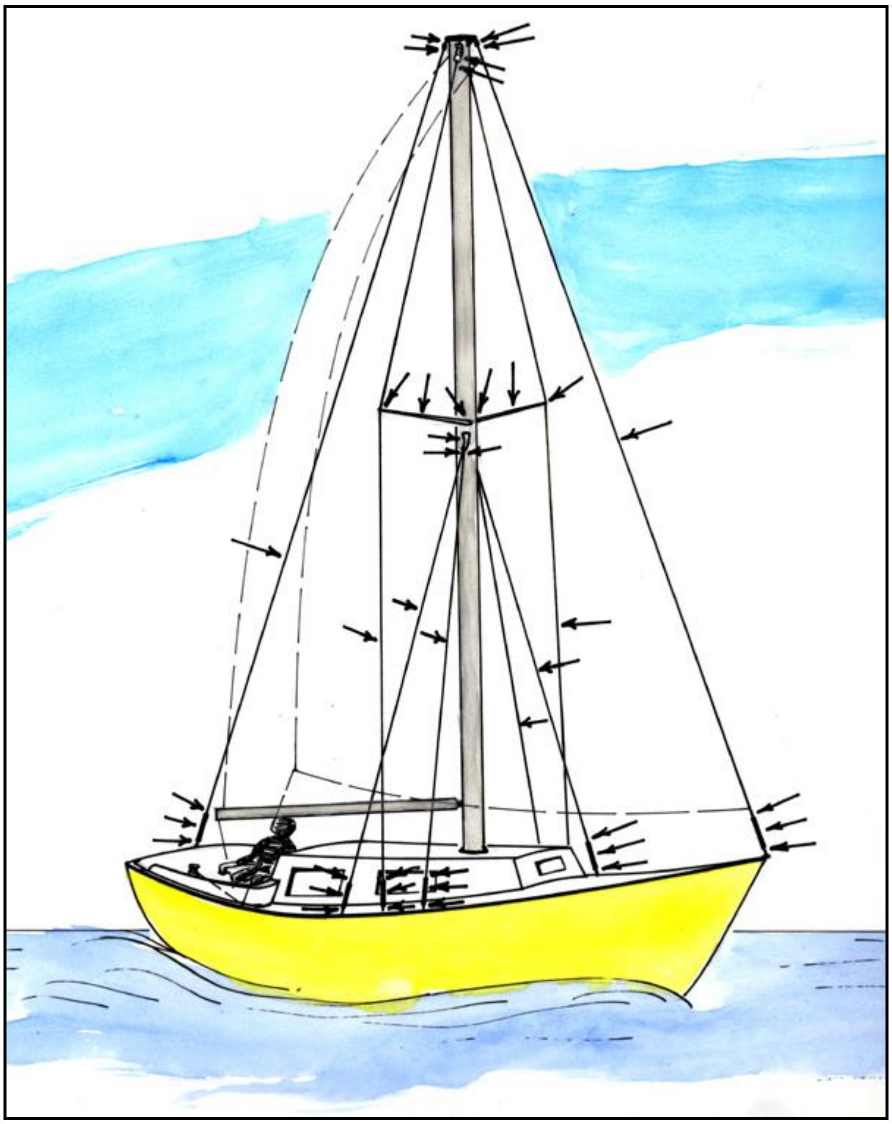
FREE-STANDING MASTS

SOME THOUGHTS ON THE STATE OF THE ART:

Safety, simplicity, efficiency.

Free-standing rigs are inherently safer, simpler, and more aerodynamically efficient than conventional rigs. They are safer because stayed rigs are held up by hundreds of little parts, any one of which could fail or slip out and cause the rig to fall down. A free-standing mast is held up by just two parts—the partners and the heel fitting—so safety of the rig increases by the ratio of many hundreds to 2!



Lose any one part of a piece of standing rigging, and the whole rig can come crashing down. Many of the parts are up high and out of sight, so even detecting the onset of a failure is problematical because inspection requires a fair amount work, and so is done rarely.

Free-standing masts are held by two parts, the heel fitting and the deck fitting. These are substantial structures that are close at hand for easy inspection. Failure here is very unlikely, and the onset of failure is easily detected because the parts are easily inspected.

Free-standing rigs are more aerodynamically efficient because without wires, the sailplan is no longer *defined* and *confined* by the triangular shape bounded by the headstay and backstay. The triangle is absolutely the <u>worst possible planform shape</u> that anyone could ever conceive of to be a lifting surface. Why?

Because of induced drag.

Induced drag is automatically created with lift. You can control it—make it bigger or smaller—but you can never get rid of it. Induced drag is a fact of life.

