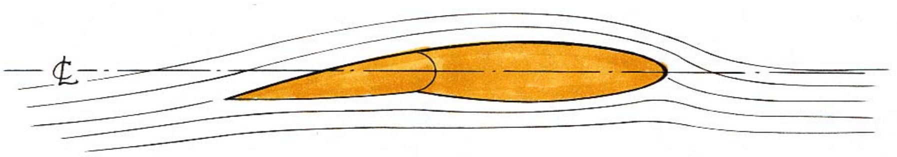
OF FLYING FOILS AND WINNING WINGS

Looking at the America's Cup boats in a different perspective



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A woman gracefully concealing her charms may certainly attract a man's interest and it seems that the skirts hiding the keels of the America’s Cup class has the same effect on most journalists. And in the America’s Cup 1992, those hidden keels certainly seem to have been worthy of their curiosity because this was the year of introduction of the new International America’s Cup Class, IACC.

In 1992, the America's Cup started out as a wild, brainstorming race between all kinds of funny foils. The defender’s series, Louis Vuitton Cup, was won convincingly by *Il Moro di Venezia*, which was beaten in the finals by the defender, *America*^{3}. After the Cup finals, however, all reports describing these two boats spoke of "conventional" keels. For those with a trust in aerodynamics experts exploring brave new ideas in super computers and wind tunnels, it may have been disappointing that those bizarre tandem keels and canards didn't quite make it. Why did they fail and, more important, why did the two most successful teams go for something "conventional"? Obviously, their appendages were second to none. Were they in fact conventional?

Definitely not. The keels of *America*^{3} and *Il Moro di Venezia* were far from conventional but employed a very radical approach in the design process, making them exceedingly superior to conventional keels. Strange to say, the very idea behind their design came to life in different people's minds at the same time. I, for one, hold a patent for this principle. As it turned out, the two best boats were already using exactly the same principle. This is how it works:

The function of a keel is to prevent leeway, and to do so with the smallest possible resistance. These requirements can be expressed in terms of LIFT and DRAG. Since this may be difficult to grasp, let's look instead at an aircraft wing. The purpose of an aircraft wing is more obvious, but wings and keels are nevertheless comparable. The lift of a wing is directed upward, that of a keel to windward; however, wing sections are generally much more efficient than keel sections.

FIG. 1 WINGS vs. KEELS

This is a typical wing section. The cross-section view is the most important projection, because it shows the direction of airflow. The shape has been thoroughly researched by NASA and the aircraft manufacturers among others, and it would be ideal for a sailboat if it was all right to sail on one tack only.

Unluckily, sailboats are required to use symmetrical keel sections. The lift/drag ratio of these keels are inferior to the aircraft wing by 20% or so. In order to create a slightly improved lift, or sideforce, the aft portion can be made movable, forming a trim tab. However, this still does not make it the most sophisticated wing section.

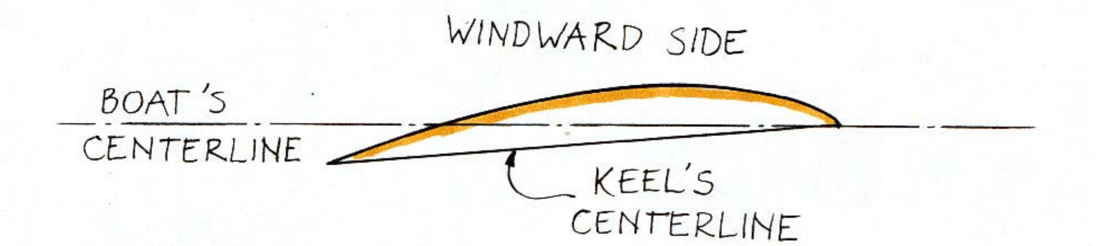
Using increasingly refined methods, keel section shapes have been perfected over the years but, basically, very little has changed. In some racing classes, people have tried to overcome the limitations of the ordinary keel. For example, if the only ambition is to reduce leeway, one may pivot the entire keel, pointing the leading edge a little to windward. This concept was used some 20 years ago on a few IOR half-ton racers but the mechanism usually failed to work and it was soon abandoned.

