Keels

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It's a clichéd question almost as old as yachts themselves; what is the "best" type of keel? The debate gets quite heated when conservative cruisers clash with radical racers in the Club bar – the long keel versus fin keel debate. This short article on a long topic will help put a bit of flesh on those beery debates. Hopefully it will not only help you understand the keel of your current boat if you have one, it will also help you decide which type of keel you want for your next boat.

Upwind performance

When sailing upwind, the keel has two jobs to do. Firstly, it has to contain enough ballast low down to stop the boat heeling over too much ("power to carry sail"). Secondly, the keel must generate a sideforce that opposes the sideforce generated by the sails. The keel does this by operating at an angle of leeway i.e. the water is flowing onto the keel at a small angle, typically 5-10 degrees. Some of the solutions for meeting these two requirements can be in conflict e.g. a big fat bulb of lead at the tip (bottom) of the keel helps stop you heeling over, but it can disturb the flow over the keel and reduces the sideforce unless very carefully designed.

Generally speaking, for good upwind performance you want a thin, deep keel with enough area to provide the required sideforce. Unfortunately we come up against another conflict, this time with the requirements for downwind performance….

Downwind performance

When sailing downwind the boat is almost upright because the sails are not generating any sideforce to speak of, so there is no need for the keel to generate any opposing sideforce. Also, you only need enough ballast in the keel to stop the boat capsizing – there is no need for power to carry sail. You almost don't want a keel at all (which is why boats with centerboards lift the centerboard when sailing downwind). If you are stuck with a fixed keel then you want something with least drag. This means small area (less friction) and thin section (less form drag). You might have noticed this is the opposite of the characteristics required for good upwind performance.

Some geometric terminology

If you are looking at the side view of the keel (profile view), the chord is the fore-and-aft length and the span is the up and down length (figure 1).

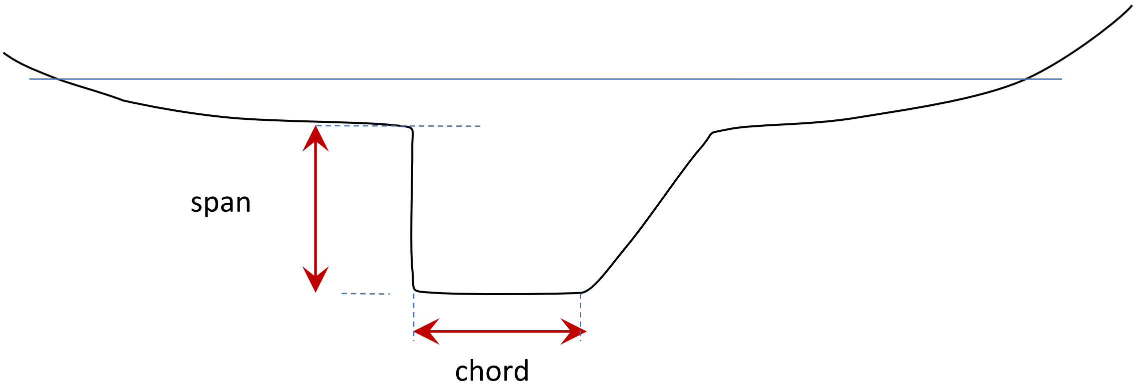

Figure 1: Profile view

If you look in plan view (bird's eye), you are looking at the keel section, the "streamlined" shape (figure 2). You will see the chord as the length of that shape and the thickness as the… well, the thickness.

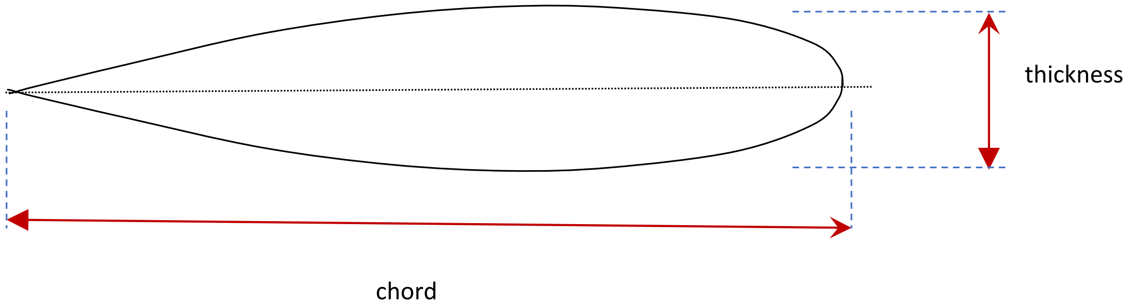

Figure 2: Plan view

Size

A bigger profile area (side view) means more surface area, which in turn means more friction drag hence slower speed. So for downwind performance at least, we want a small keel. However, for upwind sailing it is more complicated. If the keel area is reduced, friction drag is reduced but the amount of sideforce generated is also reduced. You need to generate that sideforce, so to do this the small keel operates at a larger angle of leeway, which reduces performance when sailing to windward. So in terms of windward performance the keel should be of small area, but not too small.

