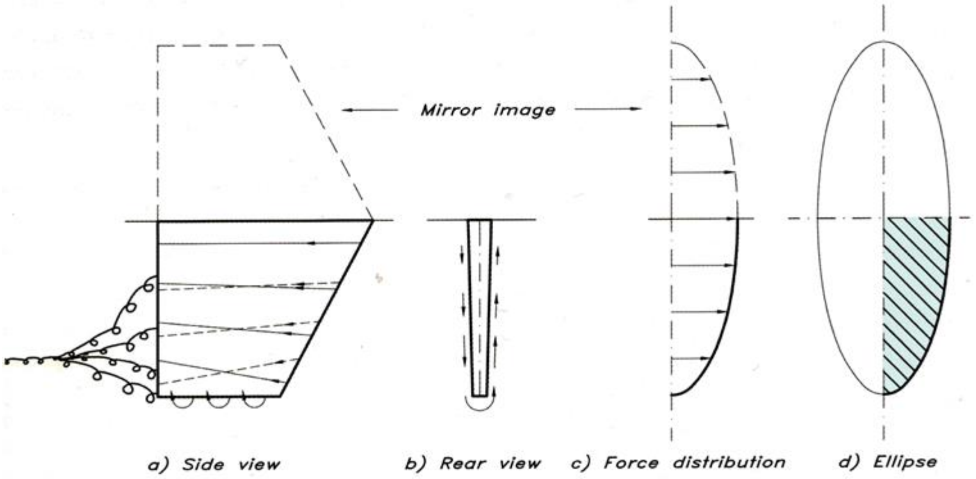


Figure 21. Force and Vortex Distribution Around a Wing Section[2]

In Figure 21 a keel is shown from the side (a) and from behind (b). Since the pressure is higher on the leeward side of the keel than on the windward side, the flow will tend to move around the tip from the leeward to the windward side. This creates a downward motion on the leeward side, gradually increasing from zero at the root to a maximum at the tip. A corresponding motion upwards is created to windward. Streamlines on the two sides of the keel therefore have different directions, and when they meet at the trailing edge vortices are created. This is particularly so at the tip, where a strong vortex is left behind the keel. Sometimes, when the yacht heels strongly this vortex can be seen, since air is sucked into the low-pressure core of the vortex when it gets close to the surface.

As appears from the figure, all the vortices created at the trailing edge tend to roll up into a single one left behind the yacht. Since this vortex contains rotational energy it gives rise to a resistance component, the induced resistance, discussed in the previous chapter.

At the tip the side force generated must go to zero, since no pressure jump between the two sides can exist in the flow at the tip. Near the root, on the other hand, the flow is uninfluenced by the tip and a large force may be generated, since the bottom acts as a wall, preventing the overflow. The variation between root and tip depends on the shape of the keel, and it may be shown that the best distribution of the force is an elliptical one. With this distribution the minimum amount of vertical energy is left behind, which means that the induced resistance is minimized.

In Figure 21 an elliptical distribution is shown. This may be imagined as one quarter of a full ellipse, as shown in (d). The simplest way to obtain an elliptical distribution of the side force is to make the keel planform elliptic.

An interesting phenomenon is indicated in Figure 21 (a) and (c). If the bottom of the hull may be considered as a flat plate of infinite extension, the flow around the keel would be the same as if the plate had been replaced by the mirror image of the keel in the plate. A flat wall parallel to the flow thus acts as a symmetry plane. Now, the bottom is neither flat nor infinite in reality, and a more complex flow pattern occurs.

3.3.1.1 Trapezoidal Keel Form: Definitions

The definitions associated with a trapezoidal keel are shown in Figure 22. First, it should be mentioned that the horizontal distance from nose to tail at all depths is called the chord. Two chords are specified in the figure, namely the root and tip chords, C_1 and C_2. These can be used to define a mean chord $C = (C_1+C_2)/2$. The most important parameter for the efficiency of the keel is the aspect ratio, AR, defined as $AR = T_k/C$, i.e. the keel depth divided by the mean chord. This is the geometric aspect ratio.

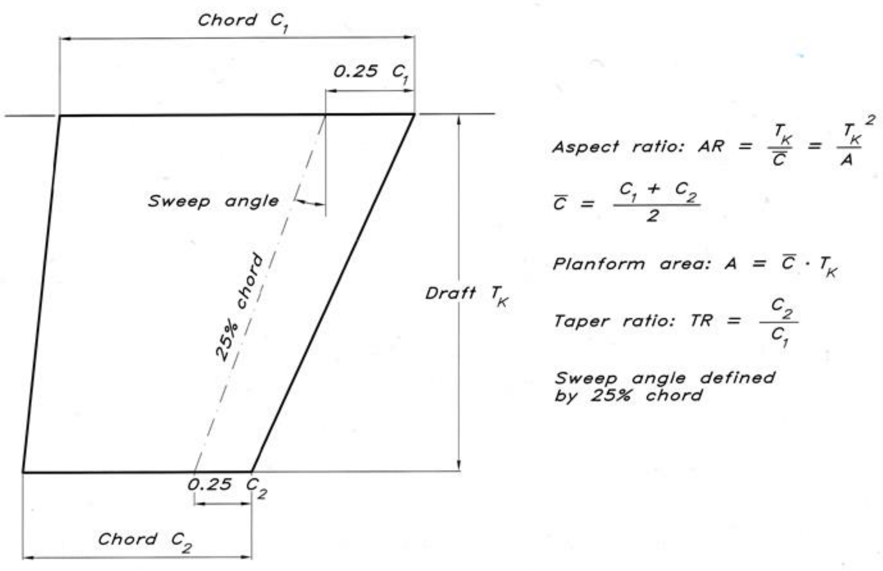


Figure 22. Definitions of a Planform Keel[1]

As explained above, the effective aspect ratio AR_e is twice as large if the keel is attached to a large flat surface. The second parameter to be defined is the taper ratio, TR, which is simply the ratio of the tip chord to the root chord, i.e. $TR = C_2/C_1$

Most keels are not exactly vertical, but sweep backwards to some extent. It is not obvious, however, how to define this sweep angle, θ. The leading or trailing edges might be used for defining the angle, or perhaps the mid-line between the two, but the most appropriate choice turns out to be the line 25% of the chord length from the leading edge. As pointed out above, under certain ideal conditions, the centre of effort at every section lies along this line. Even though this is not exactly true in a real case, it is still a good approximation for fin keels and rudders of normal aspect ratios.

3.4 Sail and Rig

A sail is also a wing, but differs in some important respects from the wing of a rudder and keel described above. The sail has virtually no thickness, but it has a camber which is quite large. It often works in the disturbed flow from a mast. Nevertheless, most of the principles described above still apply, and are discussed in more detail below.

3.4.1 Air Flow Around Sails

Figure 23 shows the flow around a single sail without a mast, together with the pressure distribution on the two sides. It can be seen that the negative pressures (upwards, Figure Inset) on the suction side are much larger than the positive ones on the pressure side. Since it is the difference in pressure between the two sides (i.e. the vertical distance between the two curves) that produces a force, it is apparent that the major contribution to the sail force comes from suction on the leeward side of the sail.

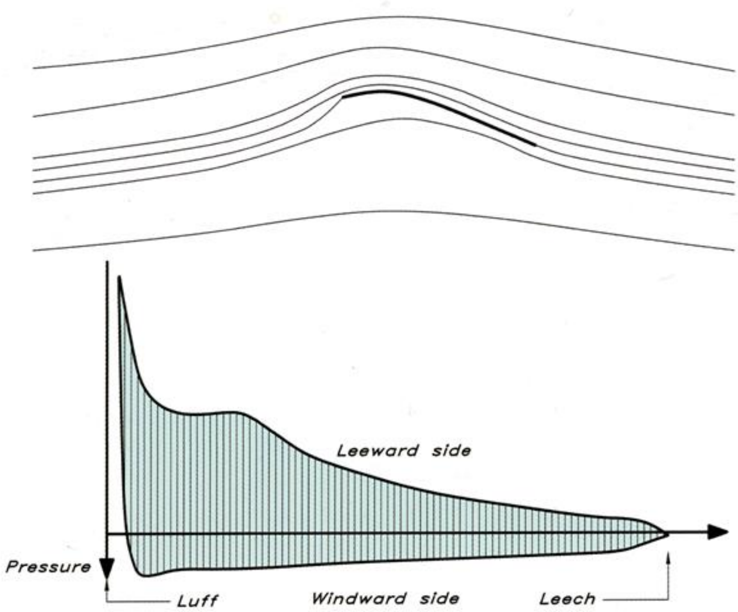


Figure 23. Flow Around a Single Sail[1]

The flow around two sails close together is shown schematically in Figure 24. Streamlines for the two sails in combination are shown as thick lines, while streamlines for the single mainsail are shown as thin lines.

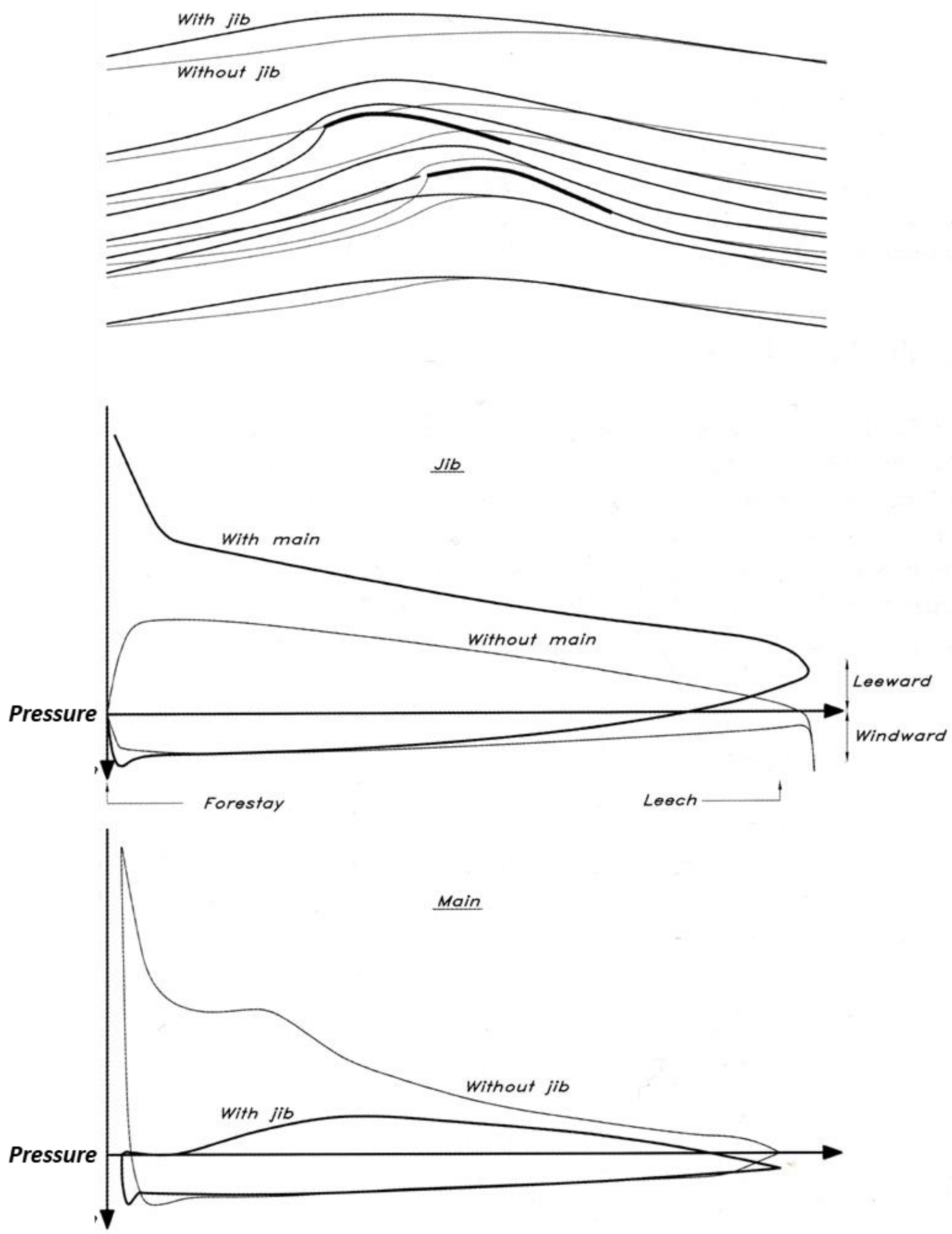


Figure 24. Flow Around a Two Sails close Together[1]

The latter are in principle the same as in the previous figure. Mast disturbances are neglected. There is a very interesting difference in the upstream flow between the two cases. Approaching the sails the thick lines bend much further apart than the thin ones.

This means that the air approaches the mainsail at a smaller angle than in the single sail case, while the opposite is true for the jib. Thus, as compared to the single sail case, the main gets unloaded, while the jib gets more load. This is reflected in the pressure plots in the lower part of the figure. Most of the suction over the forward half of the main has disappeared and the total force, represented by the area between the pressure curves on the two sides, has dropped considerably. On the other hand, the suction on the leeward side of the jib has increased from the leading to the trailing edge and the force is much larger.

This interpretation of the slot effect was presented by the American aerodynamicist A E Gentry in the 1970s, and it represented a radical departure from the common belief that the suction behind the mainsail is increased by the presence of the jib. This opinion stems from an erroneous interpretation of the so-called Venturi effect. When the flow in a tube passes a restriction, i.e. a reduction in the cross-sectional area, the speed increases and the pressure drops. This is an indisputable fact, but the situation is different between the two sails. Unlike the flow in the tube the air approaching the sails has the freedom to avoid the restriction. Rather than going between the sails some of it may bend sidewards and pass outside the jib/mains sail combination, i.e. to leeward of the jib and to windward of the main. As we have already noted, this is exactly what happens. Less air passes near the leeward side of the main if a jib is introduced in front of it.

Gentry's explanation is based on an idealized model of the flow, where viscosity is neglected. This does not alter the main conclusion, but if viscosity is considered, some further conclusions may be drawn. Thus, the boundary layer on the suction side of the mainsail experiences a much smoother pressure distribution than for the single sail. The flow in the boundary layer does not have to make its way against a rapidly increasing pressure, so the risk of separation is very much reduced. This means that the sail can be sheeted at a larger angle to the main flow, at midship or even, in fact, somewhat to windward.

3.4.1.1 Sail Dimensions and Aspect Ratio

At the top of the sail and at the boom the lift force goes to zero and vortices are shed, giving rise to an induced resistance. The larger the height of the sail, the smaller the effect of the vortices. As for the keel, the most important efficiency parameter for the sail is the aspect ratio. We define it here as the luff length (P or I) divided by half the foot length (E or J in the IOR notation). It should be mentioned that in some sailing literature the foot length is not divided by two in the definition, so the aspect ratio is half as large.

Very interesting studies of different planforms have been carried out computationally by Professor J H Milgram at Massachusetts Institute of Technology (MIT). For a masthead rig he systematically varied the aspect ratios of the main and foretriangles by changing the foot lengths. The calculations were for the upwind condition, and the computed force was resolved into its driving component R and side force S. These forces are given in coefficient form: C_R and C_S respectively, in Figures 25 and 26, respectively.

The graphs for the mainsail have been obtained keeping the foretriangle aspect ratio constant (AR = 6) and vice versa. In Figure 25 it can be seen that the driving force increases considerably with increasing AR both for the main and the fore triangle. The side forces of Figure 26 are relatively independent of the aspect ratio (note the large vertical scale!).

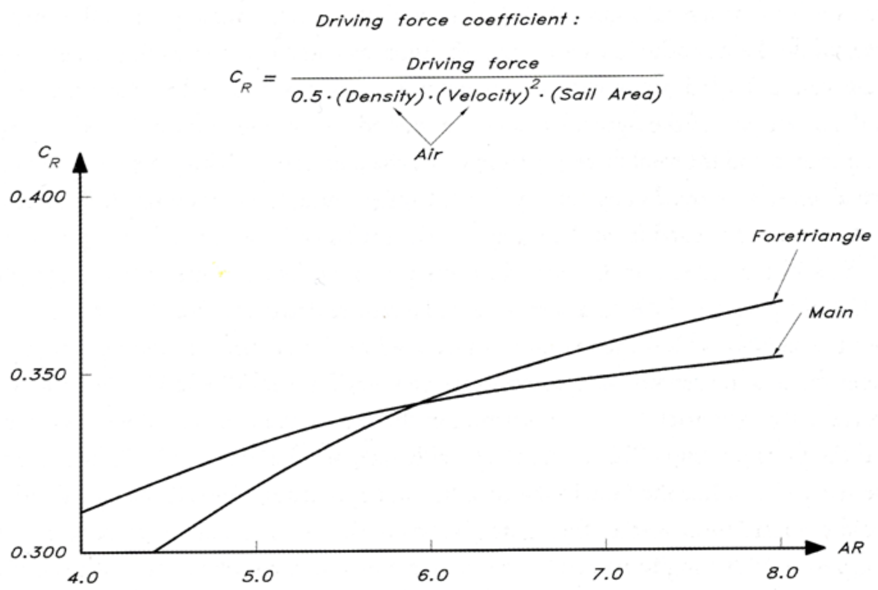


Figure 25. Computed Influence of Sail Aspect Ratio on Driving Force

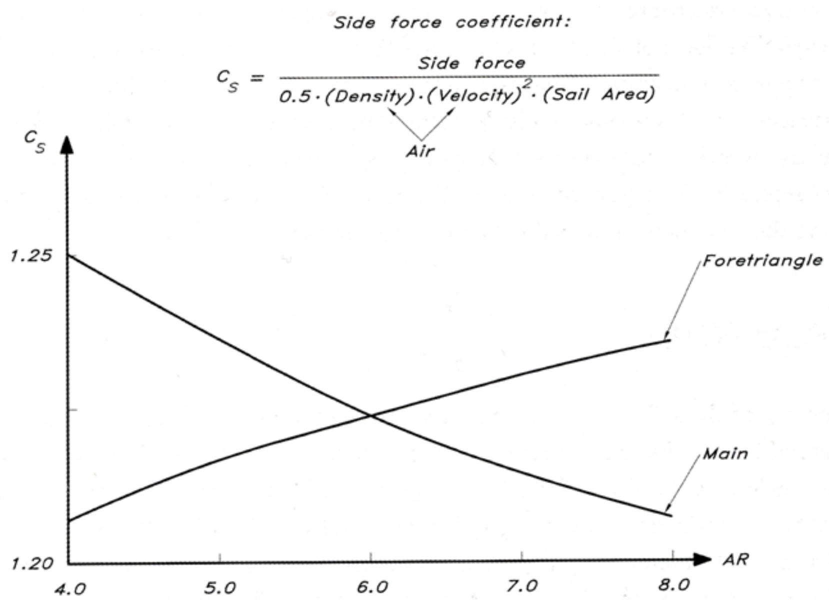


Figure 26. Computed Influence of Sail Aspect Ratio on Side Force

In another interesting series of calculations the point of attachment of the forestay to the mast is varied. Four rigs were computed, where the attachment point was at ¾ 7/8, 15/16 and 1/1 of the full mast height, respectively. The results are shown in Figure 27. There is a significant gain in driving force when the foretriangle height is increased, while the side force is almost constant.

The results of the figures seem to indicate clearly that the aspect ratio of the sails should be as large as possible. This is not true under all circumstances, however. Considerations which have to be made in a real case include:

- Points of sailing other than upwind
- The effect of the mast on the mainsail flow

- The possibilities of bending the mast to trim the main
- The increase in heeling moment with aspect ratio

The latter disadvantage is fairly obvious and its importance depends on the wind strength and the stability of the boat.