The two boats in the finals in America's Cup in San Diego 1992 dropped the entire fundamental idea of symmetrical keel sections overboard, using a different approach altogether.

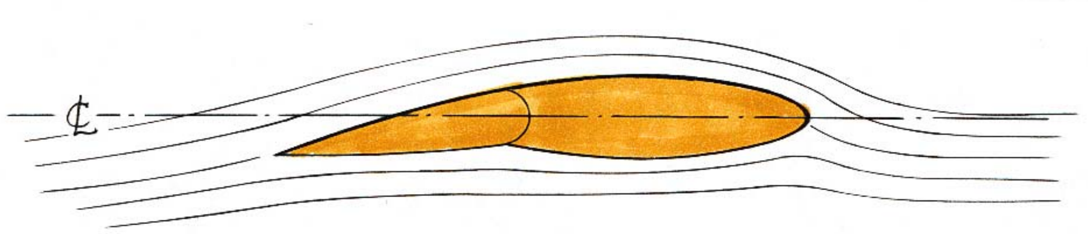
Taking a closer look at an aircraft wing, you may have noticed that whereas the upper side has an absolutely perfect, evenly curved shape and a smooth surface, the underside is often cluttered by mechanisms controlling the flaps, by engine attachments, landing gear and protruding rivets. Aircraft designers have long ago recognised that the shape of the upper, or low-pressure, side of a wing is decisive. This explains why a keel section should be designed starting with the windward side.

To sum it up, the ideal sailboat keel should be like an aircraft wing. It should have an asymmetrical shape for best lift/drag ratio. It should be set at a slight angle in relation to the hull in order to eliminate leeway. The shape of the windward side should be absolutely perfect. And, at the same time, its shape should be inverted when coming about, making it equally fit for both tacks! Such was the problem that the designers of *America³* and *Il Moro di Venezia* set out to solve. And although the task might seem impossible, the solution turned out beautifully simple. The resulting keels made an immediate impact on history: *America³*, Bill Koch's maxi *Matador II* before that, and *Il Moro*. This is how it is done:

First, the angle of the keel's centerline in relation to the hull centerline is determined, the leading edge pointing to windward by a few degrees. The windward side is then designed as a smooth curve, with a shape resembling the upper surface of an aircraft wing:



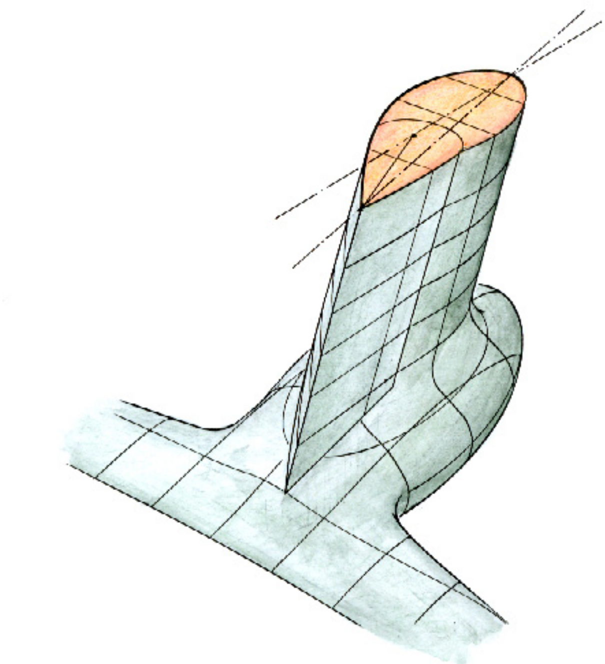
The rear portion of the keel is then carried out as a flap and the leeward side is designed as a mirror-image of first keel, then flap:



Almost any flap size can be chosen - this choice will only affect the shape of the leeward side. Of course, the actual outline of the section has to be refined through wind tunnel or computerised analysis of flow and pressure distribution, but this is true for all keel or wing sections. The America³ design team performed wind tunnel analysis on 120 different keel configurations, according to Bill Koch.