In any given aerofoil planform, the airflow on both sides of the surface are at different static pressures—high pressure to windward, low pressure to leeward—and they would really like to equalize. In a triangular planform, the airflow on the high pressure side gets a chance to equalize sooner, by virtue of the shape, than on a rectangular planform for example, by skewing up toward the tip and off the surface. This skewing of flow from the high pressure side, mixing with the flow on the low pressure side, creates a vortex off the tip. The bigger the skew, the bigger the vortex, and the greater the induced drag. In his book *Aero-Hydrodynamics of Sailing*, C.A. Marchaj (pronounced MAR-ki) shows a photo of what the tip vortex looks like.

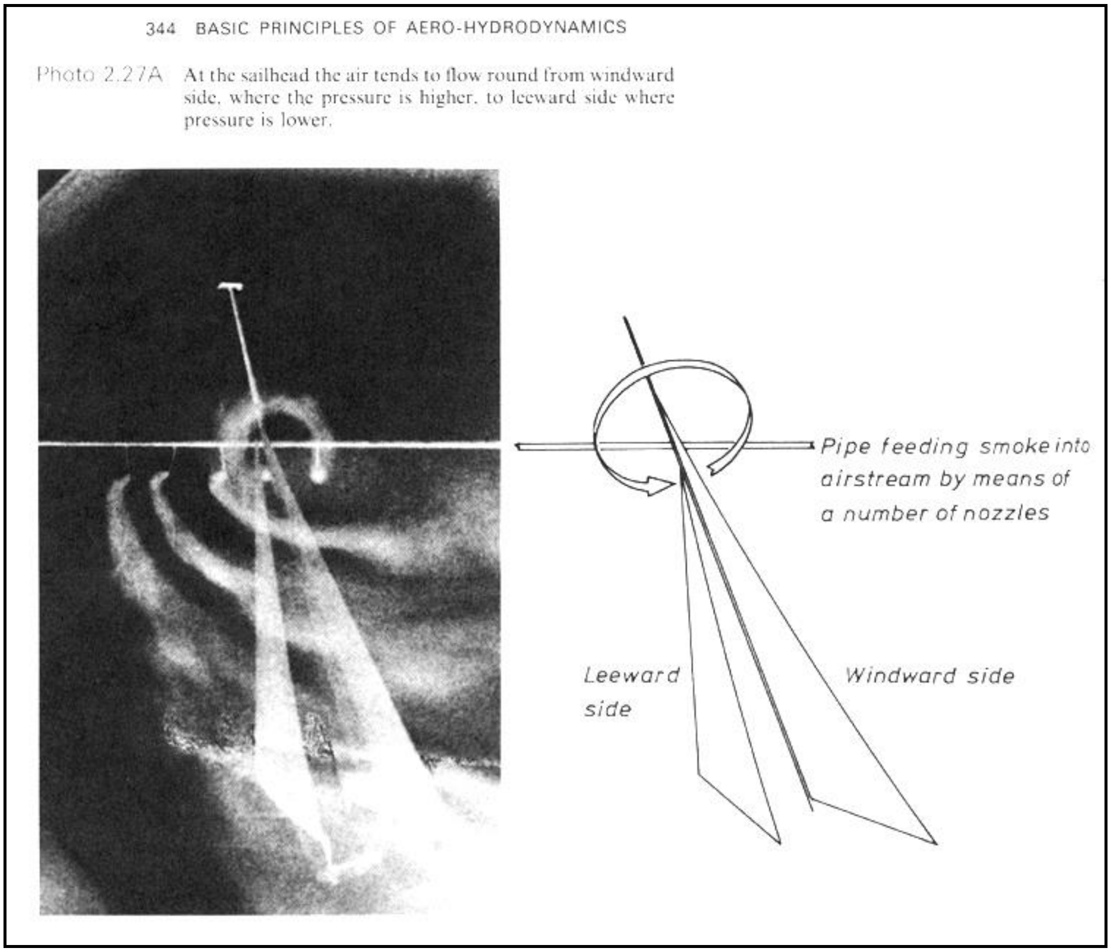
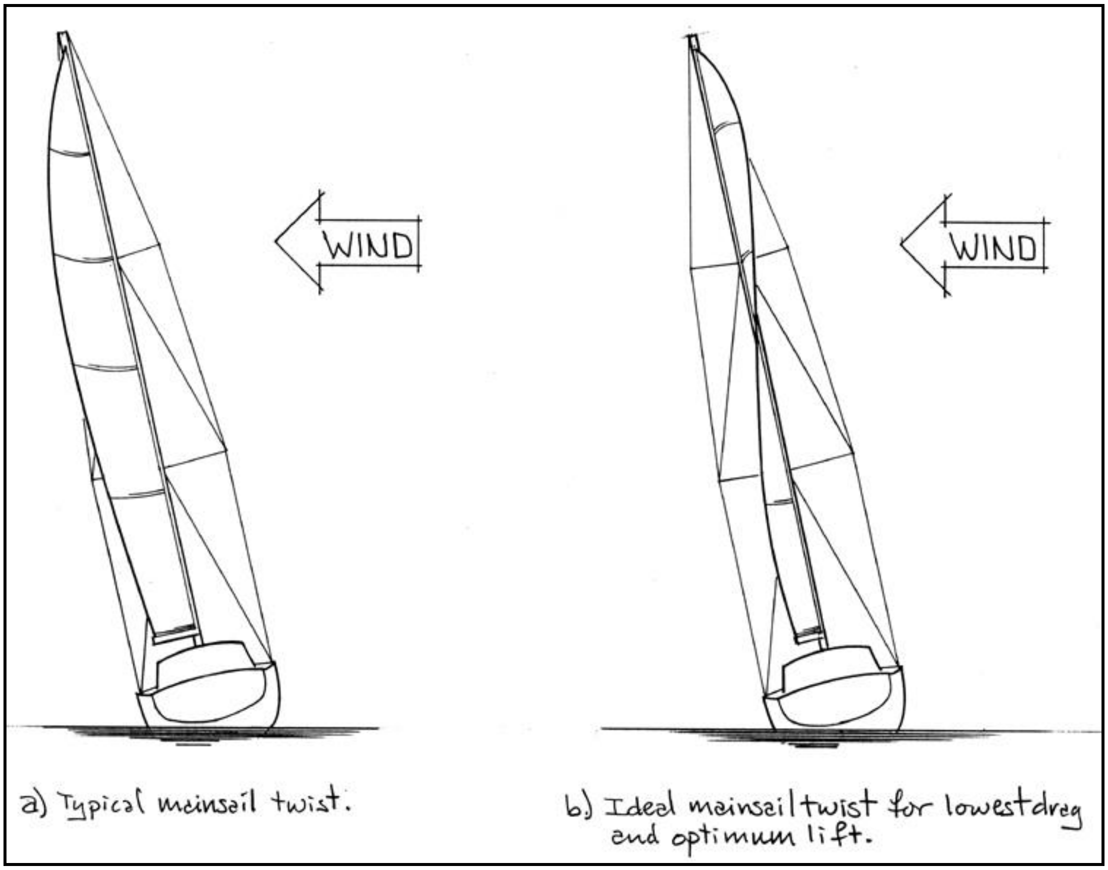

