Section 3

Boat Design and Hull Types

**Ballast.** Weight carried low in boat to improve trim or stability.

**Board Boat.** Small (car top) centerboard sailing dinghy with very low topsides and virtually no cockpit.

**Centerboard.** A pivoted board that can be lowered through a slot in the boat or keel to reduce leeway.

**Daggerboard.** A sliding board that can be lowered through the boat or keel to reduce leeway.

**Displacement.** The weight of water displaced by a floating vessel; hence, the weight of the vessel itself.

**Gudgeon and Pintle.** A metal eye and matching pin used to mount a rudder on the sternpost or the transom of a boat.

**Leeway.** Sideways movement of a boat through the water, caused only by the wind. Also, the angular difference between the course steered and the course made good through the water.

**Stringer.** A fore-and-aft structural member of a hull.

**Tiller.** A lever attached to the upper end of a rudder stock, used by the helmsman to turn the rudder.

**Wetted surface.** The portion of a vessel’s exterior which is in contact with the water.

1 Historically, boats intended to be propelled by wind power have evolved from round bottomed, stone ballasted hulls to our present high tech light displacement sleds with variations along the way such as multihulls, hydrofoils, and sailboards.

**Materials**

2 Materials available for construction often limited the size, shape, and number of vessels which could be built. Ancient Greece was denuded of forests to produce the merchantmen and warships of the time. The great oak warship *Victory* sailed by Nelson in the battle of Trafalgar would be impossible to build out of the remaining English forests. Ancient Egyptians built boats of reeds as did the peoples of the South American Andes.

3 Modern designers have a wide selection of materials to use in boat construction as well as a great deal of engineering knowledge of the hydrodynamics of hull performance, stresses, and material strengths.

4 The primary design parameters of sailboats, besides intended use, size, aesthetics and cost, are shaping the hull to have minimum resistance to forward motion and maximum resistance to leeway forces. Some of the factors considered are displacement, draft, ballast, weight distribution, waterline length, overall beam, materials of construction, and how these factors influence performance.

5 Wood, the material of choice for many years has been replaced in the last fifty or so years by fiberglass reinforced plastics and other composite materials such as Kevlar®, carbon fiber, and cold molded plywood.

**Construction**

6 A traditionally built wooden boat usually had a white oak backbone planked with a lighter, rot-resistant wood, such as mahogany, cedar, or long-leafed pine. Some other woods commonly used were Spanish cedar and red cypress. Wooden boats are still constructed this way, and they might make use of plywood, or veneers, and epoxy. Many specialized techniques still exist to produce light, strong, rot-resistant hulls from wood. These are generally cold-molded wood hulls in which veneers are glued together over a framework and the adhesive cures without being heated.

7 Fiberglass is particularly suitable for mass-produced work in which molds are used as forms for making
identical hulls. In the construction process, the female mold used is first coated with mold release agents and then sprayed with a thin layer of gelcoat. This gelcoat will ultimately be the colored outside surface layer of the boat. Next, alternate layers of fiberglass cloth, woven roving, and mat are laid into the hull and impregnated with resin. Core material of end grain balsa wood or special closed cell foam materials are sometimes incorporated in hull layers to provide rigidity and insulation, while minimizing weight. Various parts of the hull have different thickness and, hence, different strengths as the design requires. Some builders spray chopped fiberglass mixed with resin, but this is not considered as good a method as hand laying. Once the formed hull has cured, bulkheads and stringers are installed. The hull is then removed from the mold and prepared for the addition of internal parts before the deck is bonded in place.

Fiberglass hulls are strong, relatively light, and durable. While fiberglass hulls don’t require painting until years of exposure to the sun and water have caused the gelcoat to oxidize, they should have an annual waxing and buffing. Kevlar®, carbon fiber, aluminum, steel, ferrocement, and cold-molded wood are also used as construction materials. These are found primarily in medium to large-sized sailing vessels. Each has its advantages and disadvantages.