As it turns out, this novel kind of keel section has two major advantages over existing types: First, a higher lift and a lower drag are inherent in the design. Thereby, the keel can be made smaller than usual and the net result will be a significant reduction of drag . Secondly, leeway is eliminated. In practice, this means that the keel is able to push the boat to windward with zero degrees, or even a slight inverse, leeway, still maintaining an extremely favourable lift/drag ratio.

In all, this new keel was capable of speeding up a boat by as much as one or two minutes over a race so it may certainly have been decisive in the outcome of the Cup races in San Diego. If the "wing keel" of *Australia II* marked a new era in 12-m design in 1983, the wing-like keels of *America³* and *Il Moro di Venezia* in 1992 may well turn out to be an innovation of even greater future importance.

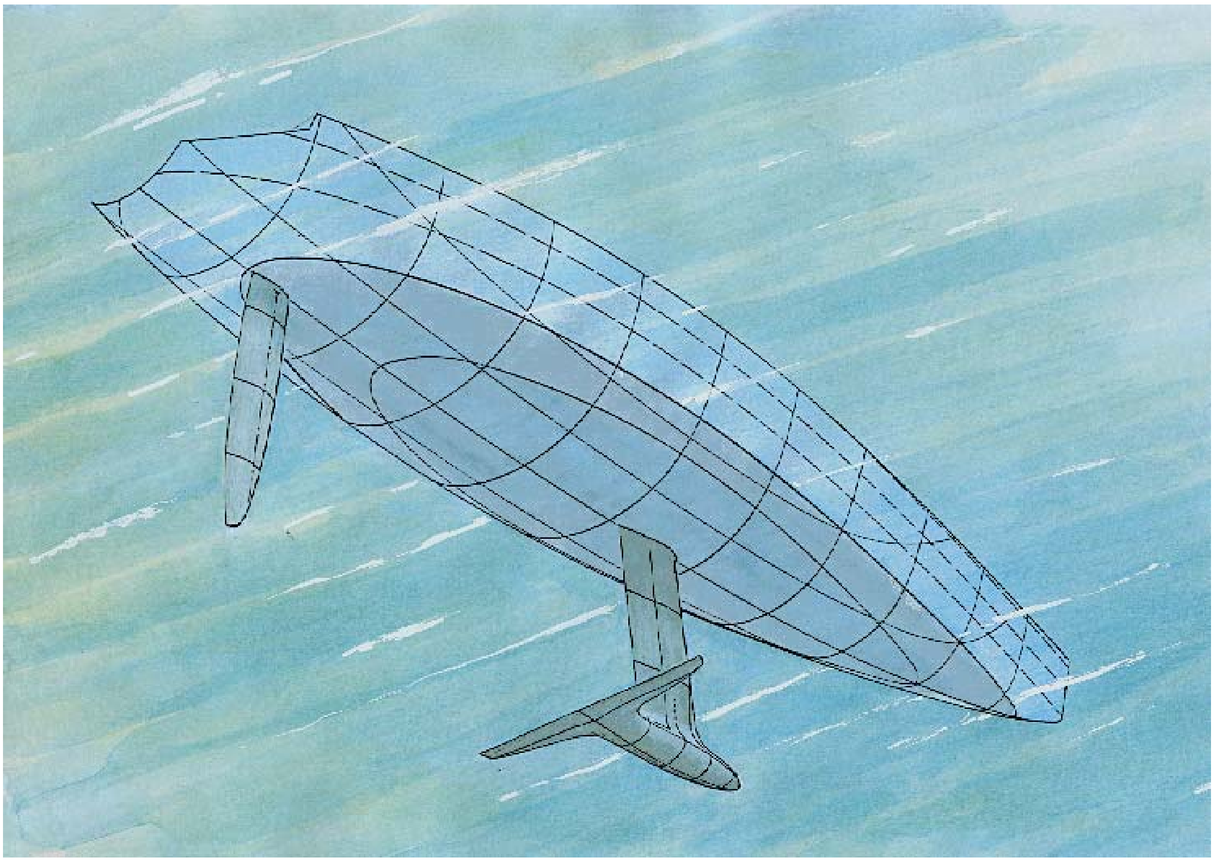


There was a difference between the winning keels in that the one used by *America³* in the finals had a smaller area and a neater bulb than *Il Moro*. In order to compensate for the loss of lift and stability it had, reportedly, larger wings and carried some ballast inside the fin, which was constructed of steel. The rudder was smaller, as well.

Interestingly, these smaller appendages were part of a greater context - the quest for a minimum wetted surface. It seems that the 'Cuben' designers were the only ones who fully understood that the light winds in San Diego