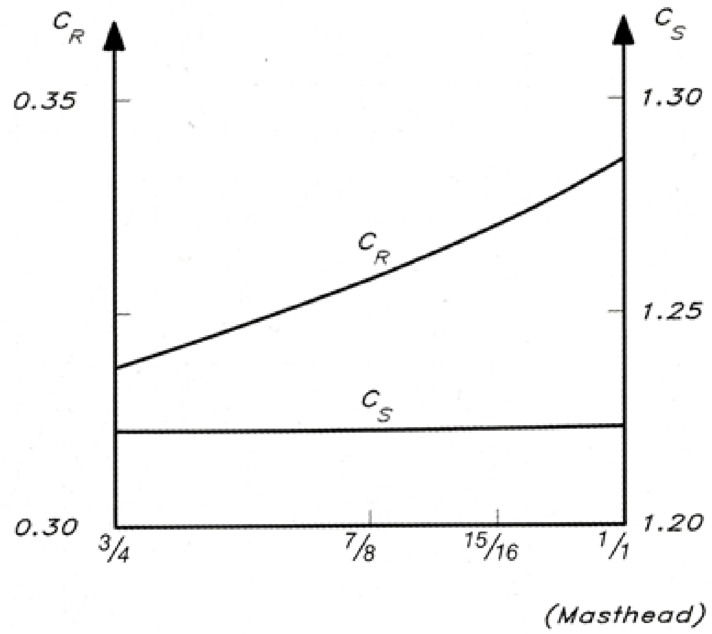


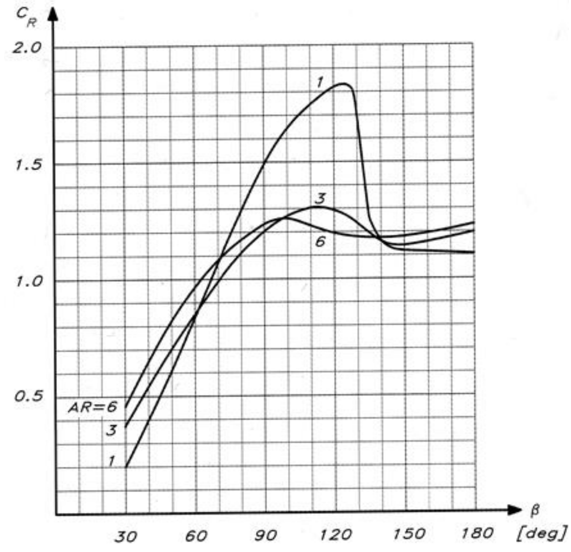
Figure 27. Computed Influence of Foretriangle Height on Driving and Side Force

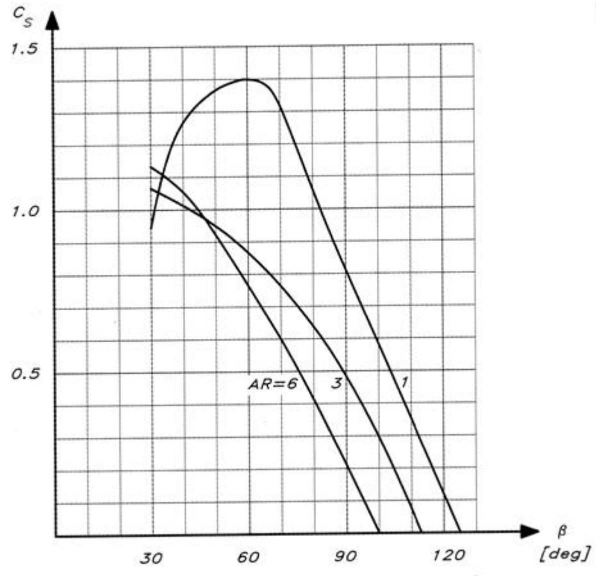
C A Marchaj has reported wind-tunnel tests for sails of varying aspect ratios. All points of sailing were considered. Figure 28-a shows the driving force and Figure 28-b the side force for three aspect ratios: 6, 3 and 1. The latter is an almost square gaff sail. It can be seen that for small apparent wind angles, i.e. upwind, Milgram's conclusions are confirmed. Around 30° the high aspect ratio sail develops more than twice the driving force of the square sail. However, at large wind angles the situation is different. Around 120° the square sail is superior, and develops 50% more thrust than the narrow sail. At 70° the thrusts are almost equal. The side force of Figure 28-b increases somewhat with aspect ratio at 30°, but the opposite is true above 45°. The general conclusion is that the positive effect of a high aspect ratio is reduced if all points of sailing are of interest.

The mast reduces the positive effect of a high aspect ratio mainsail even further. For a given sail area, the higher the aspect ratio the thicker the mast required, and the smaller the average chord length of the mainsail. Both effects tend to increase the proportion of the sail, which is ineffective due to the mast disturbance.

Marchaj found in wind-tunnel measurements that a 6.0 aspect ratio sail was less effective, even upwind, than a 4.6 aspect ratio sail, and this was attributed to the mast disturbance.

In these tests the mast diameter was 8% of the average chord length of the high aspect ratio sail. This seems to be a bit more than is used today, so the effect was probably somewhat exaggerated, but it shows that there is a limit for the positive effect of the aspect ratio of the mainsail.





(a) (b)

Figure 28. Measured Influence of Aspect Ratio on (a) Driving Force and (b) Side Force[1]

Perhaps the most important reason why modern yachts do not feature masthead foretriangles is the need for trimming the camber of the main. As will be seen below, there is a need for reducing the camber when the wind increases and that is most efficiently done by bending the mast. For a fractional rig, where the forestay is attached at a certain distance from the masthead, this can be easily achieved by tightening the backstay. For a masthead rig the bending has to be achieved in some other way, either through the lower shrouds or through a baby stay fitted between the fore deck and a point on the mast considerably below the head. Either way, the trimming possibilities are limited, not least because the mast is normally not tapered.

A high aspect ratio is not the only way to reduce the induced resistance of the sails. A very effective way is to try to seal the gap between the sail and the deck of the yacht. In Figure 29 some results of wind-tunnel measurements by Bergstrom and Ranzen at the Royal Institute of Technology in Stockholm are shown. The change in lift and drag coefficients of the sails is given as a function of the gap size in per cent of the mast height. It may be seen that the lift is decreased and the drag increased by an increasing gap. For instance, a gap of 0.1 m and a mast height of 10 m gives a drag increase of 7% and a lift decrease of 4% compared to the fully sealed case. Of course, it is impossible to seal the gap between the boom and the hull fully, so the figures should be relevant for the foresail only. Note that the drag and lift are the force components parallel to, and at right angles to, the apparent wind. They can easily be converted into the driving force parallel to, and the side force at right angles to, the direction of motion of the yacht, see Figure 30.

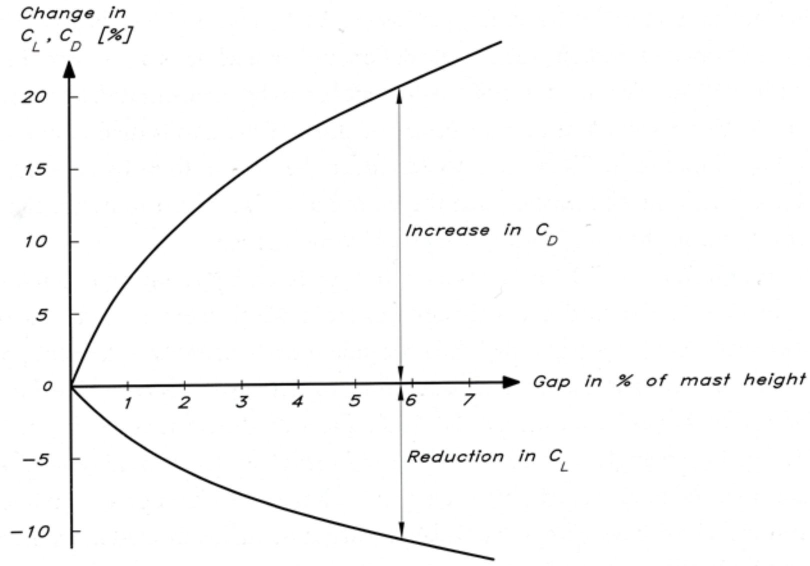


Figure 29. Effect of Gap Between Sail and Deck
[C_L – Lift Coefficient, C_D – Drag Coefficient]

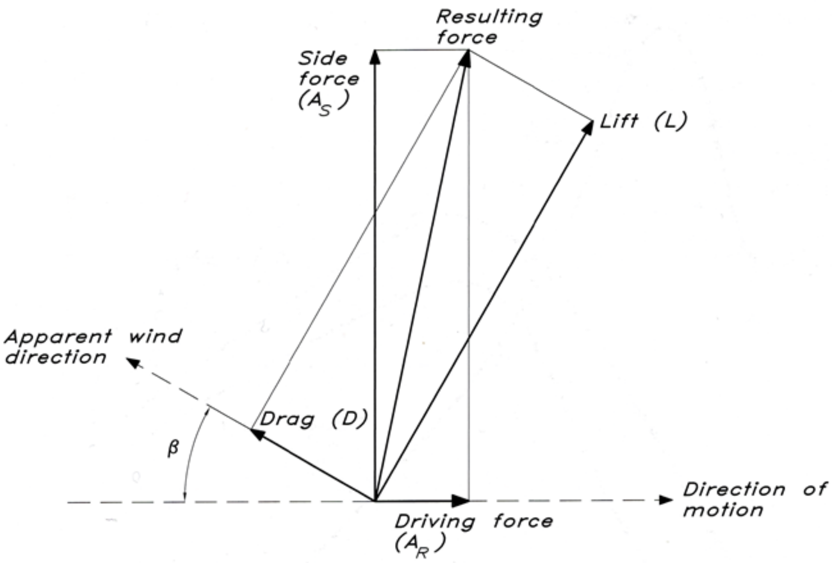


Figure 30. Relation between Aerodynamic Force Components[1]

3.5 Mast Interference

The flow around a sail behind a mast in upwind sailing is shown schematically in Figure 31. As can be seen in the figure the flow is not attached to the sail all the way Three zones of separation can often be distinguished. Two are immediately behind the mast, to windward and leeward, respectively, while the third zone is on the aft part of the leeward side. The separation behind the mast can be minimized by proper shaping of the mast section and by introducing turbulence stimulators. The aft separation zone depends, in fact, to some extent on the forward one, since a massive separation forward causes a thick boundary layer to develop in the attached part of the flow. This layer separates more easily than a thin one. To a large extent the aft separation depends also on the loading of the sail. By proper sheeting and a good mast design this zone can be very small or even eliminated.

There are two reasons why separation has to be avoided. First, the pressure distribution on the sail is disturbed, essentially in such a way that pressure differences between the two sides of the sail are reduced. This causes a reduction in lift and driving force. Secondly, separation itself causes a drag increase. Experiments at Southampton University with a mast/sail combination indicated large effects of mast disturbance. Thus, when a circular mast with a diameter of 7.5% of the sail chord was put in front of the sail the driving force upwind was reduced by about 20%, as compared to the case without a mast. A thicker mast of 12.5% was also tested and the driving force was almost halved. It was, however, possible to regain almost half of the loss by turning the mast in such a way that the leeward side of the mast/sail junction became smooth.

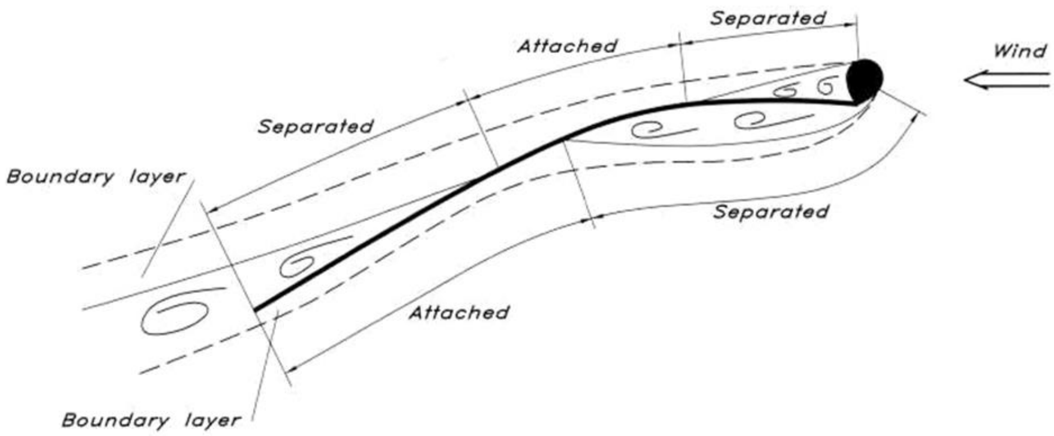


Figure 31. Flow Around a Mast/Sail Combination[1]

A well-known but seemingly paradoxical phenomenon in fluid dynamics is the reduction in drag of bluff bodies when their surface is changed from smooth to rough. The reason for this behaviour is that the viscous resistance of the hull, which is a slender body, is essentially due to direct friction (see Figure 32), while the resistance of a bluff body to a large extent is due to pressure losses in the wake (viscous pressure resistance).

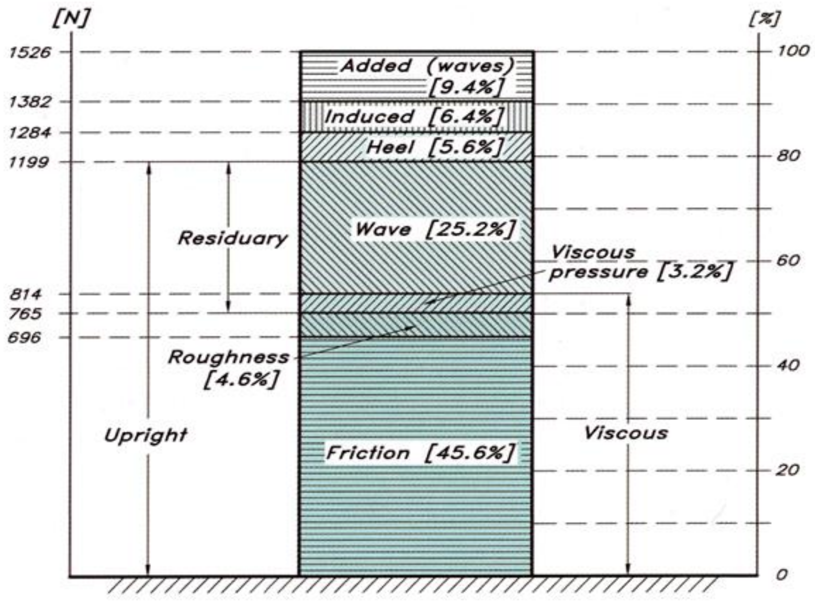


Figure 32. Components of Resistance for a Boat Hull[1]

Considering Figure 31, showing the different regions in the flow around the hull, it can be seen that the boundary layer is laminar at the bow, but undergoes transition relatively quickly. Thereafter it is turbulent, and may, in rare cases, separate from the hull at a point near the stern. The same flow regions may exist around the cylinder, but not always. If the Reynolds number (i.e. the product of diameter and velocity divided by viscosity) is small, the boundary layer never gets turbulent, but separates directly in the laminar part. This happens, in fact, before the maximum thickness (as shown in Figure 33). The wake then becomes quite wide and the drag is high. On the other hand, if the boundary layer gets turbulent before separation, the latter is delayed to a point well aft of the maximum thickness (Figure 33). The wake is then narrower and the drag smaller. The reason why turbulence delays separation is that it has a stirring effect on the flow. High speed fluid from outside the boundary layer is convected inwards and energizes the flow that is about to stop moving along the surface.

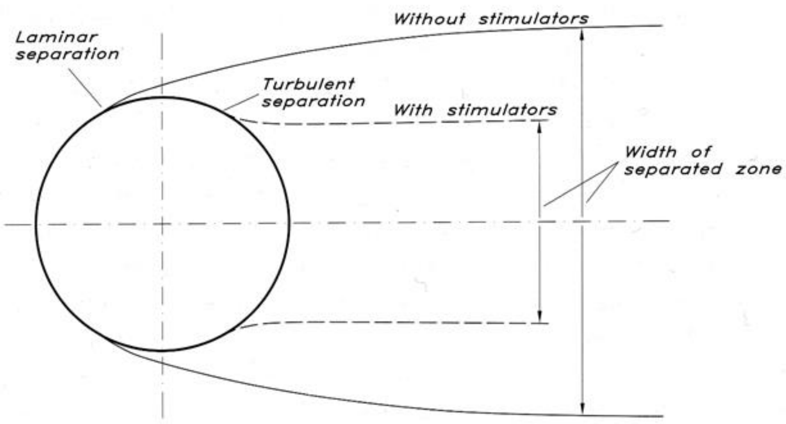


Figure 33. Effect of Stimulators on the Flow Around a Circular Cylinder[1]

With this explanation in mind, it is not difficult to understand why a rough cylinder may have a smaller resistance than a smooth one. If the Reynolds number is in the subcritical region, and laminar separation occurs, introducing roughness causes the boundary layer to turn turbulent earlier, maybe before separation. This is then delayed, as explained above, and the drag gets smaller. Now a mast is normally in the subcritical region and has a high drag, but it is close enough to the low drag region to make the roughness effect work. Figure 34 shows the drag coefficient of circular cylinders of around 0.1 m in diameter with different roughness heights. The height is given as a percentage of the diameter. It may be seen that at 11 m/s the drag is reduced by 50% if the roughness height is 0.5% of the diameter. The narrower wake also disturbs the sail much less, so there is a double gain. Unfortunately, the optimum roughness height varies with the wind velocity, but a height of 1% covers most of the interesting velocities quite well. Note that it is the apparent wind that is of interest.

Figure 35 shows results from measurements made on a plate sail with different masts, with and without roughness, was tested in a wind tunnel, and the position of the rear separation point was measured. The mast sections were the most common ones: ellipse, pear and delta. Practically no difference could be detected in the separation location for the three smooth masts, while the positive effect of the roughness was largest for the ellipse and pear masts.

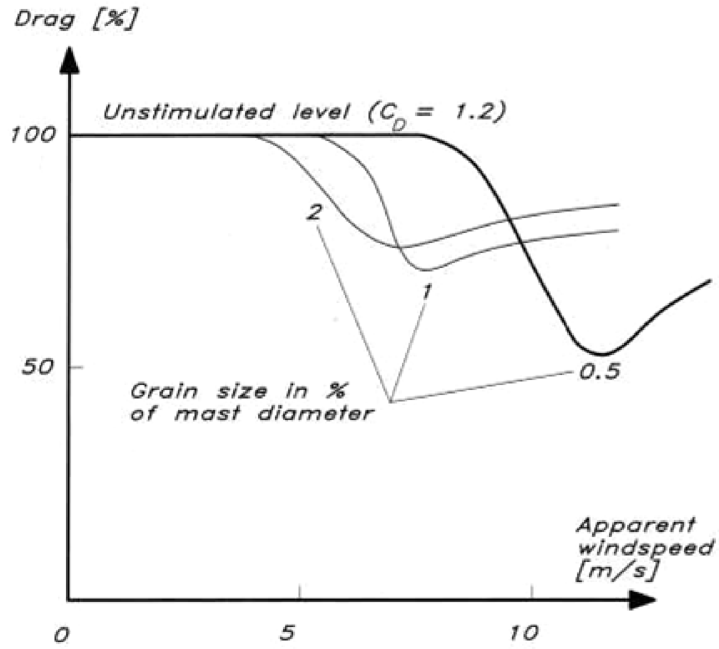


Figure 34. Drag of Circular Cylinders with Roughness

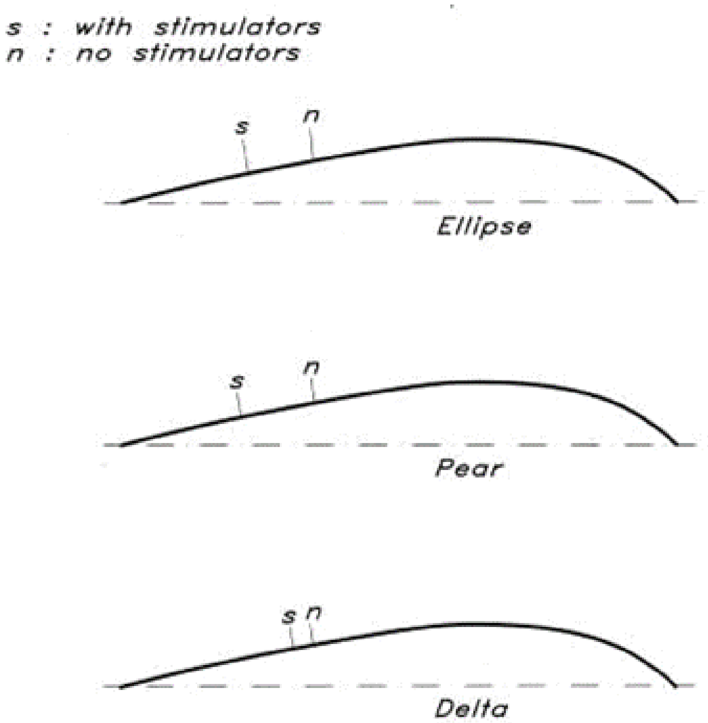


Figure 35. Position of Trailing Edge Separation on a Sail with Three Different Masts

It can be seen in the figure that a considerable increase in the effective length of the sail is obtained in all cases. The roughness in this test was 1% of the mast diameter and was created by sand grains of uniform size glued to the front half of the mast. Later tests have indicated that much less disturbance is required. In fact, a small riblet of the same height put at the leading edge of the mast produced the same effect. Note that when the sail is working, the stagnation point on the mast is always on the windward side, so the flow entering the leeward side of the sail has to pass the riblet, even if it is in the symmetry plane of the mast. There is no effect, however, on the flow on the windward side, so a better solution might be to put one riblet on each side of the mast, at 45°, say, on each side of the symmetry plane.

3.5.1 Streamlining

The windage of the mast and rig is considerable and all means of streamlining different components, such as spreaders and shrouds, are valuable. A striking figure is that of Figure 36, which shows two 2-dimensional bodies with the same drag. The upper one is a streamlined foil, where most of the drag comes from friction, and the lower one is a round bar, for which pressure drag dominates. The drag coefficient for the bar is around 1.0, while it is only about 0.03 for the foil, based on the front area. The diameter of the bar thus has to be more than 30 times smaller than the foil thickness for the same drag.