344 BASIC PRINCIPLES OF AERO-HYDRODYNAMICS

Photo 2.27A At the sailhead the air tends to flow round from windward side, where the pressure is higher, to leeward side where pressure is lower.

C.A. Marchaj, Aero-Hydrodynamics of Sailing, *Dodd, Mead & Co., first edition, 1979. Photo 2.27A.*

In order to reduce this vortex, we can do a number of things. If we keep the triangular shape, we would have to twist the head of the mainsail to *windward* in order to reduce the vortex and induced drag. But this is nearly impossible to do. And even if we could, this would increase the angle of attack in the upper part of the sail which would bring that portion of it much closer to stalling. To stall means to lose lift entirely. It is governed strictly, and by definition, by angle of attack. So to twist the head of a triangular mainsail to windward would involve lots of complicated gear only to get the sail to balance precariously between high lift and no lift. This won't work.



Twisting the upper half of a mainsail to windward is a futile exercise in contortion.

A much more workable alternative is to use a totally different shape for the planform, either elliptical or rectangular. The flow across an elliptical planform, as it turns out, has little tendency to twist off into a large vortex. In fact, the vortex is very small. A rectangular planform also has a pretty small tip vortex, and it can be made smaller, close to or better than that of an ellipse, if the tip of the sail is twisted to *leeward*. This is exactly how gaff rigs are shaped and why they are actually pretty efficient. It is also why we add roach to the leeches of mainsails—we are trying to approximate an elliptical or even a more rectangular, twisted, planform. You may have seen square-topped mainsails on modern multihulls and windsurfers. This is the reason—to reduce the tip vortex, and therefore the induced drag, to as small as possible. Less drag for the same amount of lift, or even greater lift, means more aerodynamic efficiency. More power is being devoted to making the craft move forward, not sideways. The same science applies to keels and rudders, which we refer to as hydrodynamic efficiency.