Aspect ratio

Aspect ratio is the span divided by the chord e.g. if you have a keel that is 1.6m deep below the hull (i.e. its span) and 0.8m long fore and aft (i.e. its chord) , the aspect ratio is 1.6/0.8 = 2.

The higher the aspect ratio, the more efficient the keel is, which means you can have a keel with smaller area if it has greater area. That is why racing yachts have very high aspect ratio keels. Why don't cruising yachts always have high aspect ratio keels? Three reasons:

- You end up with a very deep draft, which limits the bays and harbours you can get into.
- A high aspect ratio keel tends to stall easily. Stall? Stall is when the angle of the water flow onto the keel is too high and the keel stops generating useful sideforce; the boat just goes sideways instead of forwards. This will happen when you are coming out of a bad tack, or if sailing upwind slowly in waves.
- A high aspect ratio keel is structurally not as strong as a low aspect ratio one – it has a longer lever, increasing the load on the keel bolts.

Section shape

There's a lot of nerdy talk written about keel sections - NACA profiles, laminar buckets (!) etc. Here's a very simple guide to avoiding the worst shapes. See figure 3.

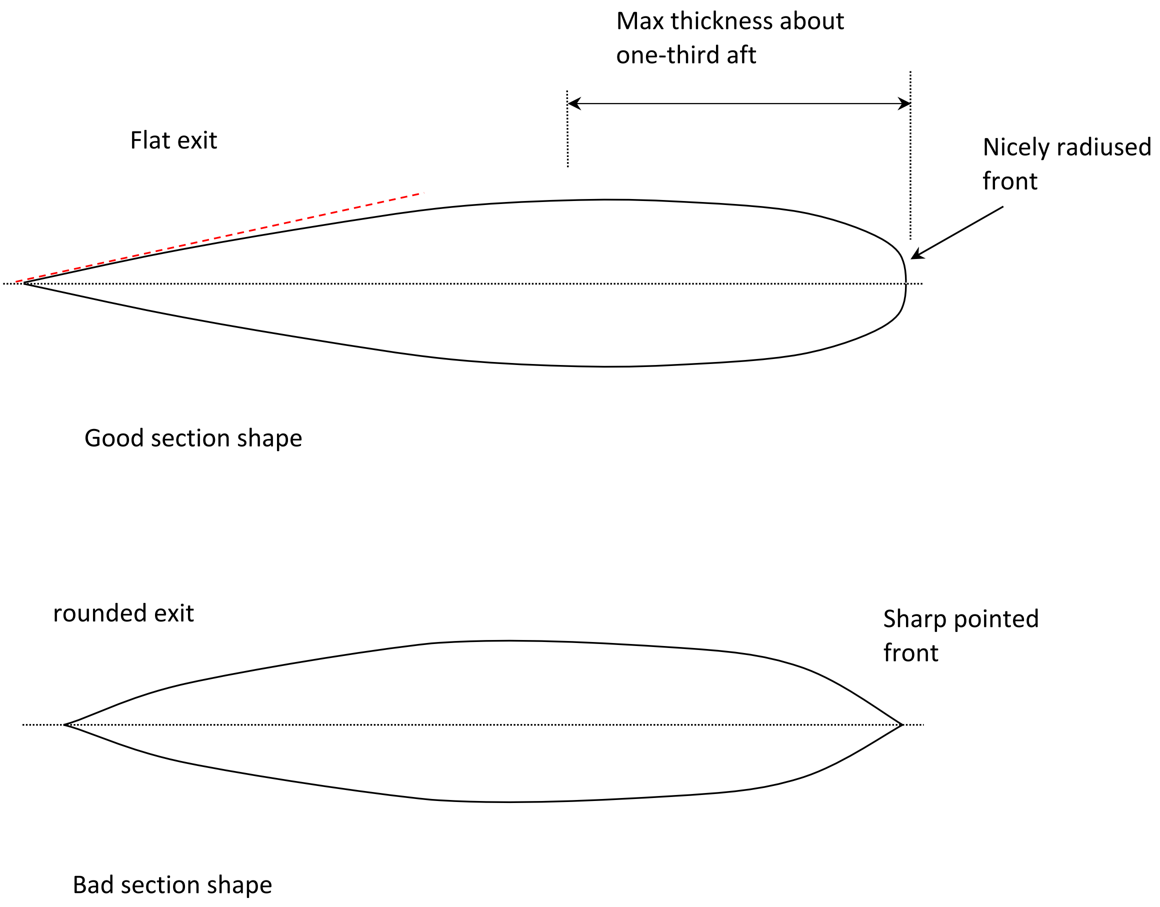

Figure 3: Section shapes

The front bit

The most important thing is not to have a sharp front bit (the "leading edge") – a fairly small radius is usually best, merging into the traditional "aeroplane wing" shape. The worst thing you can have is what you often see on keels made up of plate metal – the two sides are bent round some frames then welded together down the leading edge in a rough vee shape. Not good. It should be nicely rounded, no flat parts. So for the front part of the keel, think musically – no sharps or flats.

The thick part

The next most important thing is to make sure the position of maximum thickness (however much it might be) is about one third back from the front edge. How thick should that maximum thickness be though? In terms of hydrodynamic performance in good sailing conditions, the thinner the better. However, if you go below about 8% thickness (i.e. the maximum thickness is 8% of the chord length) you can run into the following problems:

- The keel can stall when coming out of a tack or sailing in waves. If you have been following me so far, you will now realise that a keel stalls easily if it is too thin or if its aspect ratio is too high i.e. a typical racing keel
- It is structurally weak – you have all that weight hanging off a very thin bit of metal.
- If the keel is lead or iron, then a thin keel has less volume than a thick one so you won't be able to get as much ballast into the shape. You will have to either make the chord length longer or the span longer. It might be better to make the keel section thicker instead.

The back bit

The final thing is to have the exit of the section straight i.e. if you offer a straight edge up horizontally against the rear part of the keel, it should touch the keel surface all the way from the back edge to about one quarter of the way forward. Some racing yachts have a slight hollow when you do this. Whilst such a shape might work for high performance racing keels, it is probably not worth it for cruising yachts. Why? Racing yacht keels only have to work at water flow angles up to about 5 degrees (i.e. the leeway angle) under normal sailing, when the hollow aft works well. However, if you are manoeuvring, or if the boat is not very efficient, the leeway angle can be 10 degrees or more. In those circumstances the keel which is hollow aft has worse performance than one with a straight aft section.