**Design Factors**

The designer considers many factors when drawing the lines for a sailing vessel. Consistent with design requirements to limit leeway, the general type and intended use of the boat are key factors. These factors largely determine the form of the boat’s hull. Form considerations include such items as displacement, waterline length, underbody and keel shape, wetted surface, midships section shape, entry angle, overhang lengths, freeboard, and sheer.

Waterline length is one of the factors determining potential speed of most sailboats. Just as the speed of sound is a barrier to aircraft flight speeds, waterline length is a barrier to boat speeds. Most hulls cannot exceed the speed of the waves they create, a wave that is as long as the hull at the waterline. This hull speed or wave speed in knots is considered to be about 1.34 times the square root of the waterline length in feet (1.34 x \( \sqrt{\text{wl}} \)). This barrier can be overcome by lightweight boats with flat underbody shapes, and high length-to-beam ratios like multihulls, board boats, and high performance racing boats that can climb up over the bow wave and onto plane, that is, riding more on top of the water than in it.

Wetted surface is the surface area of the underwater portion of a sailboat hull, keel, and rudder and is very much a function of both displacement and underbody form. That is, a full keel vessel of heavy displacement will necessarily have a greater wetted surface than a light centerboarder of the same length. Wetted surface creates drag and is one of the major factors involved in determining a vessel’s ability to move quickly through the water.

The midships section of a boat is one of the first things a designer draws. This helps the designer evaluate a number of variables related to the proposed vessel, and it helps establish the desired displacement. The midships section is the cross section of the boat taken at its longitudinal center. As the design develops, the progressive midships sections will show the trends of such factors as maximum beam, maximum draft, and general hull shape.

Entry angle is the angle between the sides of the boat at the bow. It is measured at the waterline level. Entry angle determines the fineness of the bow of a boat and is one of the considerations in establishing its ability to cut through the waves and maintain speed in waves. Figure 3–1 shows the entry angle.

The distances the hull extends beyond its waterline fore-and-aft are called the overhangs. As a vessel heels, its waterline shape changes. Long overhangs increase effective waterline length, and therefore potential speed. However, overhangs also increase the tendency of the boat to hobby-horse in heavy seas as the boat heels over. Waterline length is one of the major determinants of potential speed. Modern sailboats are designed with maximum waterline length compared to their overall length. Overhang is minimized in most modern designs.

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**Figure 3–1 Entry Angle**
Freeboard and Sheer
Freeboard and sheer are characteristics of the above-water portion of the hull. Freeboard is the distance from the water to the top edge of the hull. It is measured at various places along the hull. Sheer is the gentle curve formed by the top edge of the hull. Most commonly, the sheer is highest at the bow of the boat, and it dips to its lowest point about two-thirds of the distance to the stern of the boat and then sweeps up a bit to the stern. The sheer line and freeboard have a great deal to do with the aesthetic appeal of the hull, and much to do with the hull’s internal shape, particularly in regard to headroom. Older, more traditional boats had long overhangs, low freeboards, and sweeping sheers. This combination of factors produced vessels that often had little headroom below and were wet in a seaway because of their low sides amidships. More modern vessels have sometimes gone to the other extreme with high sides and no perceptible grace in their sheers or even reverse sheer. This has produced vessels that are dry at sea and have ample headroom below. As always in boat design, some compromise will most certainly produce the combined pleasures of beauty and comfort.

Dimensions
One of the major considerations in determining the dimensions of a sailboat is intended use. For example, the small size and low cost of the Turnabout sailboats make them ideal for teaching children how to sail. The Turnabout is nine feet / 2.74 meters long, five feet, three inches / 1.6 meters maximum beam, and draws just over two feet with the centerboard fully extended. Boats of this size are suitable for two or three children, or an adult and a child, to use in sheltered waters. While these boats may be capsized, the relatively broad beam does give them a fair measure of stability. Their small size makes them easy and inexpensive to buy and maintain.