And by the way, keels and rudders are not triangular, so why should sailboat rigs be triangular? They shouldn't. Look at the fastest rigs in the world--windsurfer rigs--NOT TRIANGULAR! Airplane wings are not triangular (we're talking subsonic here; it's different when you're traveling faster than the speed of sound). And by the way, airplanes shed their wires back in the 1920s--why should sailboats be so archaic? They do not have to be.

The only reason we have triangular sailplans is because we have wires that hold up the masts, and this necessarily makes sails triangular. And if you have wires in the way, you don’t want your sails to chafe too much on the wires, so we have triangular sails.

And the only reason we have wires in the rigs is because we are afflicted in modern sailboat design with arbitrary sailboat design rating rules that, for no good aerodynamic reasons, require the wires in the rigs. I have my own theory as to why this is: The reasons go back thousands of years.

Somewhere deep in history, when the first monkeys dropped down from the trees, one of them discovered that you could ride on a log in the water, and that if you stood up on the log, the wind could blow you along faster that if you just wallowed there and swam along. Then some gorilla got the bright idea of holding a few branches in outstretched arms to gain more area, more drag, Hey!—more speed. So then some orangutan stuck a whole tree in the log, and maybe another built a raft and put in a bigger tree, and sailed even faster. Pretty soon you had all these baboons sailing around in these huge rafts with these big trees, but stripped of all their branches and animal hides strung on them with yardarms and such, and pretty soon they were sailing all over the ocean.

Finally, along comes some enterprising chimpanzee who figures out that if you tie two trees together, one on top of the other, you can make masts as tall as you want. You don’t have to merely look for ever bigger trees. But you have to hold them up with vines, or else learn how to make ropes and use those to hold up the masts. Eventually, rigs got taller, rafts turned into ships, ships got bigger and carried cargo, apes started charging money for their shipping, shipping companies made fortunes, and the apes could finally afford to build and race little boats again purely for pleasure, and what the hell, let’s race, too. Naturally, these boats were built with rigging to hold up the masts. But they needed to make sure that the boats were equal in some way, so they figured out they could do that by using the tonnage rules that governed their shipping. The date was now somewhere in the mid-1500s, during the reign of Queen Elizabeth I. However, these tonnage rules included only length, beam, and draft in their formulae. Sail area was unrated.

Then in 1883, some sailors on both sides of the Atlantic decided that maybe sail area ought to be rated, too. This was a very controversial topic with the detractors claiming that sail area should be unlimited and governed only by the laws of nature and the skill of the crew. The proponents, however, felt that sail areas were getting way out of proportion and way out of control. Racing boats were becoming downright dangerous. Some baboon had to exercise control. Well, naturally, the convenient measuring points for measuring the rig were where the standing rigging attached to the hull, deck, and mast. Standing rigging was taken for granted. While many evolutionary changes have occurred in rig design over the years--most notably in new materials, first with metals, then with composites--standing rigging still remains steadfastly impacted inside the rating rules. And there is no relief in sight. Wires in the rig, and, therefore, triangularly shaped sails, are so inbred into our industry and our thinking that we blindly accept them without question.

The rating rules say the wires have to be there, so designers put them in. If you don't have wires, you cannot race. If that is how the racing fleet goes, so goes the rest of the boating market—cruising boats as well as racing boats. It is a very artificial feature of sailboat design that has absolutely nothing to do with aerodynamics. C.A. Marchaj, again in his book *Aero-Hydrodynamics of Sailing*, bemoans this state of affairs:

> *Certainly the rating rules have in this respect a more profound effect on the shape of sails than the aerodynamic requirements or wind in all its moods. The penalty incurred for example by the sail measurement system on the width of the headboard of the mainsail or length of its top batten is so high that it virtually precludes any attempt to improve the aerodynamic effectiveness of the modern tall rig. Those curious prohibitions, which after years of enforcement became part of sailing tradition, effectively discouraged ocean racing people from making experiments with unorthodox rigs which could have led to the development of less tall but more efficient rigs. So triangular rigs prevail.*

It takes a bit of courage, I guess, to ask the question: "Why do we do this?" Well, sailors and designers are insanely conservative people. There is no other explanation. The idea of a mast without wires is so foreign to most people that they just cannot fathom how a sailboat mast can stand up all by itself without something to hold it up.

Hmmm. Have you ever seen a tree? How about a flagpole? What about those airplanes I mentioned, you know, the ones that got rid of the wires holding the wings on, way back in the 1920s? Today, a Boeing 747 airliner at take-off weighs 875,000 pounds, carries 524 passengers, flies at 567 miles per hour more than 7 miles above the earth, *and it does not have any wires holding the wings on!!!!*

I have been designing free-standing masts for over 30 years, so I think I can speak from some relevant experience. From my standpoint, the single biggest reason why people do not like free-standing masts is (are you ready??):

"Because they look funny."