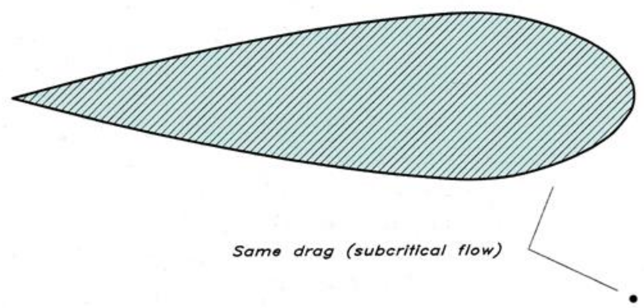
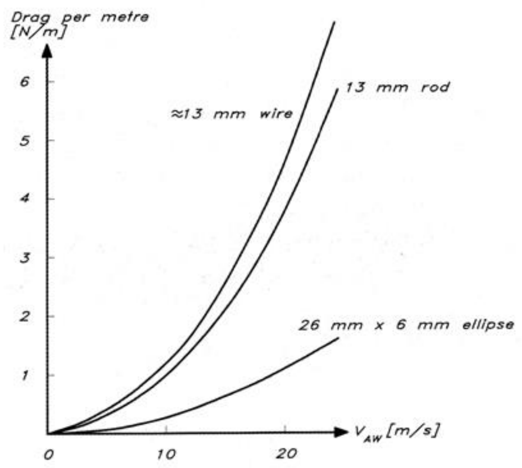


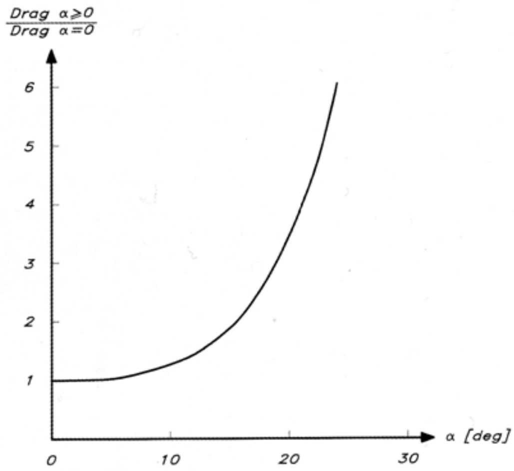
Figure 36.. Effect of Streamlining[1]

In Figure 37a-b results are presented from wind-tunnel tests at the Davidson Laboratory in New York. Drag measurements were made for three different types of shroud: a wire, a circular rod and an elliptic rod. It may be seen that the wire has the highest drag, somewhat higher than that of the rod. At first sight this might seem contrary to the findings above (that a rough mast has a smaller drag than a smooth one), but the difference is that the wire has such a small Reynolds number (due to the small diameter) that the turbulent boundary layer never appears, even if the surface is rough.

The ellipse is outstanding with a drag that is only VA of that of the wire. This is so in spite of the fact that the ellipse was tested at an angle of attack of 19°. Small as this may seem, it is probably realistic upwind, considering the fact that the sails guide the flow more in the longitudinal direction than the apparent wind. It is quite important that the angle of attack does not get too large for the ellipse, as can be seen in Figure 37b. This diagram shows the relative increase in resistance when the angle increases from zero. Up to 10° the additional drag is small, but at 20° the drag is three times larger than the minimum. Thereafter, the increase is still faster.



(a)



(b)

Figure 37a-b. Drag of Shrouds and Stays: (a) Wire Rod and Ellipse, (b) Importance of Angle of Attack

4. Cathodic Protection

4.1 Sacrificial Anodes

The sacrificial anode is simply bolted to the hull and in the case of a non-metallic hull wired up to the item to be protected, see Figure 38.

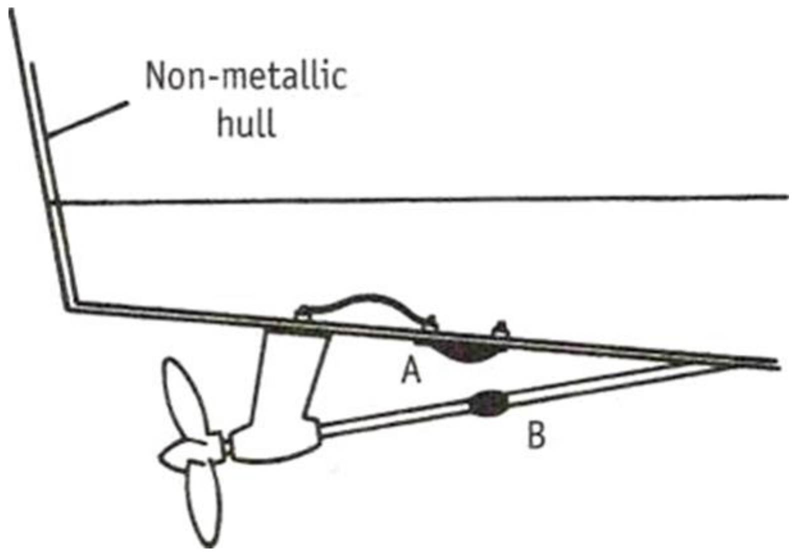


Figure 38. A simple example of sacrificial protection[3] [Anode A is wired to the shaft bracket while B is bolted directly onto the shaft]

It is important to obtain a resistance-free electrical circuit and consequently heavy gauge wire should be used for such coupling; the connections should be well made and kept on the inside of the hull and clear of bilge water. The current flowing through the circuit is quite small, but any resistance reduces the voltage difference between the anode and the cathode thus directly reducing the protection. An internal wire is far preferable to an external metal strip, which inevitably will suffer galvanic corrosion itself at one of the junctions and thus create a resistance to electrical current.

On a metallic hull, electrical continuity is ensured simply by bolting the anode direct to the plating with welded-on studs.

There are three types of anodes: zinc, magnesium and aluminium. These base metals will give protection to all other metals higher in the galvanic series, so virtually all the common metals used in boats can be protected. The protection so achieved may not be complete, or it may be excessive, depending on the voltage difference generated and the current flowing into the protected area per square metre; this depends on the exposed area of the anode and its efficiency. For each particular boat the required number and size of anodes can be calculated using factors determined from previous installations. The aim is to give the required degree of protection with a reasonable life from the anodes.

The accompanying figures are based on literature from MG Duff for small. Note that wood and fibreglass hulls are treated separately from steel hulls. On wood and GRP hulls mild steel items must have a separate anode to the one protecting the more noble items (brass propeller, stainless shaft, etc). The two systems must be electrically separate; there must be no internal electrical connection from say a steel rudder to the engine. Anode size is related to the area to be protected; propeller diameter gives a rough idea of the size of this area, hence the table of propeller diameters.

4.1.1 Protection for Class 1 to 4 Vessels

On steel boats stud-fixed anodes are recommended rather than the welded-on variety since they are easier to replace. Small craft only require a small number of anodes; those less than about 25 ft in length require only two, one on each side.

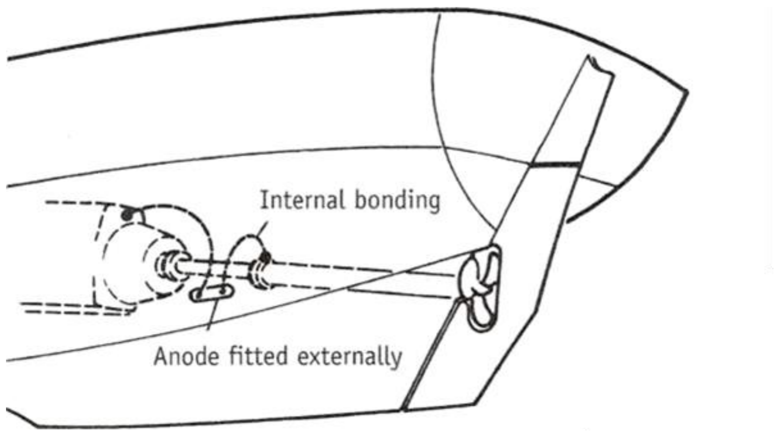


Figure 39. Anode Location for a Class 1 Vessel[3]

Class 1 vessels comprise single-screw sailing yachts, motor cruisers, fishing vessels, launches, etc. with only a very small or negligible length of propeller shaft exposed to seawater; they are fitted with mild steel rudders, or wood or GRP rudders with mild steel hangings.

As a general rule for Class 1 vessels, one anode will be required for propeller and propeller shaft protection, plus two separate anodes for rudder protection. The main anode should be located on the hull bottom below the turn of the bilge, its fore-and-aft position roughly equidistant between the engine gearbox and the inboard end of the stern tube. The additional anodes are fitted directly to the rudder.

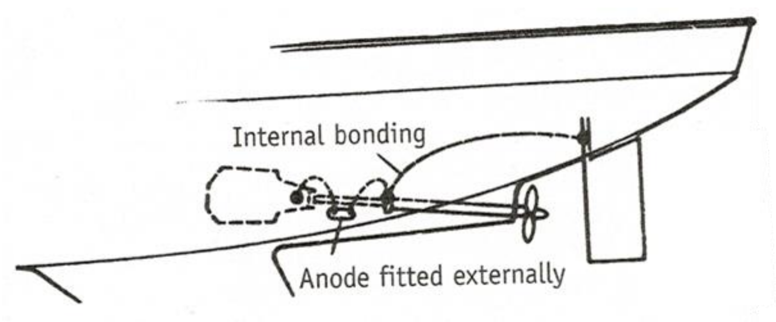


Figure 40. Anode Locations for a Class 3 Vessel[3]

As a general rule, one anode can provide protection for the propeller, propeller shaft and rudder, and should be located as for Class 1 vessels

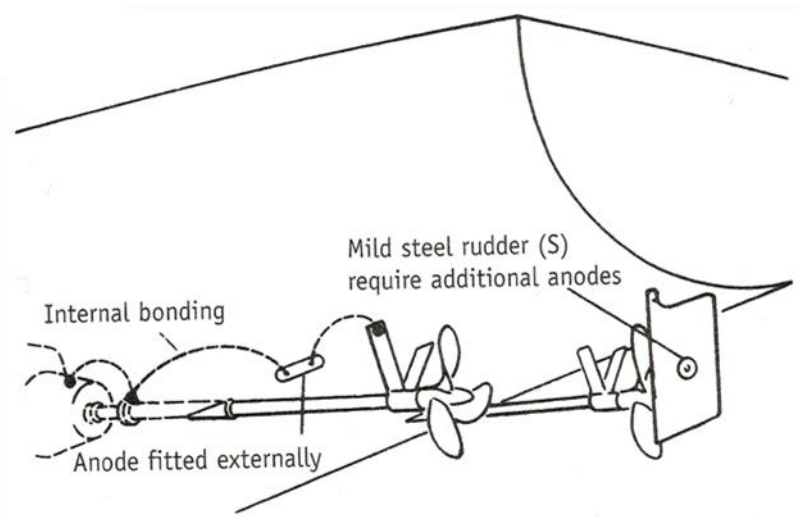


Figure 41. Anode Locations for a Class 2 Vessel[3]

Generally, one anode is required for each propeller to give it and the shaft protection, and also two separate anodes for each rudder. Locate main anode(s) in way of exposed shaft(s). The main anode(s) can also provide protection for the bronze brackets carrying the propeller shaft. The additional anodes are fitted directly to the rudders.

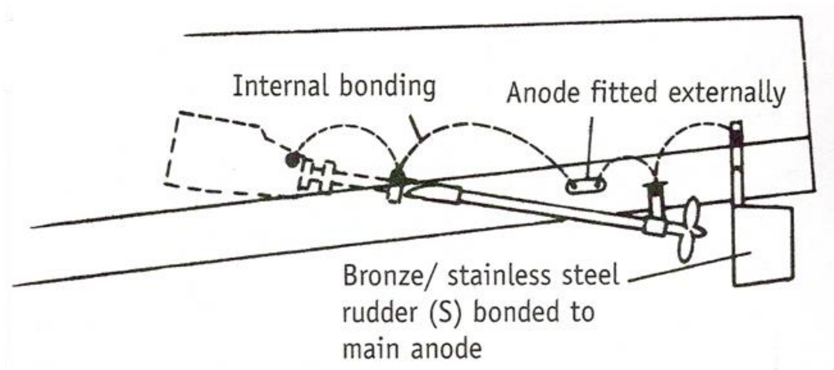


Figure 42. Anode Locations for a Class 4 Vessel[3]

Note: In all classes of vessels the positioning of anodes is not critical. The main points to remember are:

- Can the anodes 'see' the parts to be protected?

- Are the fixing studs above the bilges?
- Does the anode location ensure the minimum run of bonding cable to the parts to be protected?
- Is there reasonable internal access to the studs?

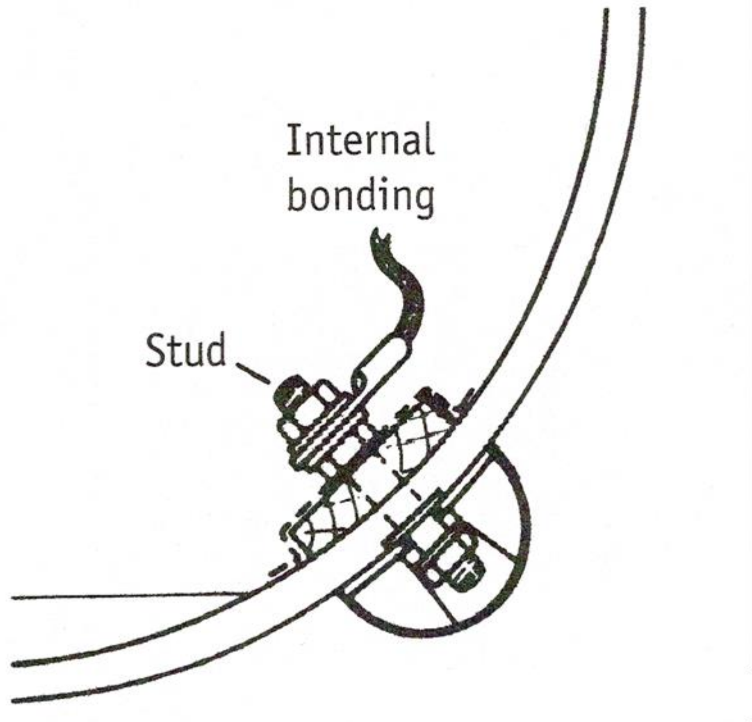


Figure 43. External Anode Fitting[3]

4.2 GRP and Wooden Hulls

Ideally the metallic items below water should be made of one of the more seawater resistant alloys like silicon bronze, copper, gunmetal, copper-nickel, nickel-aluminium-bronze or one of the super-materials like titanium and the nickel-base alloys. If any one of these is electrically isolated and not connected, for instance via metal piping, to the engine (thus bringing the possibility of corrosion from stray currents) there will be no need for cathodic protection. Isolated from any possible galvanic action, they will merely corrode at a very slow rate.

But all too often dissimilar metals are in contact or the metals themselves are not seawater resistant: steel for instance, or stainless steel, manganese bronze or brass. In any of these situations cathodic protection can be used to suppress the electrical currents generated and hence reduce or stop corrosion.

A steel rudder is protected by an anode bolted directly to it. So is a cast iron keel, but oddly enough anodes bolted here are rarely seen despite the saving in maintenance they would bring. In the case of a manganese bronze or brass propeller or shaft, dezincification can be reduced or eliminated by an anode bolted to the hull, but electrical contact has to be maintained to the rotating shaft. Sliprings on the shaft are one possibility, but far from ideal because they will need frequent cleaning. There may be electrical continuity from propeller to engine, in which case the engine can be grounded to the anode, but often a rubber flexible shaft coupling is employed which acts as an insulator. The propeller shaft bearings may be rubber or bronze: obviously rubber will act as an insulator and continuity across a grease film in a bronze bearing is not reliable enough. The way out of this situation is to fit a collar type of anode around the shaft itself or to the propeller boss.

The same argument applies if the shaft or propeller are of stainless steel. Stainless tends to pit underwater in crevices and under barnacles; on shafts, pitting often occurs in way of a rubber bearing or in the thread or keyway. Cathodic protection may reduce the possibility of pitting. It is certainly worth fitting a zinc anode, but the cathodic protection given may not reliably extend to shielded areas - which are just those where pitting may occur.

Seacocks should not be made of brass or manganese bronze, silicon bronze or gunmetal, are better options. So often, though, some internal parts of the gate valve type of seacocks are made of a brass or manganese bronze and hence tend to dezincify. It is doubtful if cathodic protection would ‘reach' into the seacock, especially when it was closed.

With ferro-cement hulls it is essential that galvanic cells involving the steel reinforcement are avoided. All underwater fittings except steel for galvanized ones should be electrically isolated from the reinforcement. This is especially the case with any fittings of copper alloys, e.g. seacocks and stern gear. It is another reason for coating the hull with a very waterproof paint scheme such as three coats of epoxide composition.

4.3 Outboards and Sterndrives

Invariably outboards, sterndrives and sail drives are made of aluminium castings for lightness and held together with stainless steel fastenings. They usually have built-in aluminium anodes in the form of a ring in front of the propeller or as part of the propeller cone and also in a form of a block bolted to the underside of the transom plate. There may also be an anode on the underside of the ‘cavitation plate at its after end. While the grade of aluminium alloy used for sterndrives and outboards is very corrosion resistant in isolation, it is so low down in the Galvanic Series that almost all other common boat metals will attack it galvanically if there is an electrical path. The sacrificial anodes incorporated do guard against this to some extent but it is very wise to ensure that any large items of bronze for example, are physically sited several metres away and have no electrical connection with the sterndrive. For example, a bronze ground plate could inadvertently be electrically coupled via the bonding wire to the sterndrive or a control cable may be a path. This should be checked with a multimeter.

Normally sterndrives and outboards have integral water pick-ups and exhausts so there is no need for hull seacocks or hull exhaust outlets. Again, the standard propeller material is aluminium.

Problems can arise though through a variety of factors:

- The degree of immersion of the drive when the boat is moored
- Substitution of the aluminium prop(s) with high performance ones made of stainless steel
- After-market stainless steel propeller guards.
- A loss of continuity between the leg and the transom plate (the insignificant looking little braid wire may be broken).
- The gaiter clips loosen through pitting corrosion.

- The stainless fittings on the unit may cause severe local corrosion of the aluminium casting
- A bronze rope cutter is fitted (usually to a sail drive)
- A bronze folding prop is fitted to a sail drive
- The manual that comes with the unit gives little advice about corrosion
- Lack of regular (i.e., monthly) visual inspection

Sterndrives are very popular on GRP sports boats but the degree of immersion depends on the boat design. Some units may be completely immersed when the boat is on its mooring; on others the waterline may be close to the gaiter, leaving the top part clear. Most owners leave the leg raised, especially on a drying mooring. These factors dictate (a) the surface area of aluminium to be protected by the anodes, and (b) whether the anodes are actually immersed or not. For example, if the anode on the underside of the 'cavitation plate is actually out of the water when the leg is raised then it cannot do its job. This problem can occur on high-powered outboard RIBs (rigid inflatable boats), where some models, by virtue of their deep vee, low freeboard designs, prevent the outboard motors from tilting enough to raise the lower unit clear of the water. The gearbox 'nose is left immersed, with the anode in fresh air, leading to rapid deterioration of the gearbox casing and resultant seawater ingress.

The size of anodes commonly fitted is usually on the small side and gives no margin for poor continuity or loss of anode material.

Similarly, any change to the metals present will overload the anodes - fitting a stainless or bronze prop or a rope cutter. In these circumstances extra cathodic protection should be fitted, for instance in the form of a large extra anode on the underside of the cavitation plate (if immersed!) or a transom anode wired into the transom plate.

Many propellers are rubber-bushed to protect the gears and drive from excessive torque if the propeller hits a hard object. This should mean that the propeller is electrically isolated from the

4.4 Potential Issues with SACP

As with any galvanic cell the area of water around the cathode (the protected item) becomes alkaline: the greater the protective potential the greater the alkalinity. Traditional types of paint - oil or lead-based ones for example - are softened and blistered by alkali. Hydrogen bubbles may also be formed under the paint surface depending on the porosity of the paint, thus lifting it off. The chances of either of these things happening is greater the higher the potential applied, so zinc sacrificial anodes are 'safest' while magnesium anodes or an impressed current system are worst. If a steel hull is overprotected or has a porous oil-based paint scheme the paint may 'saponify' as it is called, but the bare steel thus exposed will be protected against rusting. The answer is to make sure that overprotection is not being applied and then to use a more resistant paint. An aluminium-bitumen or chlorinated rubber paint is resistant, or even better are vinyl or coal tar epoxy or epoxide.

The alkaline conditions around protected aluminium can cause its corrosion rather than its protection, so an aluminium hull is better cathodically protected by zinc anodes rather than magnesium. On the other hand, since marine grade aluminium in isolation is corrosion resistant there is little point in cathodically protecting an aluminium hull unless there are also more noble metals used underwater (a bronze propeller for instance). The correct protection for aluminium in seawater is -0.985 volts relative to a silver/silver chloride electrode.

The hydrogen given off may cause 'hydrogen embrittlement' of high strength steels including some stainless steels (400 series). This has happened to bolts on sterndrives fitted with an impressed current system.