required, above all, maximum sail area and minimum wetted surface. Beam and stiffness were of much less importance. In this respect, they may not have gained much from their spy activities in the sense that they could copy others, but more so from their right to select a boat long after all others.

Consequently, *America³* was narrower on the waterline than most and considerably narrower on deck than all others, thereby reducing wetted surface, especially when heeled. However, narrow beam also meant a lighter hull and this, too, was for a specific purpose: pursuing the absolutely minimal pitching moment. Since this depends more on the distance between the boat's center and all different items than on their actual weights, weight aloft and ballast bulb weight are among the most harmful and the Cubens set out to reduce all such loads.

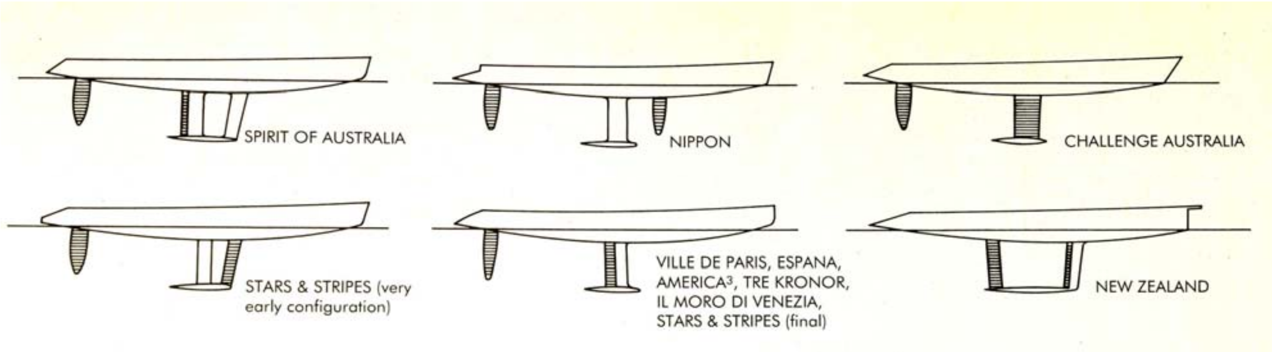
The first step was to move some lead out of the bulb to the inside of the keel fin. Considering the 54.000 lbs displacement of *America³*, the usual ballast bulb would have to be in the region of 38.000 lbs. By placing between 5.000 and 9.000 lbs. inside the fin, and possibly some in the bilge, the size and weight of the bulb could be cut drastically. Having a more tender boat, even mast diameter could be reduced by a slight percentage and, using their carbon fibre sails, sail weight was cut by some 30 percent. Pitching moment thus reduced, *America³* had a notably easier motion in the sometimes confused chop off Point Loma.