I'm not kidding—this really is true.

And the second most common reason is:

"If you take away the wires, I won't have anything to hold onto."

I can't do too much about the first reason except to say, "Hey, snap out of it!" As for the second reason, it *is* possible to put other hand-holds and stanchions around the boat, you know.

That said, there is one other big roadblock that makes free-standing masts and rigs fairly rare—Cost of and ease of construction.

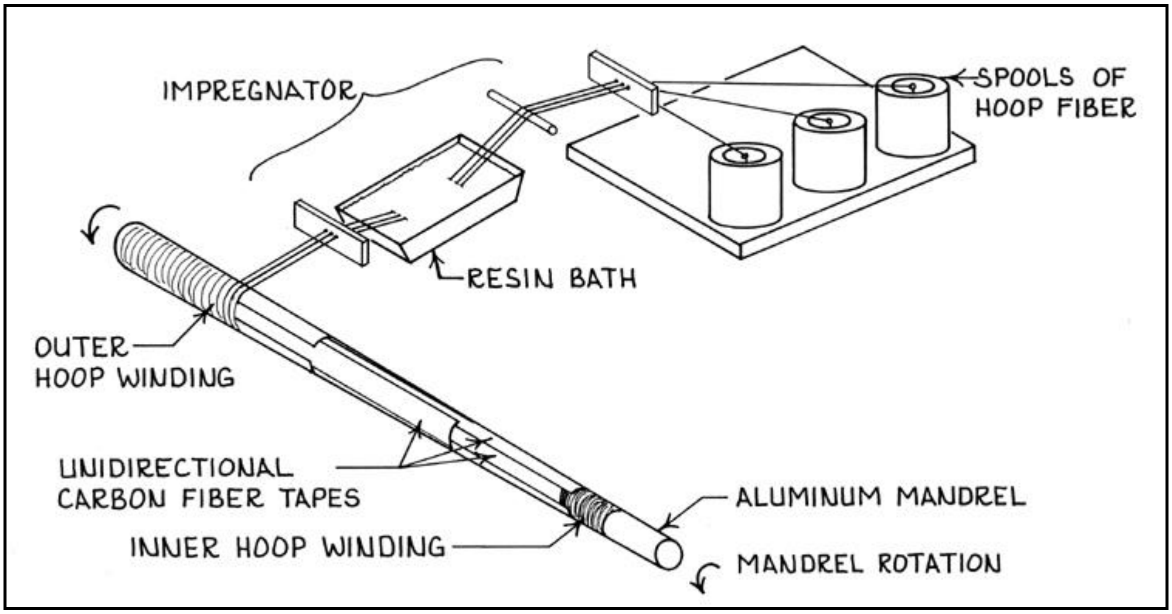
Mast design and construction.
In engineering jargon, free-standing masts are called cantilevers. Stayed masts, on the other hand, are columns. Cantilevers bend, columns compress. The two behaviors are different, and so the structures are designed and built accordingly.

In a stayed rig, the boat heels due to wind pressure on the sails. Without wires holding up a normally skinny mast, the rig would fall over. But the wires hold the mast in place, pulling on the mast in tension and with their lower ends anchored into the deck and hull. This tension in the wires induces an equal and opposite compression load in the mast itself. The mast has to be big enough in cross-section with a thick enough wall so that it can handle the stress and not buckle.

In a free-standing rig, the wind pressure on the sails causes the mast to bend sideways and back. No wires support the mast, so the mast itself has to have a big enough cross-section and a thick enough wall to handle the load. This necessarily makes the mast bigger than its equivalent stayed counterpart.

And this is where carbon fiber plays such an important role. Carbon fiber laminates are about 60% of the weight of aluminum, the most common mast material, yet carbon is more than twice as strong. This makes carbon fiber a much more efficient material than aluminum when it comes to making sailboat masts (and other weight/strength sensitive structures, like airplanes).

The trouble is, you have to engineer the mast for the boat at hand. All boats are different, so all masts are going to be different. You have to begin with a long pole, or mandrel, on which to build the mast. This pole, usually built out of aluminum, has to have a taper on it so that it can be removed from the inside of the finished mast tube. The mast is laid up with individual strips of carbon fiber, most of which (anywhere from 60% to 80%) runs parallel to the mandrel axis, with the remainder (40% to 20%) running off-axis, generally split evenly between hoop windings (90° to the mast axis) and bias windings (±45° to the mast axis). The carbon fiber laminate is thicker at the base, where the load is greater, and tapers in thickness towards the top where the load goes to zero.