Turning now to wooden boats, the production of alkalinity around protected metals can cause decay of the adjacent timber. This effect is the same as the nail-sickness mentioned earlier and is accentuated by overprotection, a porous paint scheme and time (five years plus). The timber becomes a soft and fibrous mass and one of the indications that the action is taking place is the presence of white crystal deposits on the inside of the hull around the protected item. Quite apart from cathodic protection, electrolytic action from strong currents may also cause this type of degradation.

In a sense one chooses between installing low quality, low-cost underwater fittings and then protecting them by cathodic protection with the risk of timber degradation, or alternatively installing fittings of a corrosion resistant metal or alloy and ensuring their electrical isolation. The latter method must surely be the best policy in the long run.

4.5 Effect of Stray Current

Finally, it is important to be aware of what may happen when a metal hulled boat is moored adjacent to another metallic mass, for instance steel harbour piling or another metal hull alongside a steel marina pontoon, see Figure 44. Trouble is avoided if there is no electrical link; plastic fenders and synthetic rope are good enough insulators, but if there is a link through an aluminium gangway, for instance wire rope corrosion issues can arise. In these circumstances a cathodic protection system will then suddenly find it has a great deal more area to protect - in say a steel hull/steel pontoon combination. The protection from zinc anodes will be shared and the protection on one's own boat will drop; while an impressed current system will try to compensate - probably unsuccessfully - causing very high potentials local to the anode, and blistering of the paint on the hull.

It also should be mentioned that a simple galvanic cell can be created by an aluminium hull moored to a steel one, in electrical contact.

Impressed current unit or a steel hull to a copper-sheathed wooden one again in electrical contact. In the first case the aluminium hull will suffer, in the second the steel. The rate of corrosion will depend very much on the resistance of the electrical contact and on the porosity of the paint film, and whether there are any areas of bare metal. Certainly an owner of a metal boat should bear this sort of thing in mind when mooring her in a permanent berth.

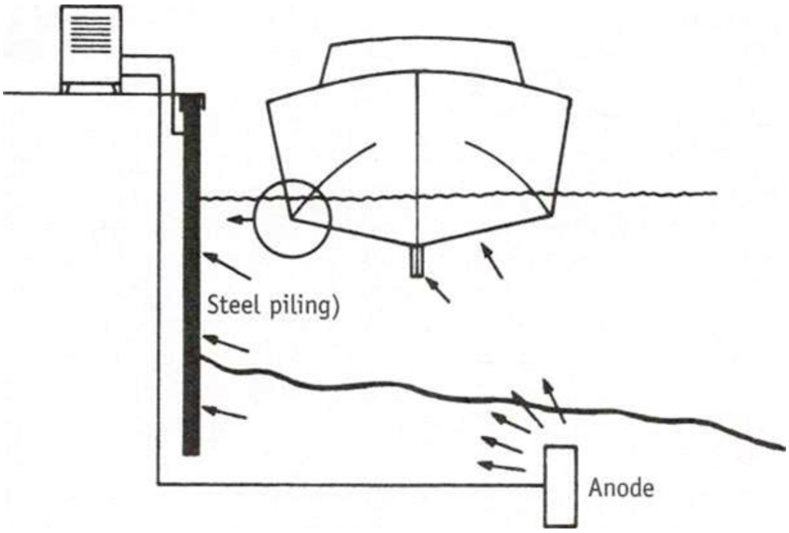


Figure 44. A Potential Source of Stray Current – Harbour Piling Protected with an ICCP System[3]

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S

Part 2: Small craft structure, strength, stability and corrosion control strategies

Section a **Yacht Types, Terminology and Structural Aspects**

Section b **Yacht/Boat Stability and Aspects of Aerodynamics and Hydrodynamics**

Section c **Corrosion Control Strategies**

Module 3: Small Craft Structure Strength, stability… etc.

Professional Qualification
in Marine Corrosion

Presented by **Mike Lewus**

Module 3
(section a)

Yacht Types, Terminology, and Structural Aspects

Module 3 (section a)

Summary

- Sailing Vessels
  - Brief introduction: history of boat building
  - Scantlings and standards
- Yacht Types
  - Sloop, Cutter, Ketch etc.
  - Yacht terminology
  - Lines drawing
- Hull Appendages
  - Keel types
  - Keel terminology and function
  - Rudder terminology and function
- Forces on a Yacht
  - Rig Loads
  - Wave resistive components

Module 3 (section a)

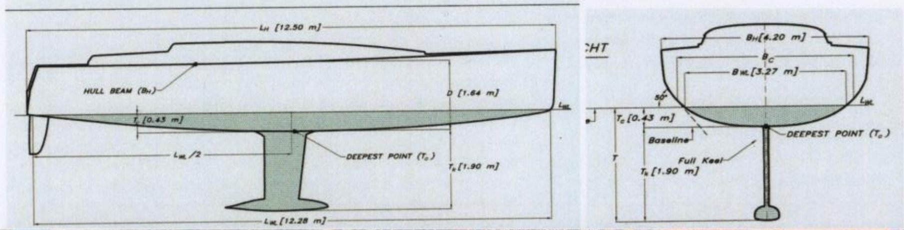
Brief History

- Small vessel strength and structure
  - Prior to the last 150 years construction of sea going vessels (usually in wood) was based on a cut-and-try, experiment-and-discard, test-and-retest approach
  - This taught us how to build vessels that generally held together most of the time
  - In the last century and a half, building vessels that are strong enough as needed have been formalized
  - The most reliable and practical rules-of-thumb are formalized *scantling rules* based on engineering analysis cross-checked against a database of successful vessels
  - Such rules define the construction materials and dimensions based on a few easily obtainable numbers such as length, overall displacement and design speed

Module 3 (section a)

Definition of Scantlings and ISO 12215: 2020

- In contrast to the historically evolved/formulated scantling rules by LR, ABS and other regulatory organisations for ships, a harmonized European BSEN ISO 12215 standard has been developed for vessels < 24m in length
- BSEN ISO 12215 parts 1 to 10 contains guidelines on all aspects of scantlings including nature of acceptable materials, strength requirements, monohull design pressures, rig loads and attachments etc. etc.



Module 3 (section a)

Scantling Rules and ISO 12215: 2020

- BSEN ISO 12215/1 to /10: 2020
  - Part 1: Small craft. Hull construction and scantlings. Materials. Thermosetting resins, glass-fibre reinforcement, reference laminate
  - Part 2: Small craft. Hull construction and scantlings. Materials. Core materials for sandwich construction, embedded materials
  - Part 3: Small craft. Hull construction and scantlings. Materials. Steel, aluminium alloys, wood, other materials
  - Part 4: Small craft. Hull construction and scantlings. Workshop and manufacturing
  - Part 5: Small craft. Hull construction and scantlings. Design pressures for monohulls, design

Module 3 (section a)

Scantling Rules and ISO 12215: 2020

- BSEN ISO 12215/1 to /10: 2020
  - Part 6: Small craft. Hull construction and scantlings. Structural arrangements and details
  - Part 7: Small craft. Hull construction and scantlings. Determination of loads for multihulls and of their local scantlings using ISO 12215-5
  - Part 8: Small craft. Hull construction and scantlings. Rudders
  - Part 9: Small craft. Hull construction and scantlings. Sailing craft appendages
  - Part 10: Small craft. Hull construction and scantlings. Rig loads and rig attachment in sailing craft

Module 3 (section a)

Yacht Types: Sloop

- Sloop: one mast, two sails
  - triangular mainsail (sometimes called a Bermuda sail)
  - a foresail (jib)
  - fore-and-aft rigged
  - medium-sized (12-50ft)
- Any sailboat with one mast and two sails could still be a sloop, even if the sails are another shape or rigged in another way

Module 3 (section a)

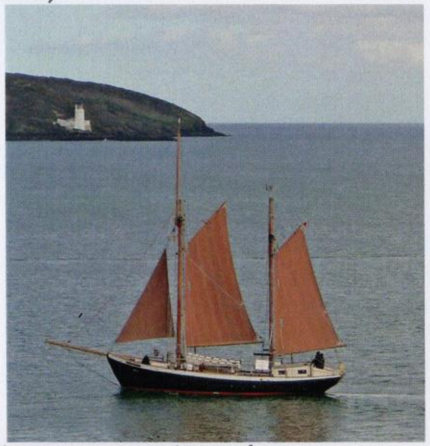
Yacht Types: Cutter

- Cutter: One mast but often three or more sails.
  Most cutters are 'Bermuda rigged' – they resemble sloops
  - Faster than sloops
  - Cutters have more sail area, which makes them faster, but are also harder to sail single-handed. More strain on the mast and rigging
  - A bowsprit is common to help support a greater fore sail area
  - Hull deep and narrow - vertical, raking transom

Module 3 (section a)

Yacht Types: Ketch

- Ketch: Gaff rigged (4 cornered sails)
  - two masts
  - medium-sized (30 ft and up)
  - smaller mast toward stern
  - taller mast forward
  - both masts have a mainsail
  - fore-and-aft rigged sails
- The ketch refers to the sail plan (mast configuration and type of rig)
- Ketches actually handle really well. The back mast (mizzenmast) powers the hull providing more control. Extra mainsail - shorter masts - less stress on masts and



Module 3 (section a)

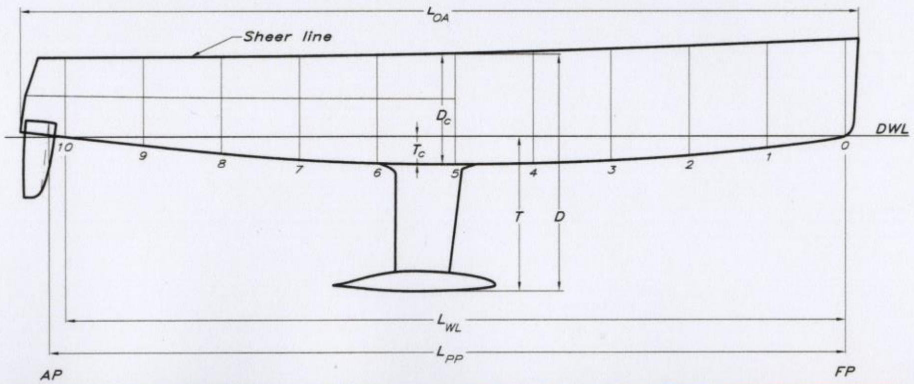
Yacht Types: Schooner

- Schooner:
  - mostly two masts
  - smaller mast in front
  - taller mast aft
  - fore-and-aft rigged sails
  - gaff-rigged mainsails
  - Schooners easy to sail but slower than sloops
- Handle better than sloops in all (cruising) points of sail

Module 3 (section a)

Yacht Terminology

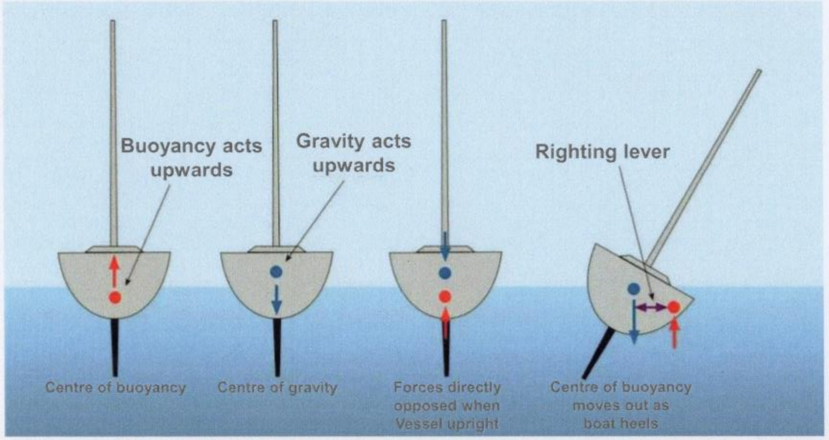
- It is important to know hull form/dimensions, displacement, gross tonnage, freeboard etc. to better understand stability, manoeuvrability, response to loading and other safety aspects



Module 3 (section a)

Yacht Terminology: Centre of Gravity and Buoyancy

- Centre of Buoyancy, B, centre of gravity and righting lever

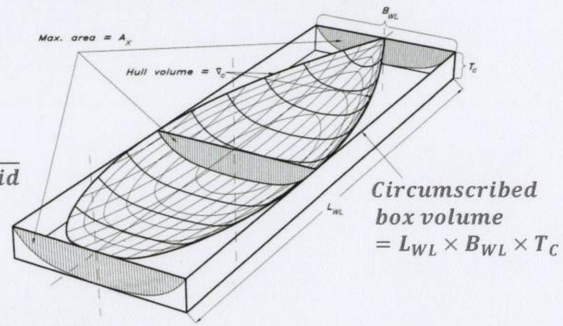


Module 3 (section a)

Yacht Terminology: Block Coefficient

- Block Coefficient, C_B
  - Describes the overall fullness of the hull

$$C_B = \frac{\nabla}{LBT} = \frac{\text{Volume Displacement}}{\text{Volume of Prescribed Cuboid}}$$



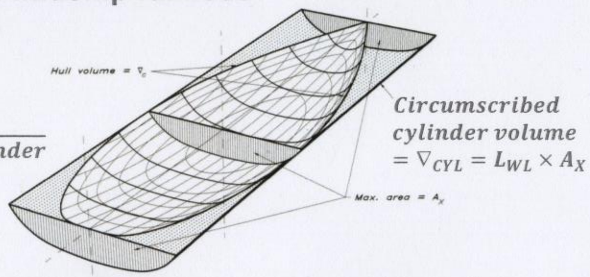
  - L usually equals LWL
    Typical values for CB, 0.45 for a naval destroyer to 0.85 for a very large tanker very large tanker

Module 3 (section a)

Yacht Terminology: Prismatic Coefficient

- Prismatic Coefficient, C_P
  - Describes fineness of the bow and stern without influence of midship fullness

$$C_P = \frac{\nabla}{A_M L} = \frac{\text{Vol. Displacement}}{\text{Vol. of Prescribed Cylinder}}$$



  - L usually equals LWL
    Typical values for C_P, 0.57 for a naval destroyer to 0.85 for a very large tanker

Module 3 (section a)

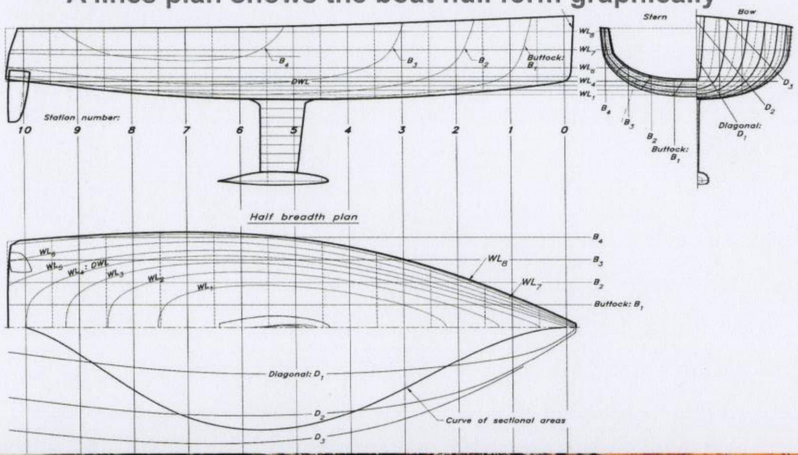
Yacht Terminology: Other Boat Parameters

- Definitions of other boat geometrical quantities
  - Draft (*T*): The maximum draft of the yacht when floating on the designed waterline [T_c is the draft of the hull without the keel (the 'canoe' body)]
  - Displacement (*m or* ∇): Could be either mass of the yacht or volume displacement (V or ∇)
  - Freeboard: Vertical distance between the sheer line and water line
  - Midship Section: For yachts common to take mid section between fore and aft ends of waterline [c.f. ships – midway between fore and aft perpendiculars]
  - Maximum Area Section: For yachts the maximum area section is usually behind the midship section (A_x)
  - Depth: Vertical distance from deepest point of the keel to the sheer line

Module 3 (section a)

Yacht Terminology: Lines Drawing

- Hull form
  - A lines plan shows the boat hull form graphically



Module 3 (section a)

Yacht Terminology: Keel Types and Function

- What is the purpose of a keel?
  - It acts as an underwater foil to minimize the lateral motion of the vessel under sail (leeway) i.e. resists sideways motion
  - A counterweight to the lateral force of the wind on the sail(s) that causes rolling to the side (heeling) i.e. acts as a counter balance
  - Provides ballast resulting in better stability (righting lever (GZ) versus heel angle plot)
  - Creates lift countering leeway (slippage to windward), reduces draught, wettable surface area and drag

Module 3 (section a)

Keel Types

- Keels: Two Main Categories
  - Fixed Keels
    - Full
    - Fin
      - Plane
      - Bulb
      - Wing
    - Bilge
  - Lifting Keels
    - Lifting
    - Moveable (Leeboards)
    - Cantable

Module 3 (section a)

Keel Types: Full

- Fixed Keels: Full Keel
  - Runs from front to aft for at least 50% of the hull and is fully integrated into the hull
  - Has the largest wetted surface of any keel type, and is the heaviest
  - Good directional stability and reduced heeling, providing the most comfortable (and slowest) ride

Keel Types: Fin

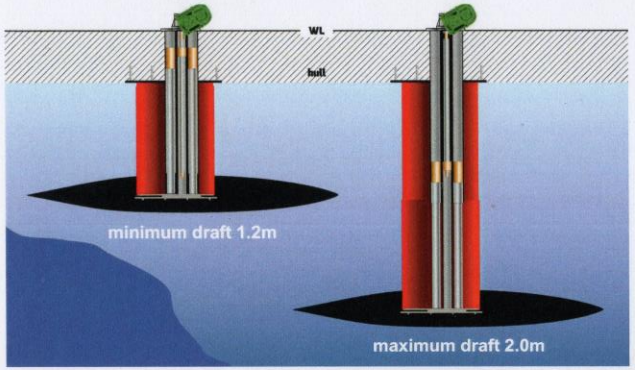
- **Fixed Keels: Fin Keel**
  - Long, weighted blade attached to the bottom of the hull
  - Lighter, faster, more maneuverable than a full keel, but also more vulnerable
  - The increased distance between ballast and sails provides a lever, reducing the need for a large wetted surface or additional ballast

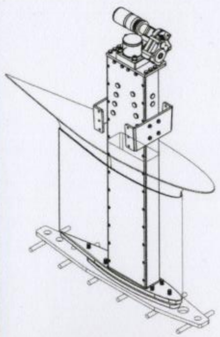
Keel Types: Bilge

- **Fixed Keels: Bilge Keel**
  - Double fin or double full keels, which allows the boat to be beached, making them a popular keel for tidal waters
  - Generally much slower and less maneuverable to fin keels

Keel Types: Lifting

- **Moveable Keels: Lifting Keel**
  - Double fin or double full keels, which allow the boat to be beached, making them a popular keel for tidal waters
  - Generally slower and less maneuverable to fin keels





Keel Types: Canting

- **Moveable Keels: Canting Keel**
  - This type of keel rests on a hydraulic canting hinge under the boat
  - It can be moved to windward, using the keel's position as a lever in countering the forces on the sails
  - Improves performance substantially by reducing the wetted surface and overall weight of the keel while increasing maneuverability
  - Used in high-performance sailing and not on cruising sailboats, mainly because of the need for underwater hydraulics in this keel design
  - A vulnerable keel type, with additional moving parts that are difficult to repair when they break down

Module 3 (section a)

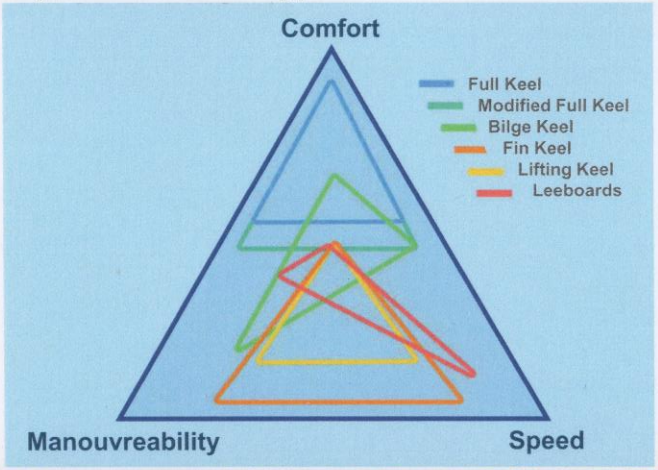
Keel Types: Leeboards

- Moveable Keels: Leeboards
  - Double fin or double full keels, which allows the boat to be beached, making them a popular keel for tidal waters
  - Generally much slower and less maneuverable to fin keels

Module 3 (section a)

Keel Types Compared

- Comparison of Keel Types



Module 3 (section a)

Keel Terminology

- Basic Theoretical Considerations: Fin Keel
  - The keel (and Rudder) can essentially be considered 'wing' appendages and aerodynamics can be used to explain their function and facilitate design optimization
  - Important geometrical quantities include:

    Mean chord length

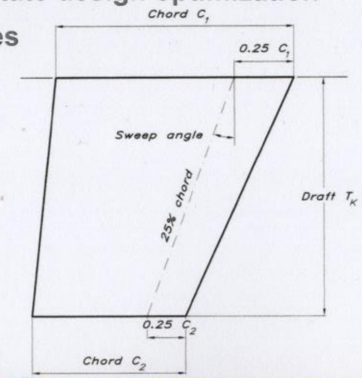
    $$\bar{C} = \frac{C_1 + C_2}{2}$$

    Aspect ratio

    $$AR = \frac{T_K}{\bar{C}} = \frac{T_K^2}{A}$$

    Taper ratio

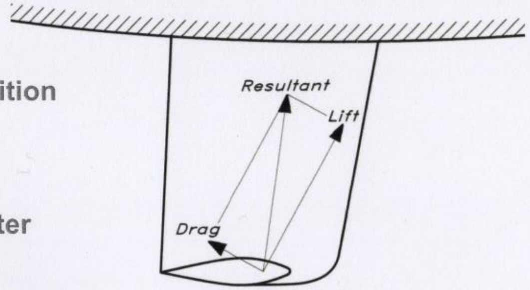
    $$TR = \frac{C_2}{C_1}$$



Module 3 (section a)

Keel Terminology

- Basic Theoretical Considerations: Fin Keel
  - Points to consider keel design:
    - Root chord
    - Pitch angle
    - Span
    - Longitudinal position
    - Taper
    - Junction fairing
    - Twist
    - Sectional character
    - Dihedral angle

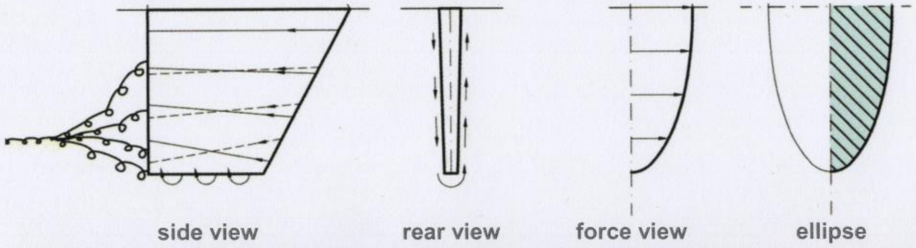


  - An effective keel design ensures drag is small relative to lift; achieved by ensuring that the force distribution is exponenential

Module 3 (section a)

Keel: Functional Aspects

- Basic Theoretical Considerations: Fin Keel
  - Pressure is higher on leeward side of keel hence flow tends to move from leeward to windward side
  - Vortices are created at the trailing edge and tend to roll up into a single one at the rear of keel – gives rise to a resistance component, the induced resistance or drag
  - An elliptical force distribution minimizes induced drag

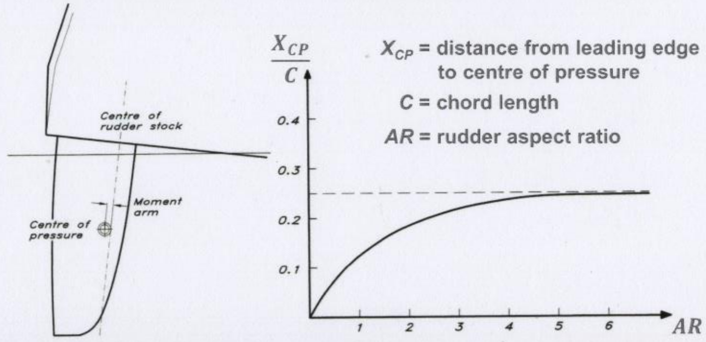


Module 3 (section a)

Rudder Terminology

- What is the purpose of the rudder?
  - Obviously to steer the boat and works….
    - In combination with keel to reduce keel load
    - If properly balanced effort is taken out of steering

For a balanced rudder the CP should not be forward of the rudder stock centreline, ideally ~50mm aft of centreline



Module 3 (section a)

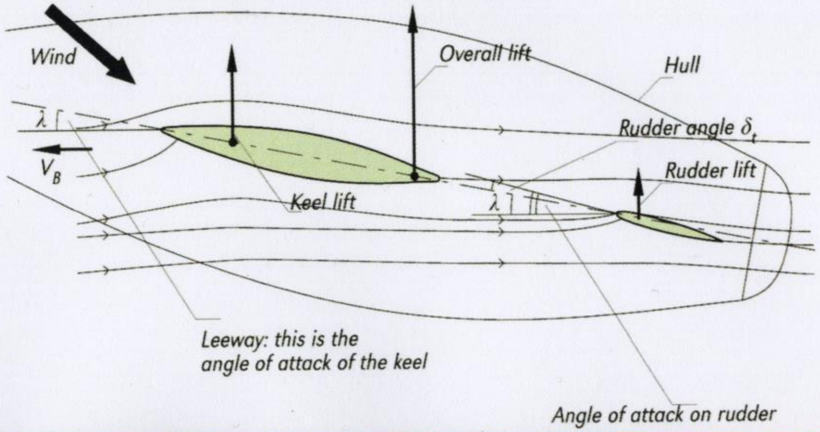
Rudder Function

- What is the purpose of the rudder?
  - Obviously to steer the boat, but how and is that all? Much of the ideas and lines of reasoning used earlier for keels can be applied to rudders – see slides in section 3b
  - The basic function of a boat's rudder is to work in tandem with the keel and develop hydrodynamic lift to balance lateral aerodynamic thrust and ensure the boat can be steered
    - This is done by modifying the amount of force developed by the wing section that constitutes the rudder, by changing the 'angle of attack' and causing adjustments in overall lift in terms of magnitude and the point it is applied

Module 3 (section a)

Rudder Function

- What is the purpose of the rudder?
  - Obviously to steer the boat,



Module 3 (section a) — Rudder Force Calculation: BSEN 12215-8: 2018

- Design rudder force calculation
  - For sailing craft corresponding to the design category sea state

$$F_1 = 23 \times L_{WL} \times k_{SEA} \times k_{LD}^2 \times k_{GAP} \times k_{USE} \times A$$

  - Where,

$$k_{SEA} = 1.4 \ \textit{for sailing craft of design categories A and B}$$

[Category A: ocean going, max. wave heights above 4m and wind speeds in excess of Beaufort force 8
Category B: Inshore, max. wave heights up to 4m and wind speeds < Beaufort force 8]

$$k_{LD} = \frac{L_{WL}}{\left(\sqrt[3]{\frac{m_{LDC}}{1025}}\right)} \ \textit{for sailing craft of design categories A and B}$$

  - k_{LD} recognises that slender craft can experience additional speeds due to surfing. It is derived from an established yacht scantling guide that has been in use for many years

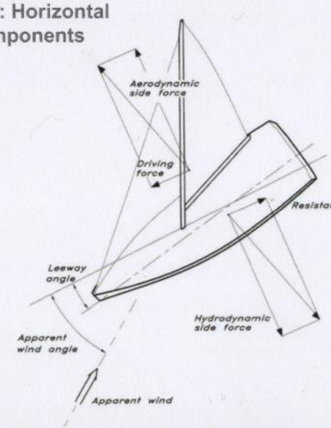
Module 3 (section a) — Rudder Force Calculation: BSEN 12215-8: 2018

- Design rudder force calculation - continued
  - k_{GAP}
    - 1.0 for rudders where the root gap (average clearance between the hull and the rudder root plane) is <5% of the mean rudder chord. This gap should not be exceeded at any rudder angle
    - 0.85 for rudders which are surface piercing e.g. transom held or exceed the gap limitation or can otherwise exhibit significant 3-D flow over the root
  - k_{USE}
    - 1 for all craft but may be taken as 0.9 for category C and D sailing craft for close inshore racing with safety precautions in place and for which the rudder can be easily inspected
      [craft operating in seas with wave heights ≤2m, BF ≤6
      craft operating in seas with wave heights ≤0.5m, BF ≤4
  - A = Total area of moving part of rudder

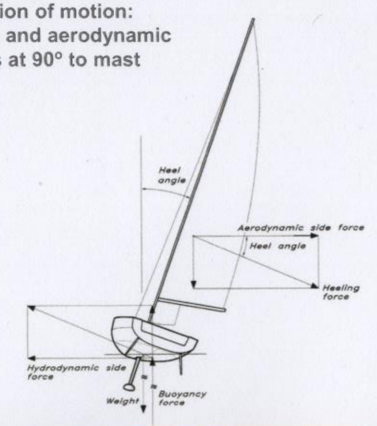
Module 3 (section a) — Forces and Moments Acting on Yacht

- Forces acting on a sailing yacht

Plan View: Horizontal Force components

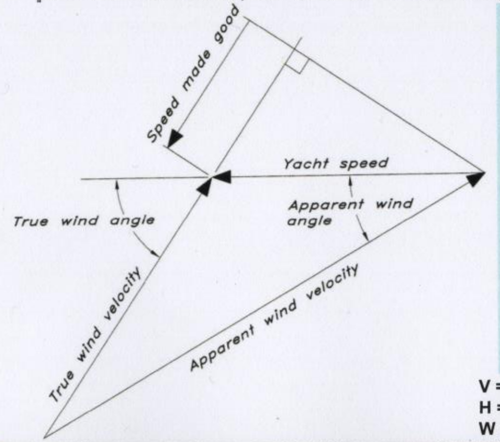


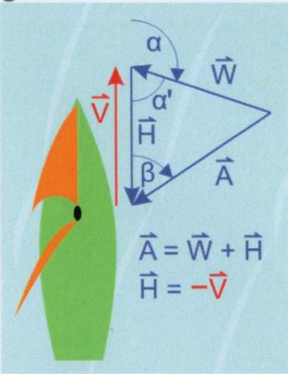
Direction of motion: Hydro and aerodynamic forces at 90° to mast



Module 3 (section a) — True and Apparent Wind

- The relationship between the apparent wind, in previous slide, and true wind angle is shown below



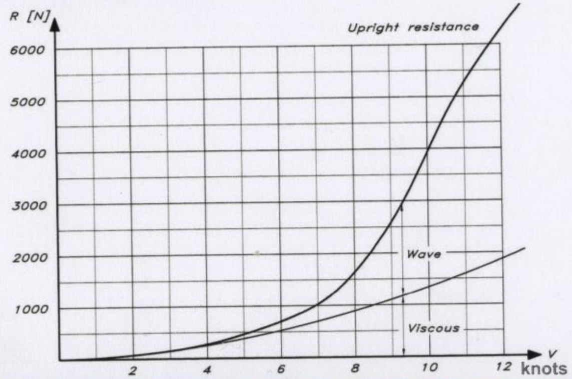


V = boat speed
H = head wind
W = true wind
A = apparent wind
α = pointing angle
β = apparent wind angle

Module 3 (section a)

Hull Resistive Components

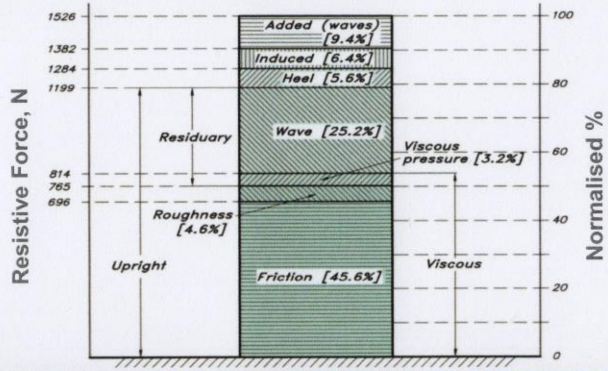
- An example of a yacht resistance curve is shown below; data is for towing upright in still water
  - At low speeds viscous resistance due to frictional forces between boat hull and water dominate
    This component increases relatively slowly with speed
  - A second componen wave resistance caused by hull generated waves – this increases
  - Viscous + wave resistance known as upright resistance



Module 3 (section a)

Resistive Components: Total Resistance

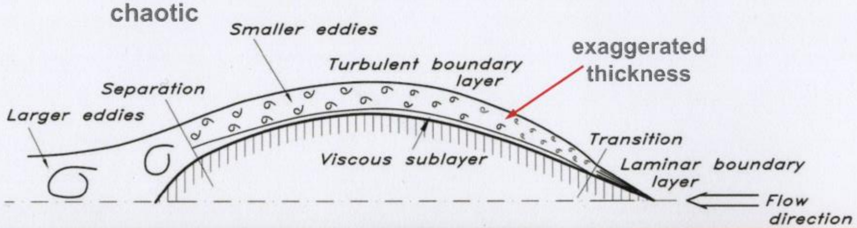
- Total Resistance: In a real sailing situation the picture is more complex; the figure below shows a breakdown of the total resistance for a specific vessel beating to windward offshore at 7.35 knots (fresh breeze



Module 3 (section a)

Hull Resistance: Viscous Resistance

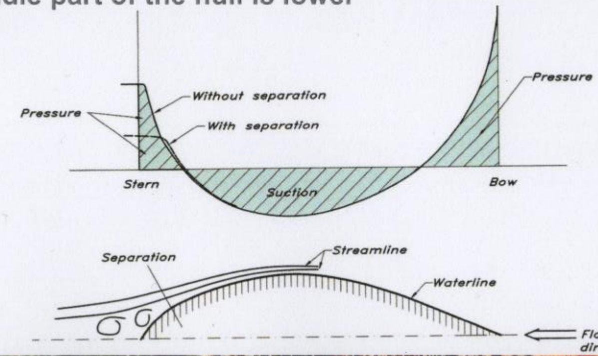
- Viscosity of the water gives rise directly or indirectly to this resistive component
  - A boundary layer exists between the hull and innermost layers of water – molecular forces are strong enough to stop the relative motion in the innermost water layer
  - Typically near the bow the flow within the boundary layer is smooth
  - After a certain distance from the bow disturbances occur and shortly after the flow structure breaks down and becomes chaotic



Module 3 (section a)

Hull Resistance: Pressure Distribution

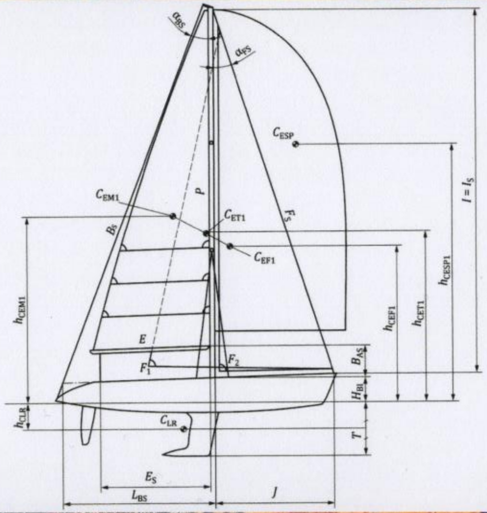
- A typical pressure distribution on the hull at a given depth is shown below
- Note, the bow and stern pressures are higher than in the undisturbed water at this depth while the pressure in the middle part of the hull is lower



Module 3 (section a)

Rig Loads and Attachments

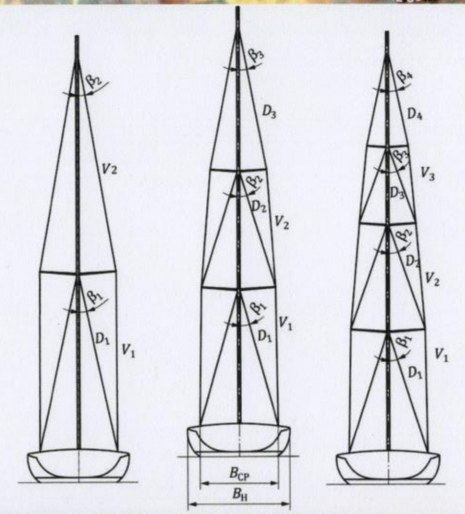
- BSEN ISO 12215/1 to /10: 2020 Part 10: Small craft. Hull construction and scantlings.
- Rig loads and rig attachment in sailing craft
- The standard covers scantling rules for rigging and chain plate loads and bolt/screw strength calculations



Module 3 (section a)

Rig Loads and Attachments

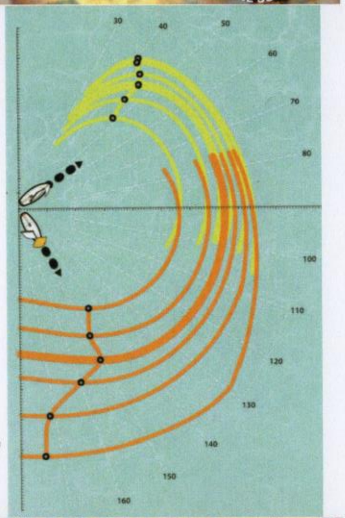
- BSEN ISO 12215/1 to /10: 2020 Part 10: Small craft. Hull construction and scantlings.
- Rig loads and rig attachment in sailing craft
- Considers cases for different spreader sets for monohulls and catamaran and trimarans

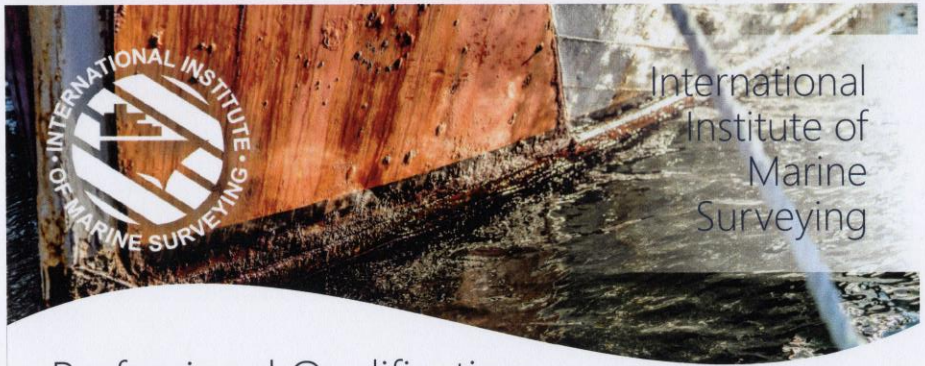


Module 3 (section a)

Polar Plots: VPP Program

- A polar plot is a graphical representation of a boat's predicted speed, based on a velocity prediction program (VPP)
- All points of sail and wind directions are considered
- In the diagram
  - True wind speed from top
  - Radiating dashed lines – increasing boat speed
  - Straight dashed lines – true wind angle
  - Yellow lines – boat speeds at increasing wind speeds moving out to right from upwind angles to reaching
  - Orange lines – same for wider angles





Professional Qualification

in Marine Corrosion

Presented by **Mike Lewus**

Module 3

(section b)

Stability and Aspects of Aerodynamics and Hydrodynamics

Module 3 (section b)

Summary

- **Laws of Flotation and Archimedes Principle**
  - Flotation and conditions for a body to float
  - Basic ship stability related parameters
- **Boat (Yacht, Box Barge) Stability**
  - Centre of gravity and buoyancy
  - Cross curves of stability
  - Stability at low heel angles
  - Stability at high heel angles
- **Sail Aerodynamics**
  - 2 sail configuration
  - Mast interference
- **Hull Hydrodynamics**
  - Centre of pressure
  - Wave resistance

Module 3 (section b)

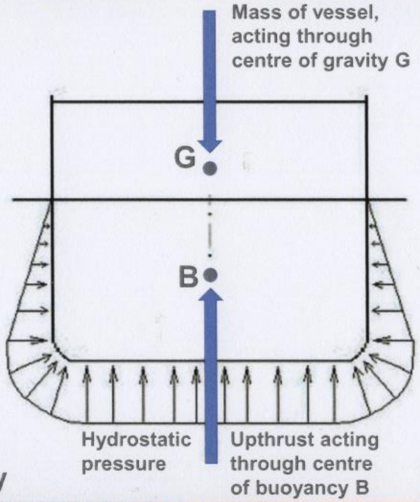
Laws of Flotation

- Archimedes Principle
  - The principle states that any object, wholly or partially immersed in a fluid, experiences an upward force equal to the weight of the fluid displaced by it
  - The weight of fluid displaced by the body is directly proportional to the volume of the displaced fluid, since the density of the fluid is constant
  - A body floats in a fluid under any of the following two conditions
    - The density of the body is less than the density of the fluid
    - The volume of the fluid displaced by the immersed part of the body is such that its weight is equal to the weight of the body

Buoyancy: Forces on a Ship's Hull

Module 3 (section b)

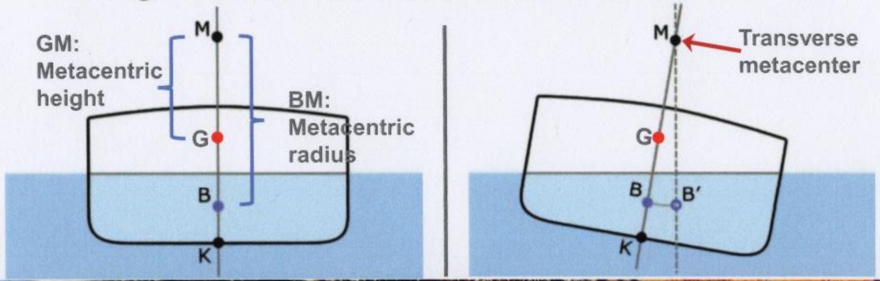
- Floating Bodies
  - The % volume of a floating body that is immersed depends upon its relative density and the relative density (rd) of the liquid
  - A body of rd 0.8 will float in fresh water with 80% of its volume immersed and in seawater, with 1.000/1.025 x 80% = 78% of its volume immersed i.e. slightly less seawater is displaced to produce sufficient buoyancy