Larger daysailers vary in size from 12 foot / 3.66 meters dinghies to boats over 30 feet / 9.14 meters long. Typical of this size is the Lightning class sailboat at 19 feet / 5.79 meters. Most of these daysailers are used for class racing as well as daysailing. As size increases, so does stability and the expense of equipment and upkeep. Many of the larger keel daysailers are sufficiently seaworthy for weekend cruising in waters where shelter is reasonably accessible.

Leeway
Sailboat hulls can be designed in different ways to reduce leeway. Hull types are often defined by the shape of the leeway control devices. These devices range from full keels, fin keels, centerboards, and daggerboards to leeboards mounted on the outside of the hull. Leeway is the tendency of the boat to move sideways under the pressure of the wind on the sails. Reducing leeway is accomplished by adding an appendage to the bottom of the hull. If the appendage is movable, it is called a centerboard, daggerboard, or leeboard; if fixed, it is called a keel.

Keels
Boats with keels are by no means all the same in underbody shape or in performance characteristics. A traditional full keel boat provides good directional stability. That is, it tracks well along a course with relatively little attention to the wheel or tiller. At the same time, this long keel with its added underwater surface area makes the boat slow to tack, and slower in speed, Figures 3–2 and 3–3.
Modern racing boats designed for speed usually have light displacement hulls with flatter underbody shapes and fin keels which are separated from the rudders. Some of the rudders are hung on skegs which are built onto the hull, Figure 3–4. Other rudders are balanced due to part of the rudder area being forward of the rudder stock, thereby reducing the power needed to turn the rudder. Such rudders are suspended on the rudder post only and are called spade rudders, Figure 3–5.

A deep narrow shaped fin keel, centerboard, or rudder is more hydrodynamically efficient in preventing leeway and providing lift when sailing to windward than a shorter, wider shape of the same area. These fin keeled vessels are quick to tack but sometimes are somewhat “squirrelly” or hard to keep on track when sailing down wind in a seaway. There is a limit to how deep fin keels can be because of the great structural strains placed on lifting surfaces, especially when subjected to violent wave action, or groundings in shallow water.

A second function of the keel, along with reducing leeway, is to place much of the weight of the ballast below the hull, thereby lowering the center of gravity of the boat and increasing stability. Newer forms for keel shapes have evolved primarily to increase performance in racing. These innovative designs include the forming of bulbs, which concentrate weight at the lower end of the keel, Figure 3–6. Winged Keels have also become popular on sailboats, Figure 3–7.

Various shapes, such as winglets, which increase the lifting characteristics and extend the apparent draft of the keels were developed for racing. They have lately been incorporated into the designs of shallow draft cruising boats, Figure 3–8.
25 New experimental designs feature canted keels were used on the Volvo Ocean Racing boats (Figure 3–9). They allow the boat to remain on an even keel while the deep ballasted keel swings to the windward side. The fore and aft vertical rudders provide lift to counteract leeway.

**Displacement and Ballast**

26 Displacement is the weight of a boat in its sea-ready condition. If a boat is slowly lowered into a tank filled with water, the water will overflow until the boat floats. The weight of the water that overflows will equal the weight of the boat, hence the term *displacement*. Displacement is normally expressed in units of weight such as pounds or tons but can be expressed in cubic feet of water.

27 *Ballast* is usually lead or cast iron placed low on a boat’s keel. Some boats will have some of their ballast in their bilges in the form of pigs of lead or iron. Ballast placed low gives the boat stability to help resist the wind’s heeling force on the sails.

28 The *ballast/displacement* ratio is the weight of the ballast in pounds or tons divided by the displacement of the boat in similar units. It is used to compare the amount of ballast relative to overall displacement and is a measure of a boat’s resistance to heeling. This is helpful in comparing boats of similar designs. Centerboard daysailers have relatively small displacements. In design descriptions for such boats, there is no mention of the ballast/displacement ratio since no ballast is built into the boat. The effect of ballast is achieved by the crew hiking (leaning) out on the windward side of the boat.