This is a typical set-up for making carbon fiber masts, whether free-standing or stayed. Most mast builders nowadays do not use wet lay-up, but rather pre-preg lay-up, in which the resin has been applied in a sticky film to the carbon fiber by the fabric processor. It is then shipped frozen to the mast builders and kept cold until needed. During cure under heat and pressure, the resin liquefies and soaks through the fiber, then solidifies into a hard plastic, encapsulating the carbon fiber as it does so. The result is an amazingly strong and lightweight material tailored exactly to the loads at hand.

Therefore, every mast laminate is tailored to the mandrel and the boat at hand. The carbon fiber strips have to be placed in precisely the correct orientations and at the right intervals in order to make the mast carry the loads properly and bend exactly the right amount. Finally, the mast has to be cured under the proper conditions. If wet epoxy resin is used, the stages of lay-up have to be timed so that the fiber can be put down correctly before the resin starts to cure. If vacuum bagging is used, the time to set the bag also has to be taken into account. If an autoclave is used (an autoclave is a heated pressure cooker), the lay-up can be done more leisurely using pre-impregnated fabrics, but the cycle time for the heat and pressure to ramp up, hold, and come down is critical. And autoclaves are expensive pieces of machinery.

When designing a mast, I cannot simply “draw up a laminate” and expect it to be built properly. I need to know details about the boat design, the shape of the sailplan, and I need to know who is going to build the mast. The details on the mast construction plans will be determined accordingly. A do-it-yourself owner is going to need far more construction information than an experienced mast builder.

I also need to know what brands and types of carbon fiber are going to be used—there are hundreds of types and styles, and the availability of each changes regularly. What was available this month will not necessarily be available next month. Lead times for ordering carbon fiber are long, and you have to buy in set quantities, usually much more than you need to use in a single mast. In such cases, we try to get small amounts of carbon fiber piggy-backed onto someone else’s larger order, and then split them off to the appropriate customers. This takes some timing and planning in the design process.

Finally, I need to know the precise dimensions of the mandrel on which the mast is going to be built. The mast is engineered for section shape and laminate thickness at every foot along the mast. From the engineering I can determine how many specific strips of each type of carbon fiber material will be placed where. I specify the length of each carbon fiber strip and its precise location in the mast. This has to be done carefully so that the laminate is as uniform as possible to carry the loads. Also, the builder has to be extremely careful that all the carbon fiber is laid down flat and in the proper orientation. Deviations from the laminate schedule—kinked fibers, air bubbles in the laminate, non-uniform layering, shifting layers under pressure—any number of little faults during the construction can lead to a premature mast failure.

Boat size and multihulls.

I have nearly 60 mast designs to my credit, and some have been built by the owners themselves, but most have been built by professional builders. I describe this process to explain why mast designs are not cheap, not until you get up to larger boats, say over 40’ or so, where the cost of construction for a free-standing mast and rig becomes comparable with its stayed counterpart. Below that size, mast design and construction generally cost more than the owner has a budget for. Above that size, the cost of the rig is more in keeping with the cost of the boat.

I get a lot of mast inquiries from people who are building little boats between, say, 15’ and 25’, who want to know if a free-standing mast will make their boat better, simpler, faster, etc. for all the reasons I explain above. In theory, yes, but it costs an inordinate amount of money to do it, again, for the reasons explained above. For small boats, you really can’t beat aluminum for strength, stiffness, and most of all, price. And the weight savings between carbon fiber and aluminum is still on the order of 40% less, but we’re talking only a few pounds here—not tens or hundreds of pounds. The cost for a carbon rig on such small boats is simply not worth it. As I said, your boat generally has to be about 40’ long before the cost becomes bearable. And by that I mean that someone who has the money to build a 40’ boat can more likely swallow the cost for the design and construction of a custom free-standing rig.

I also get a lot of inquiries for free-standing masts for multihulls. The big problem with a multihull is that it has a huge righting moment—usually much bigger than on a comparable monohull—which reaches maximum as soon as the windward hull rises fully out of the water. This is a real situation on racing multihulls and many cruising multihulls, one that is likely to occur regularly over the course of the vessel’s lifetime.