Stability: power to carry sail

One way of describing the goal of keel design is to fit the maximum amount of ballast into the most hydrodynamically efficient shape possible. This involves trading off the extra drag due to area and thickness, for the increased volume you can put the ballast into. One way of avoiding this trade-off is to have a small, thin, deep, keel which has low volume (hence not much space for ballast, but low drag), then put all the ballast in a big bulb at the bottom of the keel. This puts the ballast very low down where it has most effect, but a bulb creates a lot of drag unless designed very carefully indeed. So the trade-off now becomes bulb volume versus bulb drag. The winged keel was an example of a low drag shape that kept the ballast low. However, it is only really beneficial if you have a constraint on draught (as the 1983 America's Cup 12 metre rule had). Other things being equal, a deep keel without wings performs better than a shallower keel with wings.

Directional stability

Directional stability is the ease or difficulty with which a boat turns, or sails in a straight line. A boat with large directional stability is one which will carry on sailing in a straight line if you let go of the steering (wheel or tiller) for a minute. Unfortunately this valuable attribute also tends to make the boat very slow to turn when manoeuvring. A boat with low directional stability will turn very quickly when manoeuvring, but will probably screw up into the wind the moment you let go of the helm. That is a gross simplification of a complex phenomenon, but it is a good starting point. So what does the keel have to do with all this? Two things mainly. Firstly the fore-and aft position of the keel affects directional stability, but in a complicated way. You would expect that a keel well aft would give you better directional stability (that's why they put the feathers at the back of an arrow, not at the front). However, I know of boats with the keel located a long way forward which have good directional stability. Regardless, the matter is to some extent out of our hands because the fore and aft position of the keel is often determined by where the ballast has to be in order to keep the boat trimming level (too far forward and the boat trims bow down; too far aft and it trims down by the stern). The second and probably more important keel characteristic influencing directional stability is its chord length (fore and aft). A keel with a long chord will turn more slowly than a keel with a short chord. Taken to extreme, a full length keel is the type with greatest directional stability, and also the slowest to manoeuvre.

Take all the above with a pinch of salt, because directional stability and manoeuvrability are also strongly influenced by the design of the rudder, and to a lesser extent by the design of the canoe body. Yes, it's getting complicated!

Motions

When most people talk about the motion of the yacht they are generally thinking of the pitching and rolling.