29 All keel boats carry ballast, and hence do have ballast/displacement ratios. These ratios vary widely by boat type. A Star class racing boat, for example, displaces approximately 1460 pounds / 662 kilograms, including 900 pounds / 408 kilograms of ballast and has a ballast/displacement ratio of about .616. This means that 62% of the boat’s total displacement is ballast. A 5.5 Meter® boat, a lean, deep racing design, displaces about 4580 pounds while carrying 2700 pounds of ballast. This gives her a ballast/displacement ratio of about .590.

30 The ballast/displacement ratios of cruising vessels will be smaller than those of racing boats. For example, *Finisterre*, the first centerboarder to win the Bermuda Race, was a yawl with 6,436 pounds of ballast and displaced 21,527 pounds. This gave her a ballast/displacement ratio of .299 or about 30%. The yacht *Indigo* had a ballast/
Sail

31 Remember that the relationship between overall weight and amount of ballast directly affects a sailboat’s ability to carry a spread of sail without heeling excessively. Specifically, a high ballast/displacement ratio is indicative of a sailboat’s ability to carry a greater amount of sail.

32 In wooden construction, ballast is usually made of lead and attached to the framing of the hull with long keel-bolts. It is termed ballast keel.

33 In fiberglass boat construction, the ballast keel may be similarly bolted onto the hull. If the lead is set into a void in the molded hull, it is just called ballast.

34 A lighter displacement boat can be made to stand up better or be stiffer if some of the ballast can be moved to the most effective positions at any particular time. This is accomplished in small boats by moving the crew. Larger boats sometimes use movable ballast. The New York Sandbaggers, in the early 1900s, moved 50 pounds of sand from side to side as they changed tacks. The Whitbread 60s used water for movable ballast in the around the world race, by filling tanks located under the weather rails while they were on long tacks, Figure 3–10. The water must be pumped or transferred by gravity before or during tacking to prevent possible capsizing should the ballast end up on the wrong side in a strong wind. In the 93-94 Whitbread, these water ballasted 60 footers proved faster than conventionally ballasted 80 footers on some points of sail in some conditions.

35 Another type of water ballasting is used in some modern trailerable sailboats. Long chambers built deep in the hull are opened to the water and filled when the boat is launched. The chambers are then sealed and the boat gains about 40% more weight than it had when on the trailer. Its stability is improved by the addition of this fixed water ballast. When the boat is pulled out the water is drained.

**Centerboards**

36 Small, light-displacement boats and some modern ocean-going boats rely on centerboards to avoid excessive leeway. This movable plate, pivoted near its forward edge, can be extended and retracted through a slot in the bottom of the boat, Figure 3–11.

37 The lateral plane of either a keel or a centerboard helps the boat resist sideways pressure. The pressure is greatest when a boat is close-hauled, that is, sailing as close to the wind as it can. As the point of sail moves farther and farther from close-hauled, the tendency to make leeway becomes progressively smaller. On a boat with a permanent keel, the wetted surface area of the boat remains almost the same, regardless of the point of sail. However, a centerboard or daggerboard can be retracted in small increments as the boat heads farther off the wind reducing the boat’s wetted surface. Since reducing wetted surface increases speed, raising the board increases speed.

38 Light centerboard dinghies respond quickly and require constant attention to the helm. Changing the height of the centerboard affects the boat’s lateral plane. Depending upon the point of sail, the centerboard height is adjusted to balance the helm. Centerboards usually weigh relatively little so their position has little effect on stability when the boat is underway. In small, centerboard boats, the most significant ballast is the crew. A centerboard is normally retracted by a pendant and relies on its own weight to extend it and hold it down. If the boat sails into shallow water with the centerboard down, the centerboard hits bottom first and pivots aft limiting any damage to the board itself.

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**Figure 3–10 Water Ballast**
Some small boats, such as board boats, have a daggerboard. Instead of pivoting in a well like a centerboard, the daggerboard, Figure 3–12, slides up and down in a trunk in the hull, often held in the down position only by friction and its weight. A daggerboard is sometimes used on larger boats, but this requires a method of maintaining its position other than by friction.