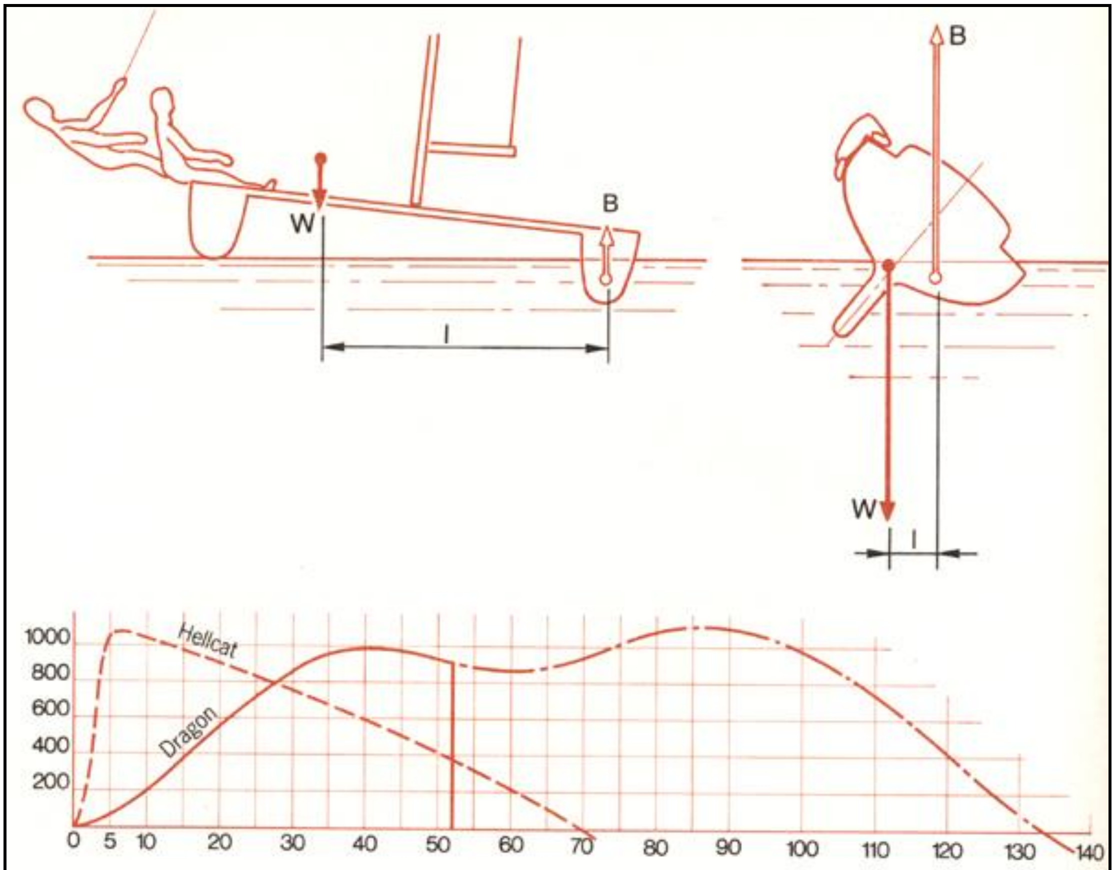


Figure IV.20 *The Hellcat catamaran and the* Dragon *have the same maximum righting couple, but the former owes her stability to her form and the latter to her weight.*

Pierre Gutelle, The Design of Sailing Yachts*, International Marine Publishing, first edition, 1979. This shows a typical comparison between the righting curves of a small multihull and small monohull. Note that the peak of the multihull curve occurs at a small angle of heel, whereas the peak of the monohull curve occurs at a much larger angle of heel. The multihull will see its maximum load much more frequently than a monohull will. This has to be taken into account when designing the mast.*

As a result, the mast section size has to be a lot bigger, and wall thickness a lot thicker for a free-standing mast on a multihull than for a monohull. This has two bad effects: it makes the mast much heavier, and it makes it much more expensive to build—two things that multihull sailors simply hate!

On the other hand, a multihull, by virtue of its width, has a much broader staying base than a monohull so that high loads in rigging are mitigated somewhat by the angles the shrouds and stays make to the mast. This has a modifying effect on the compression in the mast, allowing the mast to be made somewhat lighter and, therefore, cheaper to build than one would otherwise expect, considering the high righting moments involved. An aluminum stayed mast is a reasonable lightweight, cheap option.