With her narrow beam and her easy motion, the fine bow of *America³* sliced through the Pacific swell more easily than her opponents, to eventually win the America's Cup 1992 over *Il Moro* by a small but convincing margin. Beneath the surface, her new wing-like keel section played an important part in that victory. And, although it may not appear spectacular, it certainly is a very radical keel.

An exposé of the other keels in 1992 is given below. Some of the concepts shown did prove insufficiently waterproof and were never to be used again. However, since the Cup races were held in San Diego also in 1995, all syndicates in 1992 had reason to protect the store of knowledge in which they have invested so much. Therefore, the best keels were never officially revealed. In 1995, all syndicates were using variations on the new principle. And I doubt that we will ever again see the kind of experimentation with funny foils that we had in 1992.

WHAT DID THE OTHERS USE?

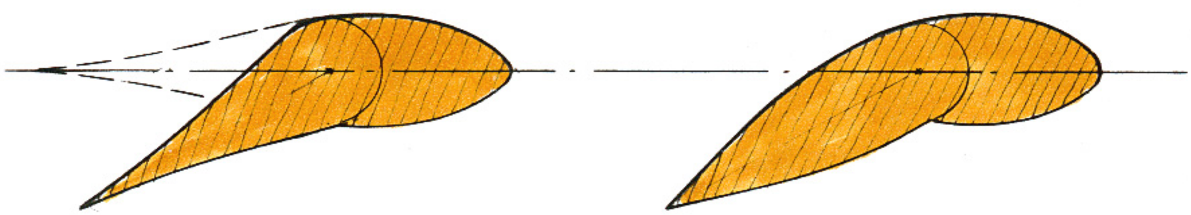


In 1992, only two teams were using the new keel concept described in this article. The others had to settle for something different, which by necessity usually meant something inferior. The designers were free to use their imagination, the main restriction being the structural demands on a slender foil 10 feet long having to support the weight of a railway carriage. Consequently, the opening races in January saw some wild ideas being used, like the tripod keel of *Spirit of Australia*.

THE LOOK-ALIKES

The keels of *Tre Kronor* and *Espana* were very basic fins equipped with trim tabs and carrying large torpedo-shaped bulbs. They obviously worked quite well, almost eliminating leeway with their trim tabs set at angles of maximum 8 or 10 degrees. Still, they suffered from being on the large side, having an undesirable drag.

FIG. 2



The figure shows two unlikely keel sections with much exaggerated trim tabs, or flaps, set at extreme angles. With the ordinary section, you will have an impossible stall situation caused by an abrupt change of hydrodynamic pressure at the flap joint.

The new keel still has a wing-like section, although much exaggerated, because it was intended that way already at the design stage.

Using normal flap sizes and angles the situation is not as bad for the ordinary section. It is then inferior only: 1) When the foils are small and under load, as in a seaway or when manoeuvring, because of stall. 2) In all conditions, because of an inferior lift/drag ratio and a greater leeway angle.

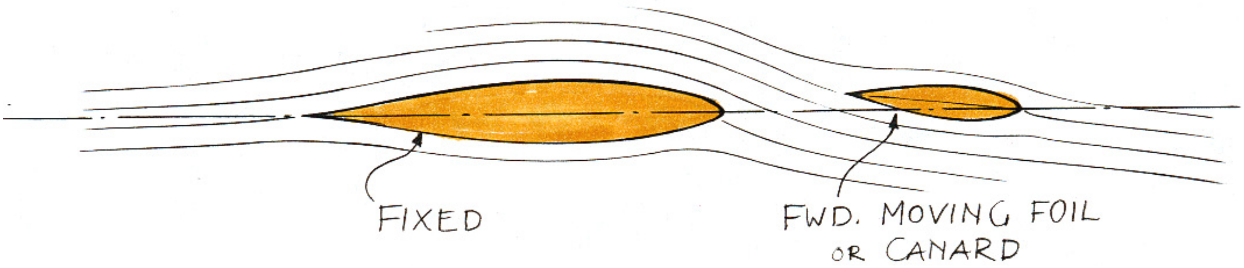
Le Defi Francais and team Dennis Conner both declined an offer to use the new keel concept. Instead, *Ville de Paris* and the last version of *Stars & Stripes* were equipped with symmetrical keels which, essentially, did not differ much from those of *Tre Kronor* and *Espana*. The sections used were modern NASA or Wortmann adaptations of the ordinary symmetrical sections, or own versions of the same, intended particularly for the use of a trim tab (by making an indentation at the keel-trim tab joint, there will not be as prominent a knuckle on the windward side when the tab is in use). In order to understand the difference between these keels and the new concept, take a look at the much exaggerated example.