Pitching

Pitching is the most sever motion when sailing to windward. The keel shape plays no direct part in the pitch motion. However, the location of the ballast within it does. Pitching motion is affected by an attribute of the boat called the moment of inertia. This is a measure of how the weight is distributed in the boat. If it is all concentrated near the centre of the boat, the boat has a low moment of inertia. Conversely, if the weight is spread out fore-and aft, or up and down, the boat has a high moment of inertia. A boat with a high moment of inertia will tend to pitch more, but at a slower rate than a boat with a low moment of inertia. If all the lead is in a bulb at the bottom of the keel, this puts it a long way from the centre of the boat, so the inertia will be high. Conversely if the ballast is mainly close to the canoe body (e.g. the top of the keel is thicker and has a longer chord than at the tip), then the inertia will be low. That's how it all works for pitch; now let's move onto roll motion.

Rolling

Rolling is generally worst when sailing downwind, or when at anchor in an exposed bay. The influence of the keel on roll motion is more complicated than for pitch.

Inertia

The moment of inertia explanation above for pitching to windward applies equally to rolling downwind; ballast low down in the keel makes for smaller roll angles but quicker roll motion.

Stability

A boat that is stiffer, or more stable, will have a much quicker roll motion than a boat that is tender. So the more ballast there is low down in the keel, the more rapid the roll motion. Note that this is the opposite effect of low ballast creating high inertia. Usually, the stability effect of low ballast is greater than the inertia effect, so a stiff boat with ballast low down has a more rapid motion than a tender boat with the ballast higher up.

Damping

The shape of the keel plays an additional role in roll motion, called damping. When the boast rolls from side to side, it must drag water with it from side to side as it moves. This generates waves at the water surface. Generating waves requires energy and that energy must come from the boat. So dragging the keel through the water sideways absorbs energy from the boat's rolling. This reduces the roll motion, the effect is called damping (the roll motion also creates extra water inertia, but that's another story). It would seem likely that a keel with a large profile area will have more damping than one with a small one. And this is approximately true. There are some subtleties in terms of keel taper and total perimeter(edge) length, but a big keel will damp out roll more than a small one.

Practicalities

For all this analysis of hydrodynamic efficiency and stability, there are other factors affecting choice of keel design. Here are a couple that might be important, depending on where you sail.

Drying out

If you sail in a region with a tidal range greater than about 2m (e.g. most of northern Australia), then you may have the option, or possibly the misfortune, of lying alongside a jetty afloat at high water but aground at low water. As the tide drops and the boat sits on its keel, it is nice to have a long length of keel to sit on, rather than a short length. A boat with a short chord length keel tends to pirouette around it as the tide goes out, leading to all sorts of strife. Most (but not all) long-keeled boats will sit comfortably on a long keel as the tide drops. I know of one boat (a Folkboat) that spent an entire winter ashore sat only on its keel, the cradle supports not touching the hull. On the other hand, I once owned a long-keeled boat (an aptly named Twister) which had its centre of gravity just forward of the bottom of the long keel. As it dried out it would pivot about the forward edge of the keel unless you took avoiding action with strategically placed shore lines.

Craypots

Craypots and crab pots are the sailor's curse in many parts of the world. The line to their surface float tangles itself round any boat the has the temerity to sail over it. If you have a keel with a swept back leading edge then you stand a good chance of escaping the rope's grasp; if it is a full-length keel then your rudder and propeller are also quite well protected. However, if you have a nearly-upright leading edge (or worse, a keel bulb that projects slightly forward of the fin), then you can find yourself in serious trouble when you sail over a craypot line. The need to avoid this situation can dictate your choice of boat design (fig 4).

Centerboards and lifting keels

By now it should be clear that keel design involves a lot of compromises between upwind and downwind sailing performance. In simplistic terms we need an efficient keel upwind, but we don't really want a keel at all when sailing downwind! Rather than compromise, you can simply get rid of the keel downwind by raising it into to the hull. This is an attractive idea, which has the further benefit of allowing the boat to operate in shallow water. So why don't all boats have a lifting keel or centreboard? The reason are mainly practical. Firstly the method of lifting the keel/centreboard is yet another thing to go wrong. Secondly, antifouling the keel and the box/slot it goes into is difficult; thirdly, it is possible to get something stuck in between the keel and the box (e.g. a stone), jamming the keel either up or down; fourthly, if you are going to operate the boat in shallow water with the keel up, then you also need to have a rudder that is shallow, which can be inefficient unless designed carefully. There are also issues of ballast placement and stability to consider, but they can also be dealt with by thoughtful design.

Conclusion

As with most design features, choice of keel is a question of compromises, the design point determined by the type of sailing you do. Hopefully, with the information provided in this short article, you are now better equipped to work out what type of keel best suits your type of sailing.