Centerboards on larger boats normally pivot and are raised and lowered into a shoal draft slotted keel by a crank or winch. This design provides keel boat stability and good windward performance with the board down, and shoal draft capability for operation in shallow water with the board up, Figure 3–13.

Leeboards

Some boats use leeboards as their means of preventing lateral motion. Leeboards, large airfoil-shaped plates attached to the sides of the boat, can be swiveled down when tacks and points of sail are changed. The crew of a boat going to windward would put its leeward board all the way down to maximize resistance to lateral motion, and leave the windward board up. On tacking, the crew would lower the new leeward board, and raise the windward one. This type of board has been common in the Netherlands for several centuries on boats large and small. It is used in this country on sailing canoes (Figure 3–14).
Several other variations of the twin-board configuration bear mentioning, though they are not commonly seen in the United States. These are bilgeboard and twin-keel boats.

The bilgeboard boat has two centerboard trunks, port and starboard, and the centerboards are used exactly as described for the leeboards.

The bilge-keel boat is popular in areas of Europe where yacht basins dry out at low tide. As the tide falls to less than the boat's draft, the boat comes to rest on the ballasted keels. The bilge keels hold the boat upright until the rising tide refloats the hull (Figure 3–15).

**Sailboards**

In the late 1960s a group of California surfers invented a type of sailing surfboard that is in worldwide use today. It exists under many commercial names, such as Windsurfer®, Windglider®, etc. These sailboards are capable of speeds of over 40 knots. The World record is approaching 50 knots. Typically they are 12 feet / 3.66 meters long, weigh about 40 pounds / 18 kilograms and carry about 70 square feet of sail fitted over the mast like a sock. They have a wishbone boom that is held by the sailor. They have a skeg, but no rudder, and are steered by maneuvering the sail and the sailor’s weight. They are excitingly fast, very unstable, and wet, Figure 3–16.

**Multihulls**

All the boats discussed so far have been monohulls or single-hulled boats. For much of history, boats with two or three hulls attached to each other have been sailed successfully. The Polynesians with their two-hulled voyaging canoes navigated vast expanses of open ocean for centuries. Vessels with two equal-sized hulls are called catamarans.
47 Today there are many large cruising catamarans, and small, daysailing catamarans, Figure 3–17, are common. Catamarans have a very high initial stability because their great beam resists heeling. At the same time, the intentional light weight of catamarans means that no ballast keels are attached to the hulls. Consequently, they have little ultimate stability. Should a catamaran heel excessively in a strong gust, it is likely to capsize. Righting a capsized catamaran can be difficult.

48 A vessel with three hulls is called a trimaran, Figures 3–18 and 3–19. The central hull is the longest, with a shorter hull attached to each side. Most trimarans are large cruising boats.

49 Multihulls, as catamarans and trimarans are called, are much faster through the water than monohulls of similar length. But they tack slowly because of insufficient momentum and the resistance to turning offered by the two or three hulls.

**Rudder-Tiller**

50 There are several types of rudders and rudder control arrangements for small to moderate-sized sailing boats. On the smallest boats, the most common arrangement is the transom-hung rudder with a tiller, Figure 3–20.

51 The rudder is equipped with pintles: pins affixed to the rudder which run parallel with the edge of the rudder. These pintles fit into rings called gudgeons, which are through-bolted on the centerline of the boat’s transom. Generally, the pintles are long enough and the rudder is heavy enough so that it isn’t necessary to secure the pintles once they are dropped through the gudgeons. However, on boats with light rudders and shallow transoms, it is sometimes necessary to ensure that the rudder will remain in place by some device such as putting a pin through a hole in the end of each pintle.

52 On larger daysailers and on many cruising-sized sailboats, the rudder is placed forward of the transom, either suspended on its own rudder post or attached to the trailing edge of the keel or a skeg.

53 On virtually all daysailers, the helmsman controls the rudder by means of a tiller. On the smaller boats, the tiller is attached directly to the rudder head, usually in such
a way that the tiller can be raised, should the helmsman decide to steer while standing up.