Challenge Australia was different from all others and obviously did not hit on any secret formulas for winning. It may be surprising that she sported the kind of pivoting keel described in the article. Soon enough, they were simply using it as a fixed keel.

TANDEM KEELS

When the races started, tandem keels were on everybody's lips. *Spirit of Australia*, *Stars & Stripes*, *Nippon* and *New Zealand* used different varieties of such keels. The idea behind the tandem keel could be said to be related to the interaction between jib and mainsail. For a given sail area, two sails are better than one. The question is whether the same argument is valid for keels. The interaction between the two foils requires that water flows at an angle onto the first foil, then the slot between the two, and then the second foil - just like the way the wind hits the sails! This can only be achieved if the boat has a substantial leeway angle – see figure:

FIG. 3 TANDEM KEEL

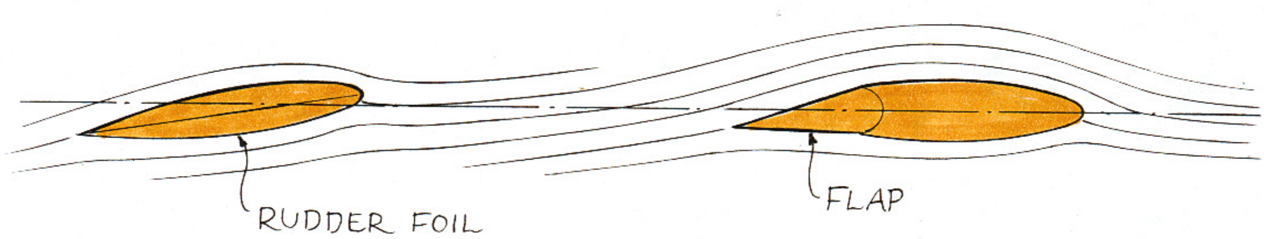


Nippon sported a slightly different setup in the form of a fixed main keel carrying the ballast bulb and a canard, much like a forward rudder, ahead of this. One object was to break the tip vortex up into smaller, and less retarding, portions (the wings of monokeels serve the same purpose, among others). Between each round robin series they altered the relative positions and sizes of their foils but never really found the boatspeed to match *Il Moro* and *NZ IV*.

WHY DIDN´T *N.Z.* HAVE A RUDDER AFT?

There is one way to make a tandem keel perform well. If both foils of a tandem setup are made adjustable they may create the lift required even without leeway. The problem is, the new IACC rule only allows the use of two moving appendages so if both foils of a tandem keel are moving, this means that the ordinary rudder aft has to be dispensed with. This was the basic arrangement used by *New Zealand*, making it the only successful boat with a tandem keel - alas at the price of occasional steering problems. Team Dennis Conner also used this idea at one stage but never got it working. See figure:

FIG. 4 NEW ZEALAND



The keel of *New Zealand* was described by Bruce Farr as a breakthrough but, whatever its virtues, it was not possible in this year's America's Cup to assess it properly, because *NZ IV* was also some 17 percent lighter than *America³* and *Il Moro* and carried less sail area. Thus, she might possibly have performed just as well, or better, with the novel kind of wing-like keel described in this article.