Ship Stability at Small Heel Angles

Module 3 (section b)

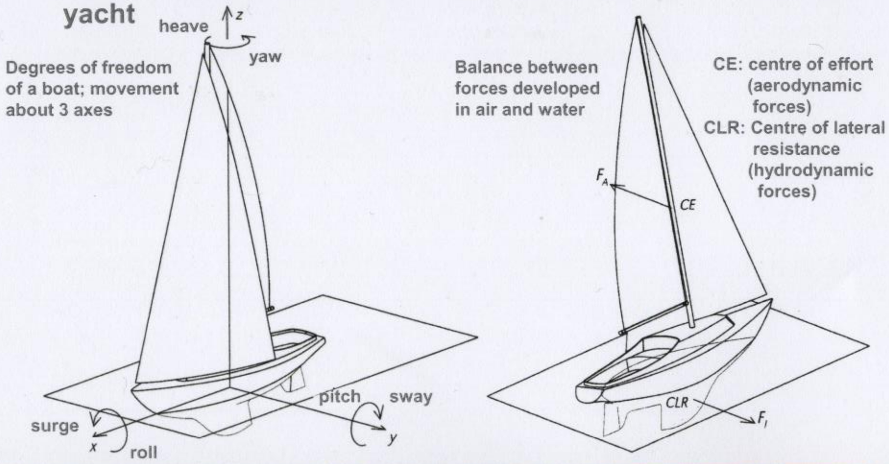
- Transverse Stability at Small Heel Angles ≤ 6°
  - On a ship with an even keel we can identify the keel K, vertical centre of gravity G and the centre of buoyance B
  - For small heel angles the centre of buoyancy B moves through a small arc and a vertical line drawn through the new centre of buoyance B/ intersects the original vertical line through K-B-G at M, the transverse metacentre



Forces Acting on a Sailing Vessel

Module 3 (section b)

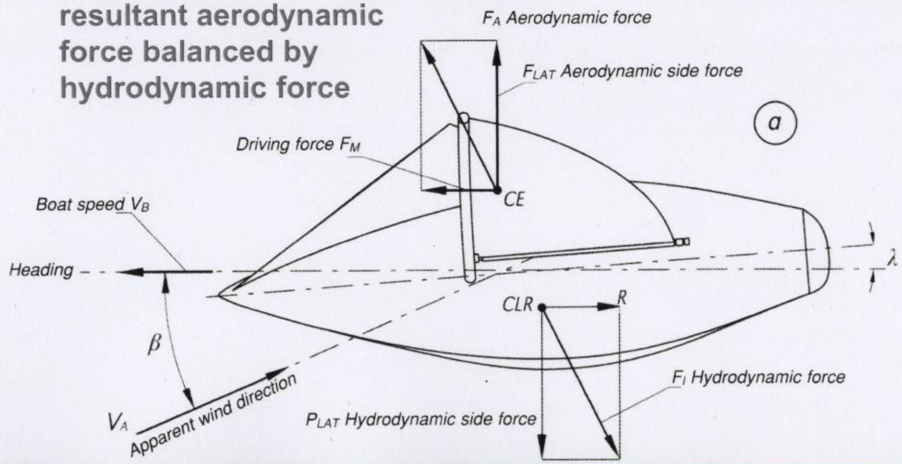
- Hydrodynamic and Aerodynamic forces acting on a sailing yacht



Forces Acting on a Sailing Vessel

Module 3 (section b)

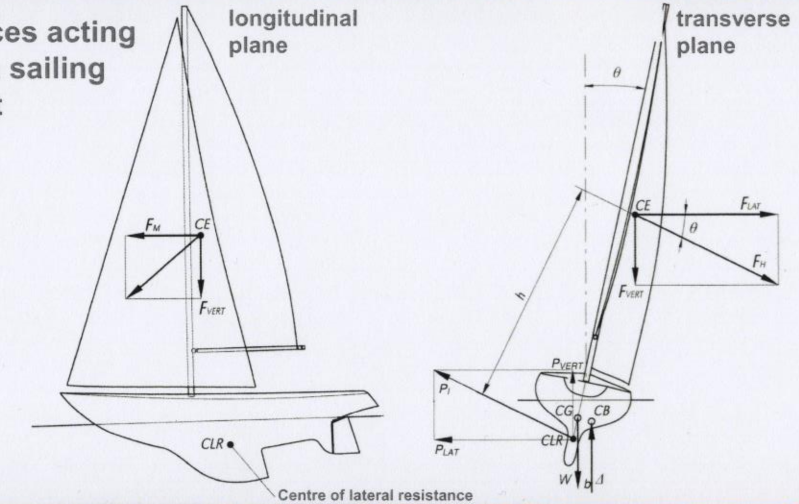
- Forces acting on a sailing boat; resultant aerodynamic force balanced by hydrodynamic force



Forces Acting on a Sailing Vessel

Module 3 (section b)

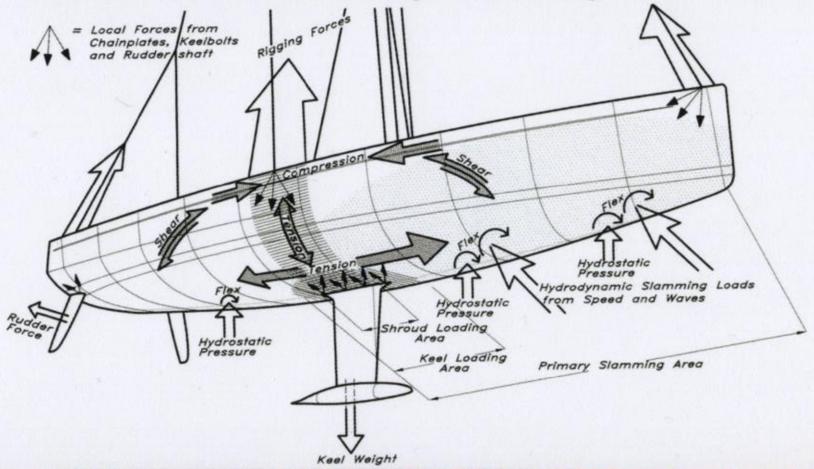
- Forces acting on a sailing boat



Stress Distribution on a Sailing Vessel

Module 3 (section b)

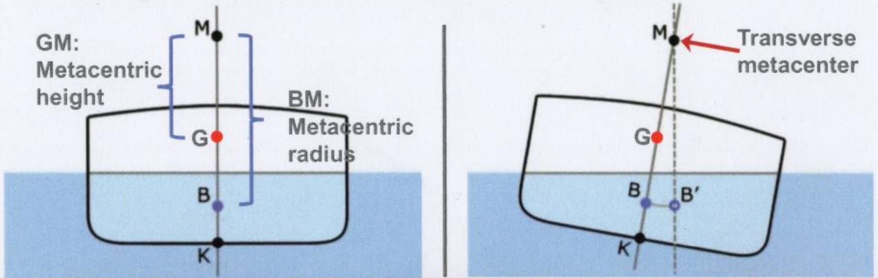
- Forces and stresses acting on a sailing boat



Ship Stability at Small Heel Angles

Module 3 (section b)

- Transverse Stability at Small Heel Angles ≤ 6°
  - On a boat with an even keel we can identify the keel K, vertical centre of gravity G and the centre of buoyance B
  - For small heel angles the centre of buoyancy B moves through a small arc and a vertical line drawn through the new centre of buoyance B/ intersects the original vertical line through K-B-G at M, the transverse metacentre



Transverse Stability at Small Heel Angles

Module 3 (section b)

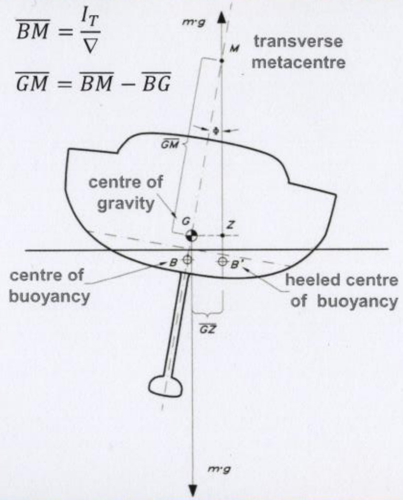
- The centre of buoyancy moves from B to B\` while the weight still acts through G creating a righting moment $\overline{GZ}$
- The vertical through the new centre of buoyancy B\` intersects the centreline at M, the transverse metacentre and from figure we have

$$GZ = GMSin\theta$$

- For small heel angles $\overline{GZ}$ is a function of $\overline{GM}$ and the initial stability of a ship

$$\overline{BM} = \frac{I_T}{\nabla}$$

$$\overline{GM} = \overline{BM} - \overline{BG}$$



Module 3 (section b)

Ship Stability: Metacentre

- Why is a boat's Metacentre important?
  - The position of the metacentre is found by considering small inclinations or angles of heel about the boat centreline
  - When a boat heels (rolls sideways), its centre of buoyancy moves laterally. It might also move up or down with respect to the water line. The point at which a vertical line through the heeled centre of buoyancy crosses the line through the original, vertical centre of buoyancy is the metacentre
  - The relative positions of vertical centre of gravity G and the initial metacentre M are extremely important with regard to their effect on a boat's stability
  - The boat is in stable equilibrium if G is below M, in neutral equilibrium if the vertical centre of gravity (VCG) and M are coincident and in unstable equilibrium if VCG is above M

Module 3 (section b)

Boat Stability: Determining GM

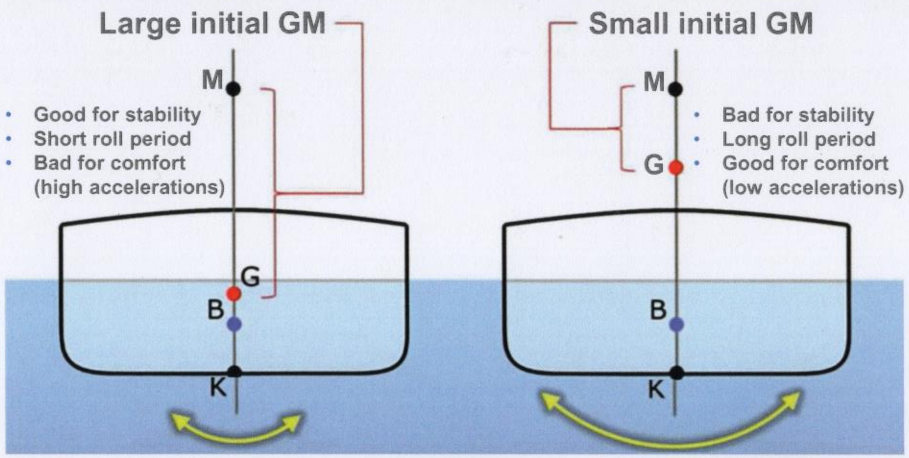
- KB, BM and KM depend on the shape of the hull
  - KM provided from ship's hydrostatic curves
- KG and GM depend on the loading of the ship
  - KG determined by 'weights and moments' calculation

$$GM = KM - KG$$

GM > 0	GM = 0	GM < 0
stable	neutrally stable	unstable

Module 3 (section b)

Boat Stability: Influence of Initial GM



Module 3 (section b)

Longitudinal Boat Stability at Small Heel Angles

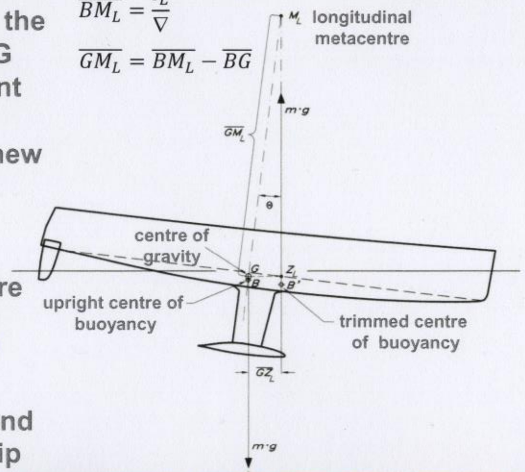
- The centre of buoyancy moves from B to B` while the weight still acts through G creating a righting moment $\overline{GZ}_L$
- The vertical through the new centre of buoyancy B` intersects the centreline at M, the transverse metacentre and from figure we have

$$GZ_L = GMLSin\theta$$

- For small heel angles $\overline{GZ}_L$ is a function of $\overline{GM}_L$ and the initial stability of a ship

$$\overline{BM_L} = \frac{I_L}{\nabla}$$

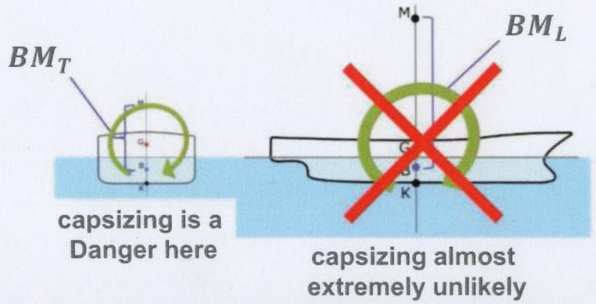
$$\overline{GM_L} = \overline{BM_L} - \overline{BG}$$



Module 3 (section b) — Boat Stability: Trans. Vs Long. Stability

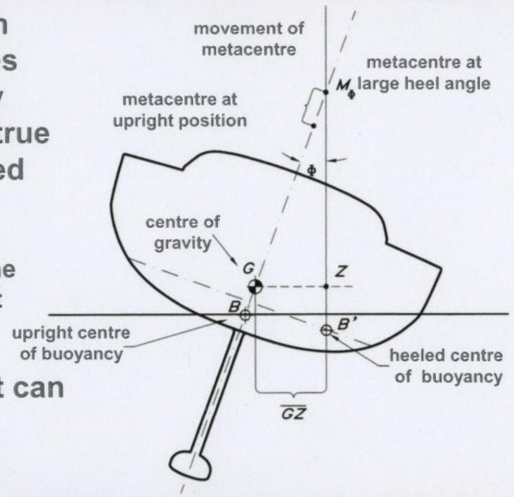
- Transverse versus longitudinal boat stability

$$BM = \frac{I}{\nabla} \qquad I_L \gg I_T \rightarrow BM_L \gg BM_T$$



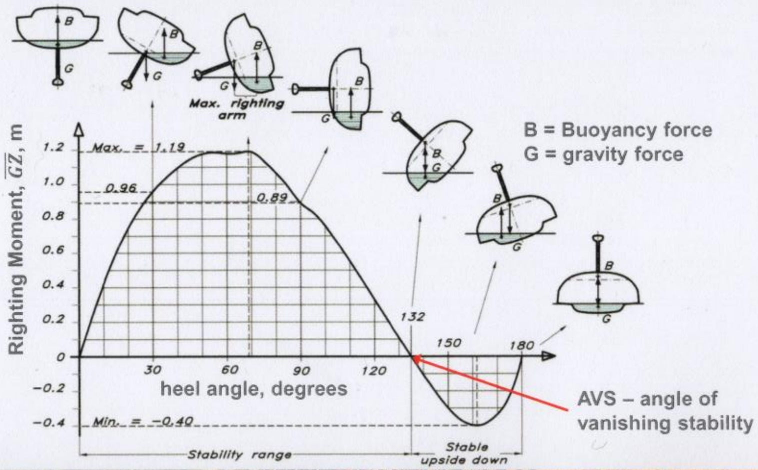
Module 3 (section b) — Transverse Stability at High Heel Angles

- When a boat heels to an angle >10° the principles on which initial stability is based are no longer true i.e. formula for BM based on assumption that
  - the two waterplanes intersect at the centre line
  - that the wedges are right angled triangles
- The stability of the boat can determined from first principles or estimated



Module 3 (section b) — Transverse Stability at High Heel Angles

- Typical static stability curve for large heel angles



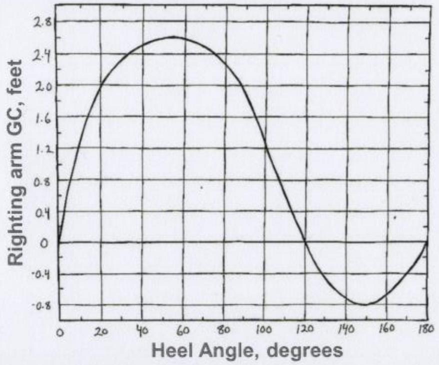
Module 3 (section b) — Boat Stability: GZ Stability Curve

- Features of a Statical 'GZ' Stability Curve
  - The slope of the GZ curve at the origin is a measure of the initial stability GM
  - The maximum ordinate of the curve multiplied by the displacement gives the largest steady heeling moment the boat can withstand without capsizing
  - The range of angle over which GZ is positive is termed the range of stability
    - Freeboard and reserve buoyancy are important factors in determining the range of stability
  - The angle of deck, cabin and hollow mast immersion are sometimes revealed by points of inflexion or depression on the stability curv, due to additional buoyancy at the heeling angle

Module 3 (section b)

Stability: Single Number Measures

- Stability Ratio
  - Calculate the area of the positive part of the GZ versus heel angle stability curve (PEA) and divide it by the area of the negative part (NEA)
  - The areas can be estimated by counting, using simpsons rule or using a planimeter
  - In this case, simply by counting we have a stability ratio of ~25/4 = 6.25
  - In general a stability ratio of > 3 is good for coastal cruising and > 4 for blue water cruising



Module 3 (section b)

Capsizing Screening Value (CSV)

- CSV: A stability indicator developed after the 1979 Fastnet Race. More than a third of the 300 boats that entered the race, most of them beamy, lightweight IOR designs, were capsized (rolled to 180 degrees) by large breaking waves $CSV = Beam \div \sqrt[3]{DCF}$
- For example: consider a 35ft boat that displaces 12000lbs and has an 11ft beam

Displacement of 12000lbs ≡ 5443kg
5443kg ≡ 5.30m^3 ≡ 186.91ft^3
[$\rho_{(seawater)}$ = 1028kg/m^3 and 1m^3 = 35.3ft^3]

So, $CSV = \dfrac{11}{\sqrt[3]{186.91}} = 1.93$

Module 3 (section b)

Capsizing Screening Value (CSV)

- Interpretation of CSV
  - A value ≤ 2 indicates a boat that is sufficiently self-righting to go offshore
    - The further below 2 you go, the more self-righting the boat is; extremely stable boats have values on the order of 1.7
  - Values > 2 indicate the boat may be prone to remain inverted when capsized and that a more detailed analysis is needed to determine its suitability for offshore sailing
- Convenient though CSV is, it has limited utility. It accounts for only two factors - displacement and beam - and fails to consider how weight is distributed aboard a boat
- For example, increasing the load of the boat will tend to increase the CSV, but take no account of how the load is being distributed – if it is high the boat may be less stable

Module 3 (section b)

IMS Stability No.