54 Smaller cruising vessels usually have the tiller fastened to a rudder post that passes up through the bottom and the deck of the boat. A packing gland around the rudder post keeps the water out. The tiller is attached to the rudder post and pivots to permit steering at various angles.

55 Wheel steering provides the helmsman with mechanical advantage to reduce the force required to turn a large rudder in a seaway. These steering systems employ chains, cables, gear linkages, or some combination of these between a wheel in the cockpit and the rudder head.

**Summary**

Various types of sailboat hulls have evolved over the years. Each type is intended to prevent undue lateral movement (leeway) resulting from wind forces. Each has advantages and disadvantages resulting from its particular type of appendage. New materials and construction techniques provide improved designs. The material most often used in the construction of small sailboats is fiberglass-reinforced plastic. The designer considers many factors when drawing the lines for a sailing vessel. The general type and intended use of the boat are key. These factors largely determine the form of the boat’s hull. Form considerations include displacement, waterline length, underbody shape, wetted surface, midships section shape, entry angle, overhang lengths, freeboard, and sheer. Waterline length is a major determinant of boat speed. A boat’s overall weight and amount of ballast has much to do with the spread of sail a boat can carry without heeling excessively.
Homework: Section 3: Boat Design and Hull Types

Name ___________________________________________

1. The primary purpose of keels and centerboards is to:
   a) reduce leeway.
   b) provide a deeper bilge.
   c) slow down the boat when sailing off the wind.
   d) increase the maximum draft of a smaller boat.

2. When included in the boat design, keels usually:
   a) do little to prevent leeway.
   b) are retractable for sailing downwind.
   c) are weighted to lower the boat’s center of gravity.
   d) are buoyant so that the boat will not sink if filled with water.

3. Sailboats with full keels compared to those with fin keels:
   a) tack more quickly.
   b) go better to windward.
   c) have less wetted surface area.
   d) have better directional stability.

4. A sailboat with a fin keel compared to one with a full keel:
   a) is faster.
   b) is heavier.
   c) is slower to tack.
   d) is inherently better balanced.

5. On fin keel boats, the rudder is:
   a) not necessary.
   b) attached to the keel.
   c) attached to a skeg forward of the keel.
   d) not attached to the keel.

6. A daggerboard is:
   a) a stationary centerboard.
   b) pivoted at the forward end.
   c) often held in place by friction.
   d) usually pivoted at the after end.

7. A centerboard is a:
   a) large daggerboard.
   b) board above the keel.
   c) board separating port from starboard.
   d) board which is raised or lowered by a pendant.
8. Consistent with limiting leeway, the design of a sailboat’s hull is based primarily on:
   a) overall length and freeboard.
   b) general type and intended use.
   c) overhang length and entry angle.
   d) wetted surface and midships section length.

9. Freeboard and sheer primarily determine the:
   a) boat’s speed.
   b) displacement.
   c) aesthetic appeal of the hull.
   d) effective waterline length of the boat.

10. To design for increased speed:
    a) reduce sheer.
    b) increase displacement.
    c) add wetted surface area.
    d) increase waterline length.

11. Which of the following is true? Ballast:
    a) is usually iron or lead.
    b) in centerboard daysailers is non-movable.
    c) was usually kegs of rum in old sailing vessels.
    d) is carried low in the keel to improve lateral resistance.

12. The displacement of a boat is:
    a) the weight of the boat.
    b) the same as the wetted surface.
    c) measured by the size of the waves it makes.
    d) the area of the underwater portion of the boat.

13. Ballast/displacement ratios are:
    a) greater than 1 in small boats.
    b) determined by the rudder size.
    c) between 0.5 and 1.0 for cruising sailboats.
    d) a key factor in determining ability to carry sail.

14. The wetted surface of a boat is:
    a) the surface area of its deck.
    b) the part that is exposed to the elements.
    c) the underwater surface area excluding keel and rudder.
    d) the surface area of its underwater portion.

15. The waterline length:
    a) increases with boat speed.
    b) has no relationship to boat speed.
    c) is a major determinant of boat speed.
    d) usually decreases when the boat heels.