- Another single-value stability rating often encountered is the IMS stability index number
- Developed under the IMS rating system to compare stability characteristics of race boats of various sizes
- A formula essentially relates a boat's AVS (angle of vanishing stability) so as to account for its overall size, awarding higher values to longer boats, which are inherently more stable
- IMS index numbers range from ~100 to >140
  - Category 0, 1 and 2 races typically require IMS values of 120, 115 and 110, respectively
- IMS numbers do not take into account cabin or cockpit structure, assumes a flush deck from gunwale to gunwale and, does not account for downflooding angle

Module 3 (section b)

Dellenbaugh Angle

- A rapid method for judging the stability of a yacht is to compute the Dellenbaugh angle!
- This is approximately the heel angle the hull will attain when sailing to windward in a 8 m/s breeze
  - This is computed from a simple formula

$$Dellenbaugh\ Angle = 279 \times \frac{A_S \times HA}{m \times \overline{GM}}$$

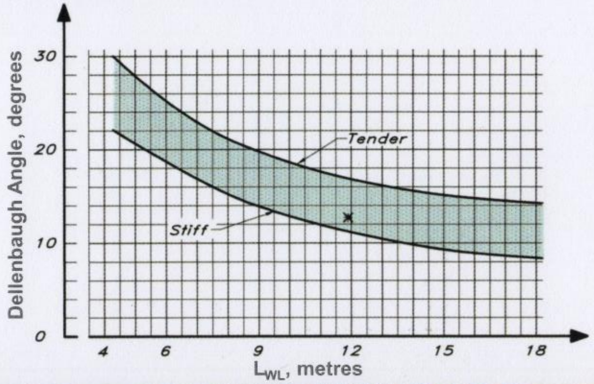
Where
 A_S = sail area (triangular), m^2
 HA = heeling arm, m
 m = displacement, kg
 $\overline{GM}$ = metacentric height, m

  - The heeling arm is defined as the vertical distance between the centre of effort (CE) of the sails and centre of lateral resistance (CLR)
  - The Dellenbaugh angle says nothing about the stability at large angles of heel

Module 3 (section b)

Dellenbaugh Angle

- Most modern yachts fall within the band in the plot below, with an approximate 6° difference between 'stiff' and 'tender' yachts



Module 3 (section b)

STIX: Stability Index Calculation

- A stability index 'STIX' is defined in BSEN ISO 12217-2: 2017, 'Small craft – Stability and buoyancy assessment and categorization'
  - STIX is a parameter defining how well a monohulled vessel can resist, and recover from a knockdown or inversion
  - STIX consists of a length factor which may be modified by 7 factors which each address a separate aspect of stability and buoyancy properties
  - Each modifying factor can be obtained in any of 3 ways:
    - The minimum permitted value, without further calculation
    - Using approximate methods
    - From rigorous calculation
  - Each modifying factor has an upper and lower limit

Module 3 (section b)

STIX: Stability Index Calculation

- Calculation of STIX

$$STIX = (7 + 2.25L_{BS})(FDS \times FIR \times FKR \times FDL \times FBD \times FWM \times FDF)^{0.5}$$

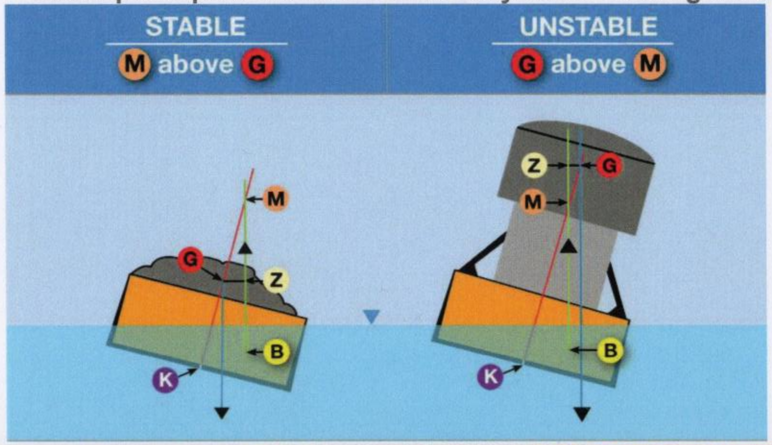
  - Where:

 L_{BS} - $L_{BS} = (2L_{WL} + L_H)/3$ in metres
 FDS - relates to righting energy needing to be overcome
 FIR - relates to the ability to recover from an inversion
 FKR - relates to the ability to spill water out of the sails and hence recover after a knock-down
 FDL - relates to favourable effect of heavier displacement on a given length increasing the resistance to capsize
 FBD - accounts for the increased susceptibility to capsize in 'beam seas' of boats with significant topside flare and increased beam relative to displacement
 FWM - wind moment factor
 FDF - downflooding factor

Module 3 (section b)

Narrowboat and Box Barge Stability

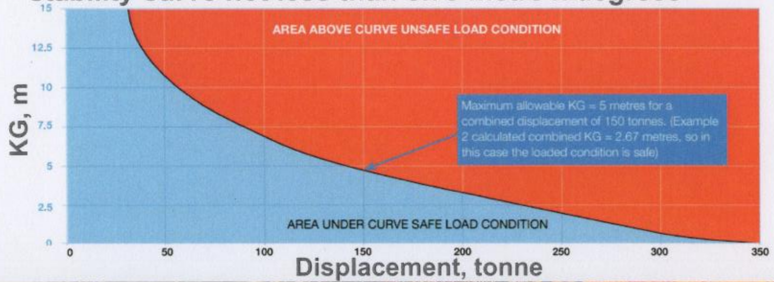
- Transverse Stability of Narrowboats and Box Barges
  - Basic principles the same as for any other floating vessel



Module 3 (section b)

Narrowboat and Box Barge Stability

- As part of a stability analysis, a naval architect will draw a limiting KG curve
  - The limiting KG curve has safety margins built in. These margins are achieved by using recommended minimum values i.e. initial GM greater than 0.35 metres
  - AVS (positive GZ) to greater than 35°; and area under the GZ stability curve not less than 5.73 metre x degrees



Module 3 (section b)

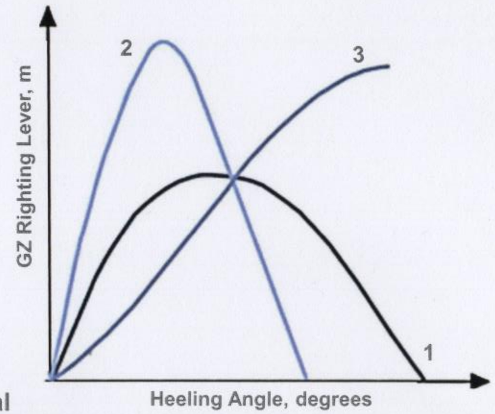
Narrowboat: Structural Aspects

- Standard steel certification, BSEN 10025: 2019 'Hot rolled products of structural steels - Technical delivery condition for flat products of high yield strength structural steels in the Q&T condition
  - A typical steel designation is S275JR (see Module 7, section 7a slides 3-6)
    - S – denotes a Structural Steel specification
    - 275 – denotes minimum yield strength of 275 MPa
    - JR – Charpy impact test value at room temperature, in Joules
  - Typical steel plate thickness used are 10mm, 6mm, 5mm, 4mm for hull base plate, hull sides, cabin sides and roof, respectively

Module 3 (section b)

Ship Stability at Small Heel Angles

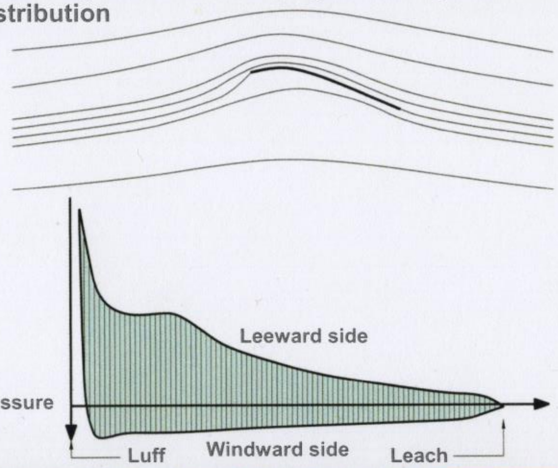
- Different vessel-hull shapes have a strong influence on the stability curve
  - Curve 1: traditional deck vessel, the righting lever peaking at 25° and stability range is 0-70°
  - Curve 2: Wide flat-bottomed vessel, very difficult to heel, but the righting arm falls quickly after peaking
  - Curve 3: vessel with very different properties, typical of a shelter deck vessel



Module 3 (section b)

Aerodynamics: Flow Around Sails

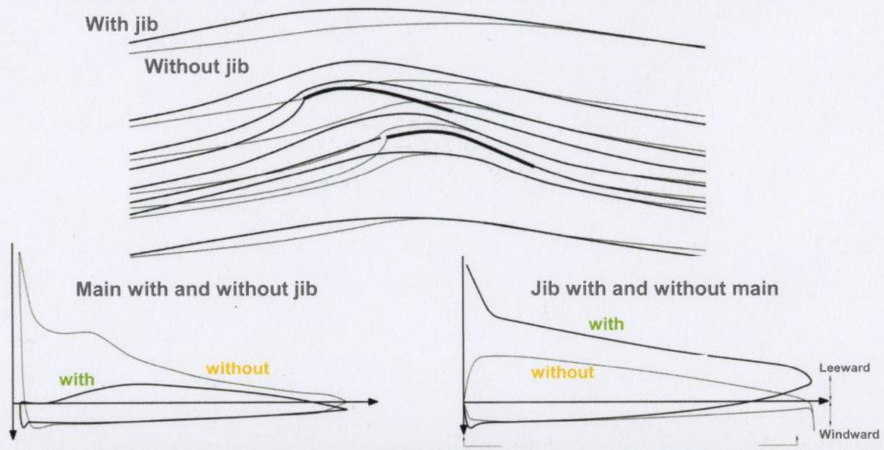
- Schematic showing flow around a single sail, together with pressure distribution between the two sides



Module 3 (section b)

Aerodynamics: Flow Around Sails

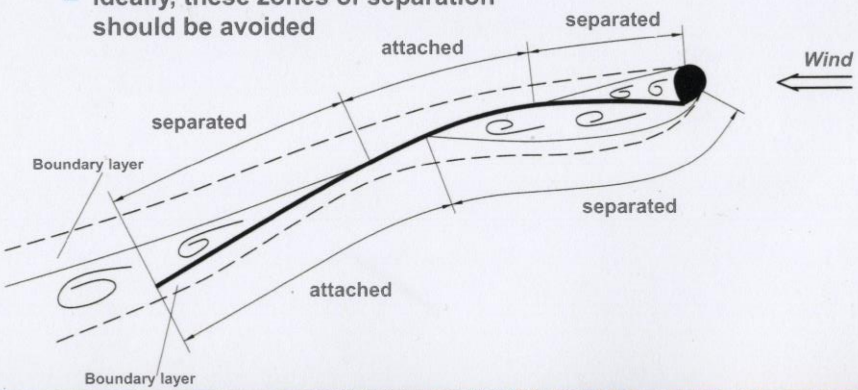
- Schematic showing flow around a single sail, together with



Module 3 (section b)

Aerodynamics: Mast Interference

- Schematic showing flow around a sail, behind a mast in upwind sailing conditions
  - 3 zones of separation can be identified
  - Ideally, these zones of separation should be avoided

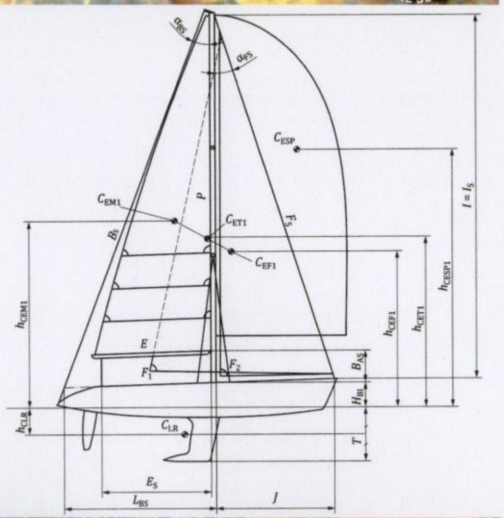


Module 3 (section b)

Rig Loads and Attachments

From section 3a

- BSEN ISO 12215/1 to /10: 2020 Part 10: Small craft. Hull construction and scantlings.
- Rig loads and rig attachment in sailing craft
- The standard covers scantling rules for rigging and chain plate loads and bolt/screw strength calculations

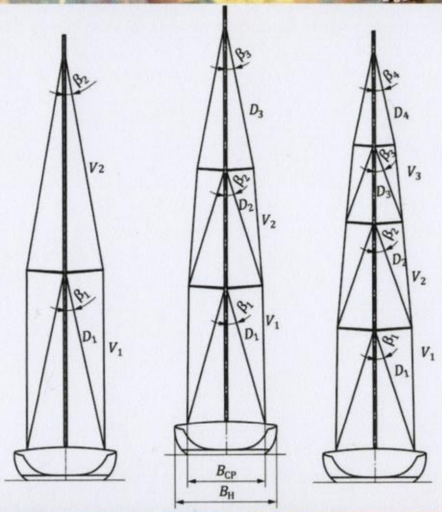


Module 3 (section b)

Rig Loads and Attachments

From section 3a

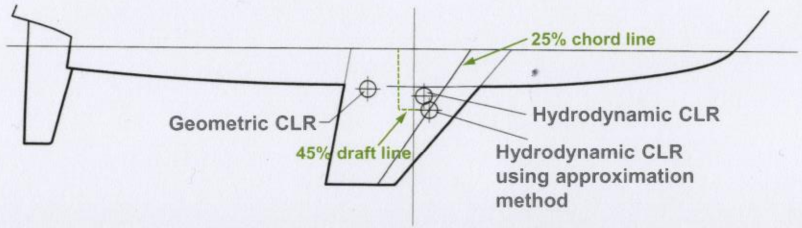
- BSEN ISO 12215/1 to /10: 2020 Part 10: Small craft. Hull construction and scantlings.
- Rig loads and rig attachment in sailing craft
- Considers cases for different spreader sets for monohulls and catamaran and trimarans



Module 3 (section b)

Hull Hydrodynamic Center of Pressure

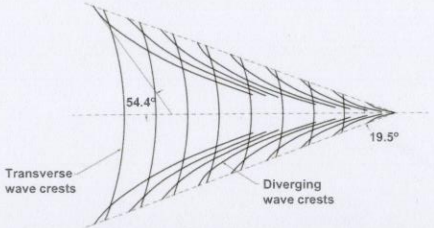
- The hull centre of lateral resistance or 'centre of pressure' is the point on the boat where the total sum of hydrodynamic pressure field acts, causing a force and no moment about that point
  - A first approximation for fin keel yachts can be made by taking the intersection of the keel 25% chord line and the 45% T (draft) line

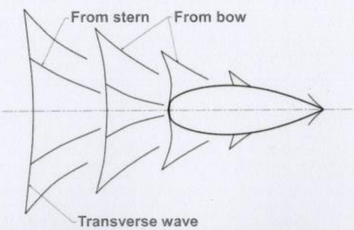


Module 3 (section b)

Wave Resistance

- Wave resistance, the 2nd most resistive component, is split into two sub-components
  - A vessel generates two wave systems, diverging waves moving sidewards and transverse waves at right angles to the direction of motion of the boat
  - The speed dependence of the wave systems give rise to the phenomenon of interference which impacts the boats progress

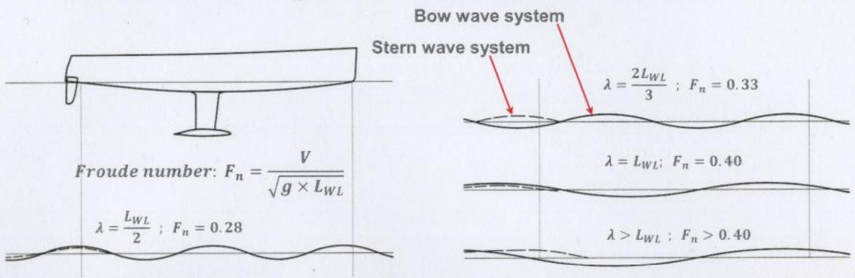




Module 3 (section b)

Wave Resistance: Froude Number

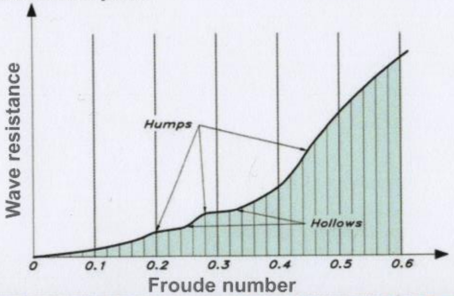
- Schematic showing interference between the bow and stern wave systems
- The speed dependence of the wave systems gives rise to the important phenomenon of interference
- If the crests from the bow coincide with those from the stern, large waves will be created, if the bow wave crest coincides with the stern wave trough, the result is an attenuated wave



Module 3
(section b)

Wave Resistance: Froude Number

- The Froude number determines how many waves there are along the boat hull
- The properties of the wave resistance curve are highly dependent on the Froude number
- As wave resistance occurs because energy is transported away, amplification and attenuation due to interference has an effect on the wave resistance plot



International Institute of Marine Surveying

Professional Qualification
in Marine Corrosion

Presented by **Mike Lewus**

Module 3
(section c)

Corrosion Control Strategies

Module 3 (section c)

Summary

- **Corrosion Protective Paints**
  - General requirements
  - Paint Types
  - Surface preparation
  - Application
- **Antifouling Paints**
  - Soluble matrix
  - Insoluble matrix
- **Cathodic Protection**
  - SACP
- **Stray Current Corrosion**
  - Testing and prevention

Module 3 (section c)

Corrosion Prevention: Protective Paint Systems

- **Critical areas for painting**
  - Underwater hull sections
  - Keel
  - Rudder and stern gear
- **Requirements from a paint system**
  - For underwater parts a ship coating should be corrosion-inhibiting, antifouling, abrasion-resistant, smooth, and compatible with cathodic protection
  - Coating should remain smooth in-service to minimize fuel costs
    NB hull friction due to fouling can result in up to 40% more fuel consumption compared to a clean hull and greater air pollution due to additional fuel burned to maintain speed

Module 3 (section c)

Corrosion Prevention: Protective Paint Systems

- Protective coatings have the capacity to:
  - Create a barrier that keeps out charged ions and retards the penetration of water and oxygen
  - Provide metallic contact between the steel and a less noble metal, such as zinc are aluminium in the paint, which provides cathodic protection of the steel by utilizing the galvanic effect
  - Cause water on its passage through the paint coating to take on special properties or form compounds that inhibit its corrosive action
  - Retain a sufficient level of smoothness or increase smoothness i.e. self polishing copolymers (SPC)

Module 3 (section c)

Corrosion Prevention: Protective Paint Systems

- Coatings Types
  - Cross-Linked Thermoset Coatings
    - Epoxy resins
    - Polyurethan resins
    - Alkyd resins
    - Inorganic resins
  - Thermoplastic Coatings
    - Chlorinated rubber resins
    - Vinyl resins
  - Antifouling and Foul Release Coatings

Module 3 (section c)

Corrosion Prevention: Protective Paint Systems

- Organic, Cross Linked 2-Component Thermosets
  - Epoxy based paints are used in both underwater and above water situations and show good resistance to many marine environments
    [these paints generally cover the greatest vessel area and include seawater ballast tanks]
    - The rate of cross-linking or curing is dependent on temperature. The curing rate of standard epoxies are considerably reduced below 5°C (41°F). Full cure is essential to obtain optimal film properties
    - Epoxies will cure or set with special curing agents at temperatures down to –5°C (23°F)
    - Tendency to chalk in sunlight. This occurs when the binder is degraded by ultraviolet light to produce a loose and friable surface, with the pigment particles remaining on the surface

Module 3 (section c)

Corrosion Prevention: Protective Paint Systems

- Organic, Cross Linked 2-Component Thermosets
  - Polyurethanes based paints are used topside and superstructure applications
    - These are polymers formed by reaction between hydroxyl compounds and compounds containing isocyanates
      [In two-pack systems, a special polyether or polyester resin with free hydroxyl groups is reacted with a high molecular weight isocyanate curing agent]
    - Polyurethane resins have excellent chemical and solvent resistance and are superior to standard epoxies in acid resistance
      [Epoxies are more resistant to alkaline than polyurethanes]
    - A problem with these polyurethanes is their water sensitivity on storage and on application hence care must be taken during transport and application

Module 3 (section c) — Corrosion Prevention: Protective Paint Systems

- **Inorganic Resins-Component Thermosets**
  - Comprise silicates which are almost always used in conjunction with zinc dust pigments
    - Water-based inorganic silicates based on lithium, potassium, or sodium silicate and solvent based inorganic silicates normally based on ethyl silicate
    - Coatings based on these resins are very hard, corrosion resistant and temperature resistant. They require a good standard of surface preparation and are often repaired using organic coatings
    - Zinc in the inorganic resins can dissolve under acid or alkali conditions, coatings perform best at neutral pH and are often used as tank coatings
    - Often used as tank coatings

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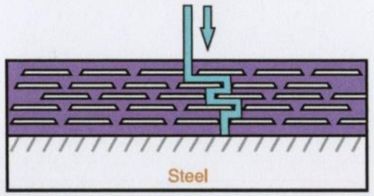
Module 3 (section c) — Corrosion Prevention: Protective Paint Systems

- **Paints Containing Anti-corrosive Pigments**
  - Metallic zinc is widely used in primers for protecting steel from corrosion
  - Metallic aluminum flake is commonly used as an anti-corrosive pigment by producing a circuitous pathway for water and also forming aluminum oxides which fill up pores
  - Zinc phosphate ($Zn_3(PO_4)_2$) pigments are also widely used in corrosion-inhibiting coatings for steel surface corrosion protection

Flake pigments increase diffusion path length for water



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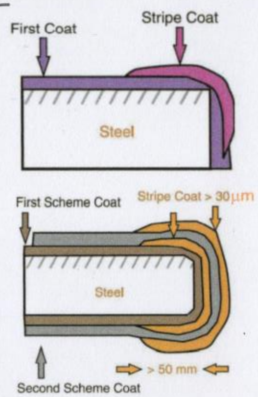
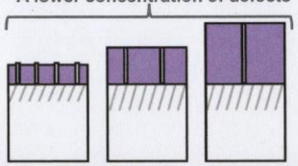
Module 3 (section c) — Corrosion Prevention: Protective Paint Systems

- **Factors Affecting Coating Performance**
  - Oxygen Permeability
  - Water Vapor Permeability
  - Liquid Water Uptake
  - Ionic Permeability
  - Coating Porosity
  - Surface Contamination
  - Surface Profile

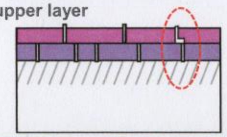
To achieve specified DFTs with good adhesion stripe coatings are recommended at welds and edges before sprayed coatings are applied



Thicker coatings tend to contain A lower concentration of defects



Defect density in multilayer less likely, but pores in lower layer can nucleate pore in upper layer



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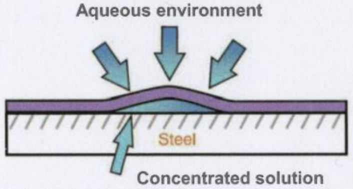
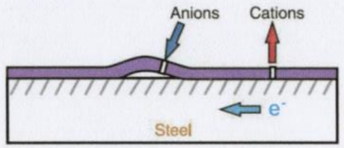
Module 3 (section c) — Corrosion Prevention: Protective Paint Systems

- **Types of Coating Breakdown**
  - Coating should remain smooth in-service to minimize

Osmotic Blistering



Electro-Osmotic Blistering



  - Osmotic blisters are usually small and relatively closely spaced
  - Electro-osmosis typically produces larger blisters
  - Osmosis and electro osmosis tend to occur early in the lifetime of a coating while it retains a degree of plasticity

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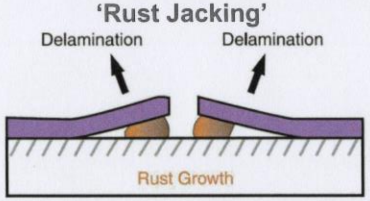
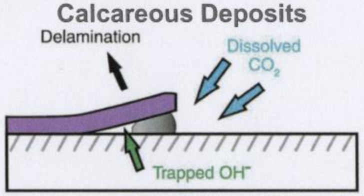
Module 3 (section c) — Corrosion Prevention: Protective Paint Systems

- Types of Coating Breakdown
  - Rust jacking or rust leverage is the predominant mechanism of coating failure during the late stages of the service life of the coating

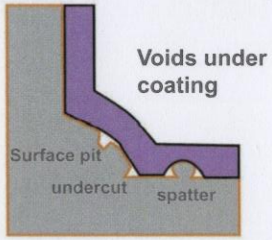


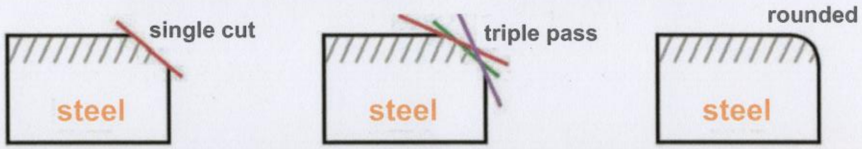


  - Calcareous deposits breakdown is similar to rust jacking in that the coating is levered from the surface by a deposit growing beneath it but, in this case, hydroxyl ions are generated at the cathodic site and induce a precipitation reaction by changing local seawater pH

Module 3 (section c) — Surface Preparation: Welds and Edges

- Cleaning and dressing welds and, edge preparation are vital for ensuring well adhered paint coverage





Module 3 (section c) — Corrosion Prevention: Protective Paint Systems

- Surface Preparation:
  Good surface preparation is the most important part of the entire coating process in that the greatest percentage of coating failures can be traced directly to poor surface preparation
  - All paint systems fail prematurely unless the surface has been properly prepared to receive the coating. No paint system gives optimum performance on a poorly prepared surface
  - Surface preparation has two important effects:
    - It provides mechanical keying, by providing an 'anchor roughness' for the coating
    - It provides a chemical bridge, by allowing intimate contact (cleanliness) of between coating material molecules and the steel (or other material) substrate

Module 3 (section c) — Corrosion Prevention: Protective Paint Systems

- Preparation Methods:
  Good surface preparation is the most important part of the entire coating process in that the greatest percentage of coating failures can be traced directly to poor surface preparation
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Module 3 (section c) Organic Coating Defects

Blistering

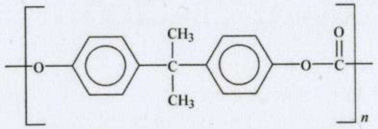
Runs

Orange Peel

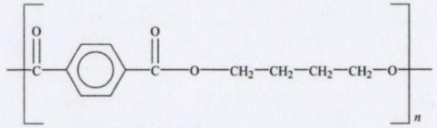
Poor Adhesion

Module 3 (section c) Polyester Systems: GRP Yacht Hulls

- Nearly all GRP production boats are made from polyester resin, which is about a quarter of the price of epoxy



Structure of PC polyester



Structure of PBT polyester

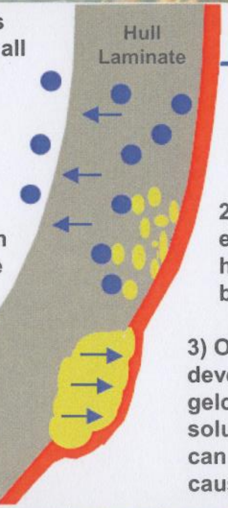
- Polyesters have very favourable properties including:
  - High impact resistance
  - Toughness at low temperatures
  - High heat resistance
  - Resistance to UV light
  - Lower moisture absorption than Nylon
  - Good flame retardant properties

Module 3 (section c) Protective Coatings: Gelcoat

4) Treatment requires complete removal of all hygroscopic solutes to return hull to its original inert state

☺ Timescale between stage 2 and 3 may be as long as 30 years

Bilge



Polyester gelcoat

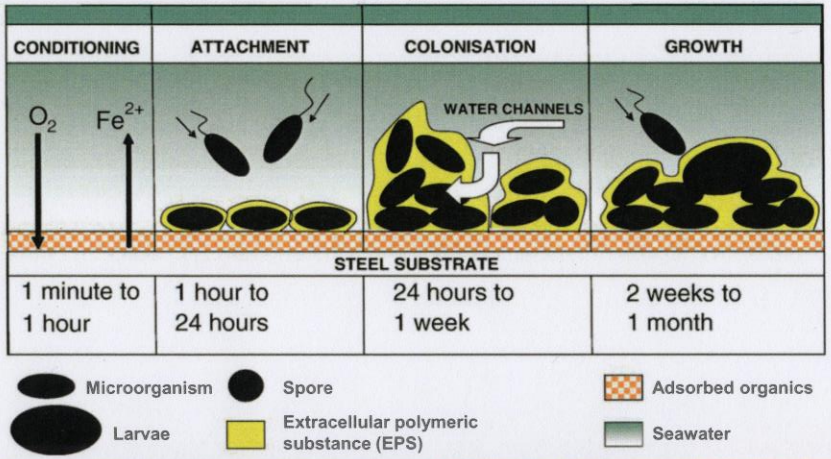
1) Moisture permeates through the protective gelcoat – moisture readings can be high - no osmotic pressure

2) Moisture in the laminate will encourage the migration of hygroscopic solutes forming a 'foci' behind the gelcoat

3) Once an 'osmotic cell has developed moisture will pass through gelcoat in an attempt to equalize solution strengths – osmotic pressure can exceed 60psi and may eventually cause blistering

Module 3 (section c) Antifouling Coatings

- Critical steps in biofouling



Module 3 (section c)

Antifouling Coatings

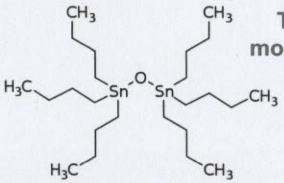
- Due to penalties associated with and the severe impact of unwanted colonisation of a hull surface by marine organisms, primarily through negative impact on hydrodynamics via increased drag, antifouling systems are in great use in the maritime industry
  - Three main forms of biocides that can be used in anti-fouling systems:
    - Metallic
    - Organometallic
    - Organic
  - Few biocides have had the necessary combination of characteristics to make them safe, yet effective antifouling agents

Module 3 (section c)

Antifouling Coatings

- Mercury, arsenic and their compounds, and now the organotins, are examples of effective antifouling agents that have been deemed unacceptable due to adverse environmental or human health risks
- Tributyltin (TBT) based coatings were introduced in the mid1960s and were common in the latter half of the 20th century as an effective anti-fouling solution

  Their acute toxicity to non-target marine organisms and severe environmental impacts led to a ban on TBT paints in September 2008

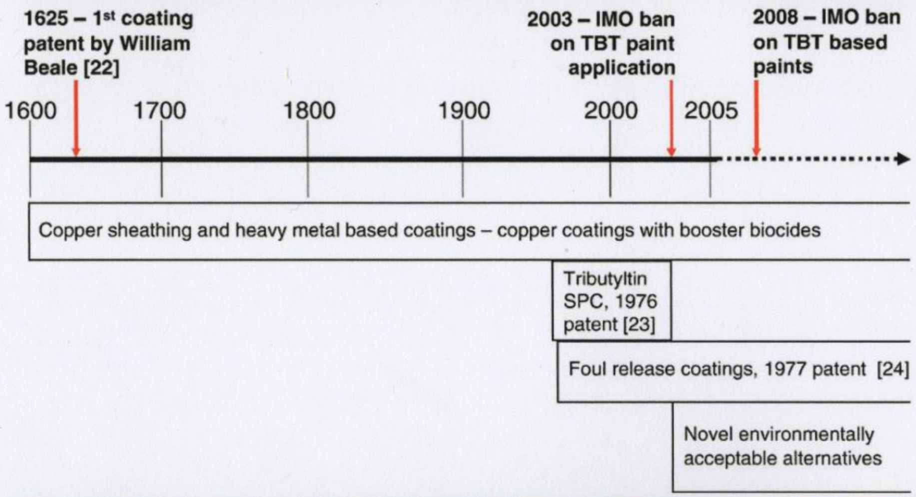


TBT molecule

- Copper-based biocides are the most commonly used, and often in combination with organic biocides

Module 3 (section c)

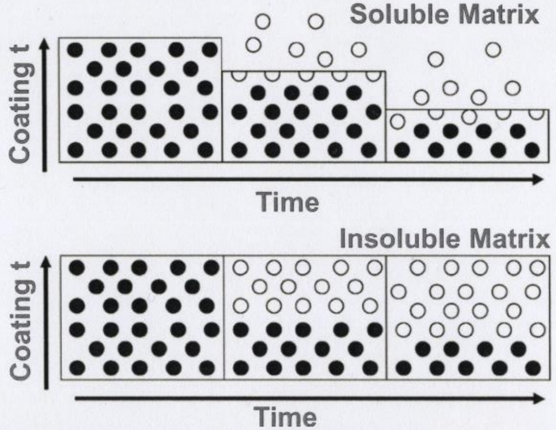
Antifouling Coatings



Module 3 (section c)

Antifouling Coatings

- Two key methods for controlling the release of antifouling compounds from a coating, by using either a soluble or insoluble matrix
- In insoluble matrix systems biocide leaching rates decrease exponentially with time



Module 3 (section c)

Antifouling Coatings

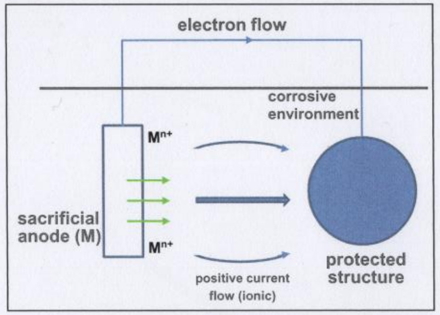
Module 3 (section c)

Antifouling Coatings

Module 3 (section c)

Principles of Cathodic Protection

- **Two main cathodic protection methods:**
  ii) SACP sacrificial anode cathodic protection



a simple SACP system

Module 3 (section c)

Bow Thruster & Hull Anodes

Module 3 (section c)

Cathodic Protection

- Advantages and Disadvantages of ICCP and SACP

ICCP		SACP	
Advantages	Disadvantages	Advantages	Disadvantages
Smooth surface, little drag	Continuous power supply required	Simple installation, no external source	More limited application than ICCP
Flexible: wide use – oil/gas platforms, large vessels	Current always to flow in right direction	Maintenance free between slips	Driving voltage fixed – only other options Al, Mg
Long lifetime	More complicated installation	Availability	Relatively higher cost c.f. ICCP
Fully automated	Less economic for small vessels	Low cost for short-term operation	
Light weight for large vessels			

Module 3 (section c)

Cathodic Protection

- Sacrificial Anodes:
  - Zinc, Aluminium, Magnesium
  - Consumption affected by
    Water flowrate (or speed/time of boat in water)
    Water conductivity, pH, temperature, salinity
  - Composition of anode:
    Ensure anode is marine quality i.e. Zinc anode to Mil-A-18001

	Zinc	Aluminium	Magnesium
Voltage in Seawater	-1.03V	-1.1V	-1.6V
Relative Life (Zinc = 100 same size)	100	150	30
Relative Density (Zinc = 100)	100	42	27
Mil Spec.	MIL-A-18001	MIL-A-24779	MIL-A-21412

Module 3 (section c)

Cathodic Protection

- Sacrificial Anodes: under and over-protection

Ag/AgCl, Reference Electrode

Hull Material	Recommended Potential
Wood	-600 to -550mV
Polyester with IB	-1000 to -750mV
Polyester with OB or S-Z Drive	-1050 to -900mV
Aluminium	-1100 to -900mV
Steel	-1050 to -800mV

- Under protection – more corrosion
- Over protection – hydrogen evolution at cathode with associated problems; hydrogen cracking !

Module 3 (section c)

Principles of Anode Weight Calculation

- Small Vessels:
  - For steel and aluminium boat hulls (or underwater structures) the following formula can be used to calculate the total weight of sacrificial anodes required

$$Anode\ Weight(lbs) = \frac{[(wetted\ Surface\ Area)\times(Current\ Density)\times(Immersion\ Time)]}{[(Energy\ Content)\times(1000mA/A)]}$$

  - Estimating Wetted Surface Area of Boat Hulls
    = 1.0 LWL x (Beam + Draft) for full displacement vessels (motor yachts and sail boats)
  - Estimating Current Density: primarily a function of water flow rate and the quality of the hull protective paint coating
    - e.g. low water flow velocity (0.5-2m/s) and new coating – 2mA/ft^2
    - e.g. med. water flow velocity (2-5m/s) and poor coating – 5mA/ft^2

Module 3 (section c) — Principles of Anode Weight Calculation

- **Small Vessels:**
  - **For steel and aluminium boat hulls (or underwater**

What anode weight? What anodes weight?				
Needs protective current (painted steel coastal water: 20)			20 mA/m²	
L. flotation L. at water line	12.0 M	Largeur + Tirant Width + Depth	5.2 M	
Coef. (.6 to/to 1)	1.0 x surface	Duration / Time	8760 h	
Nature	zinc	aluminium	magnesium	
Destination	sea sea	sea - brackish sea - brackish	soft soft	
Poids / Weight	15.6 Kg	4.5 Kg	14.8 Kg	

Calculate anodes (galvatest.com)
www.galcatest.com/anodes

Module 3 (section c) — Stray Current Corrosion

- **Electrolytic corrosion occurs due to electrical currents from within a boat, from a nearby boat or from shoreside power outlet going to ground (via seawater surrounding a boat)**
- **It is due to electrical current going 'astray' and hence is often referred to as 'stray current corrosion**
- **For clarity the difference between galvanic corrosion and electrolytic (stray current) corrosion is:**
  - **Galvanic corrosion is due to the potential difference developed between 2 contacting metals and hence is measured in mV**
  - **In electrolytic or 'stray current' corrosion the power source is usually a battery or shore power system and hence the voltage can be between 12 and 240 V**

Module 3 (section c) — Stray Current Corrosion

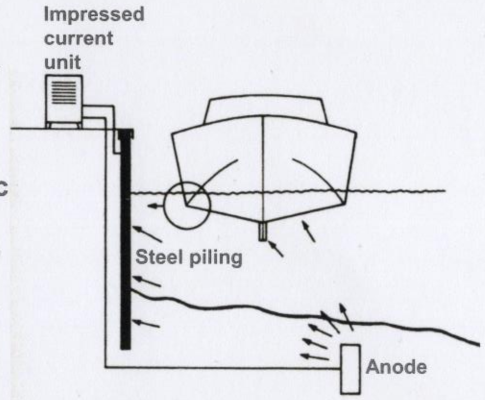
- **Small Vessels:**
  - **For steel and aluminium boat hulls (or underwater**

What leak? What leak?			
Observed weight loss observed	1000 g	Duration During	365 j - d
Consumed material		steel-steel	aluminium
Estimated leakage current intensity		0.10 Ah	0.32 Ah
(non-alloyed metals)		zinc	magnesium
Estimated intensity of stray current		0.09 Ah	0.24 Ah
Modifiez valeurs noires sur fond bleu - Sous réserves Change black values in blue background - Under reserves - (c) 2016 GPS			

Calculate stray current leakage (galvatest.com)
www.galcatest.com/current

Module 3 (section c) — Stray Current Corrosion

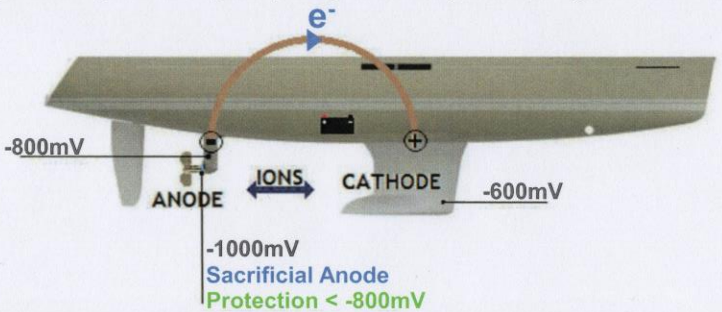
- **Consider a metal hulled boat berthed adjacent another metal mass i.e. steel piling, another metal hulled boat or a steel marina pontoon**
- **If there is no electrical link, plastic fenders and synthetic rope are good insulators**
- **If there is an electrical link current will take a short-cut/circuit and exit from a small area closest to the jetty/pontoon causing rapid corrosion**



Module 3 (section c)

Stray Current Corrosion

- A 'corrosive circuit loop' is responsible for corrosion of metal immersed boat components. The circuit can be galvanic, electrolytic (stray current) or both galvanic in origin



- The Anode is the metal with the lowest potential

Module 3 (section c)

Stray Current Corrosion

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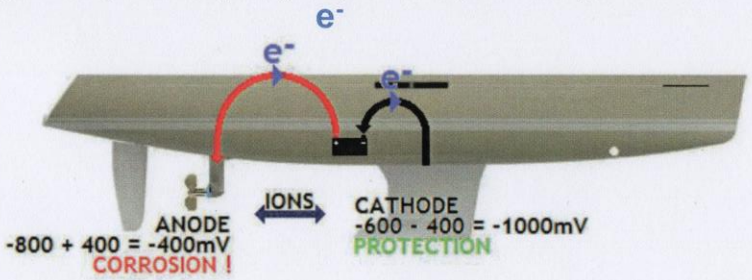
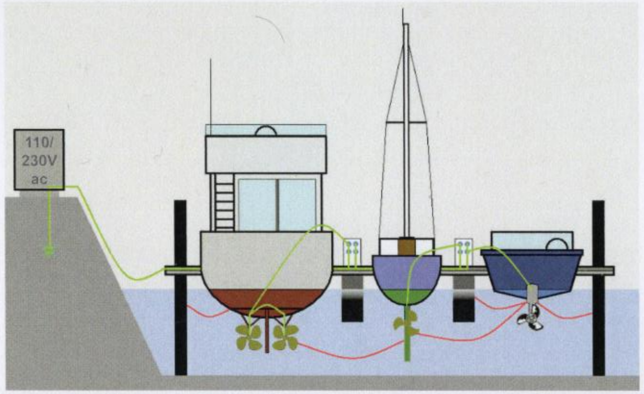


- The Anode is the metal with the lowest potential

Module 3 (section c)

Stray Current Corrosion

- Stray currents link through earth contacts and can cause corrosion on a boat when moored



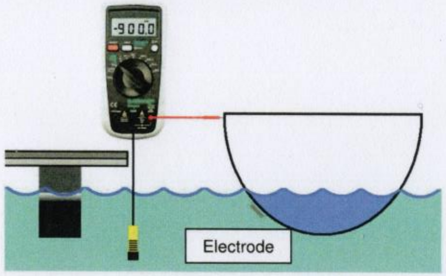
- Safety regulations require the presence of a ground connection; these are needed for the correct operation of RCDs

Module 3 (section c)

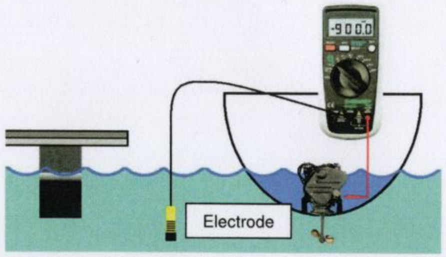
Principles of Cathodic Protection

Measurement of hull potential on metal, wood or GRP hulled boat

Measurement on a metal hull (steel and aluminium)



Measurement on immersed equipment (wood and GRP)



Module 3 (section c) Stray Current Corrosion

- Testing for stray current leaks
  - Corrosion inducing electrical leaks cause corrosion potential measurements to move upwards or downwards, according to polarity
  - Successive switching of onboard electrical circuits (cabin lights, water pump system, batteries etc.) mains and appliances should not influence reference electrode/multimeter reading, hence instant detection leakage currents and potential premature failures are possible
  - Similarly, these measurements must not vary while shore power is plugged in or unplugged.

Module 3 (section c) Stray Current Corrosion

- The risk of stray current corrosion can be mitigated by using a galvanic isolator. The isolator blocks stray direct current (DC) flow while permitting AC to pass, thus maintaining an unrestricted path for ground-fault currents
- The practical installation is shown schematically in principle opposite