Wingmasts

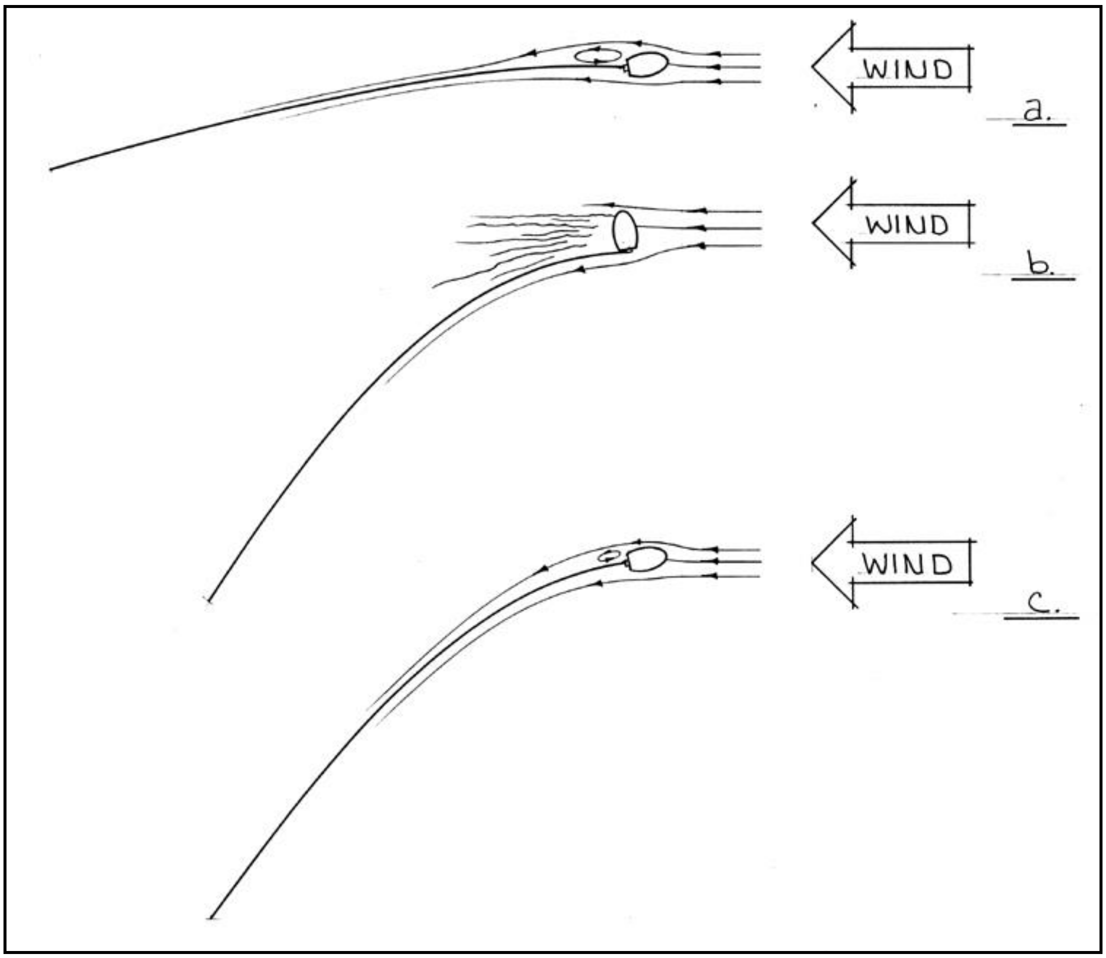
A wingmast is a mast shaped like a wing that is allowed to rotate. Wing shape and rotation further increase the efficiency of a free-standing rig. Unfortunately, mast rotation also falls victim to traditional rating rules—it is not allowed. This prohibition can be traced back to L. Francis Herreshoff, who had a patent on a rotating mast design, one of which he installed on an R class boat (Lwl = 20’) called *Live Yankee* in 1925. But when the regatta committee of the New York Yacht Club heard about this rig, it promptly passed a rule prohibiting “revolving masts, double luffed sails and similar contrivances.” This prohibition remains in current rating rules, and no changes to eliminate it are in sight. It really smacks of spite against a progressive designer and the yacht club’s desire to protect the status quo of the fleet at the time. But that was almost 80 years ago! It is truly amazing to me that such a prohibition has remained in place for so long.

A popular misconception about wingmasts. They are not as silly-looking as these, but some people in boating do have funny notions. The picture is accurate in two respects: 1) Wingmasts are unusual, and 2) they do cost money, usually significantly more than a stayed rig because construction is complicated, and the bearings are expensive. That is why our intrepid owner is holding a bag of it.

However, in spite of the rules, rotating a stayed mast is difficult to say the least because the rigging wires simply get in the way. And actually, when sailing on the wind, stayed rigs are really very good. The airflow over a non-rotating mast attaches really well over the mast and mainsail. The power generated by a stayed rig on the wind and a free-standing wingmast rig on the wind are pretty comparable. Two boats of the same type but with different rigs—stayed and unstayed—do not have much advantage over each other—they sail about the same. The differences are really apparent when sailing off the wind. See the figure below.

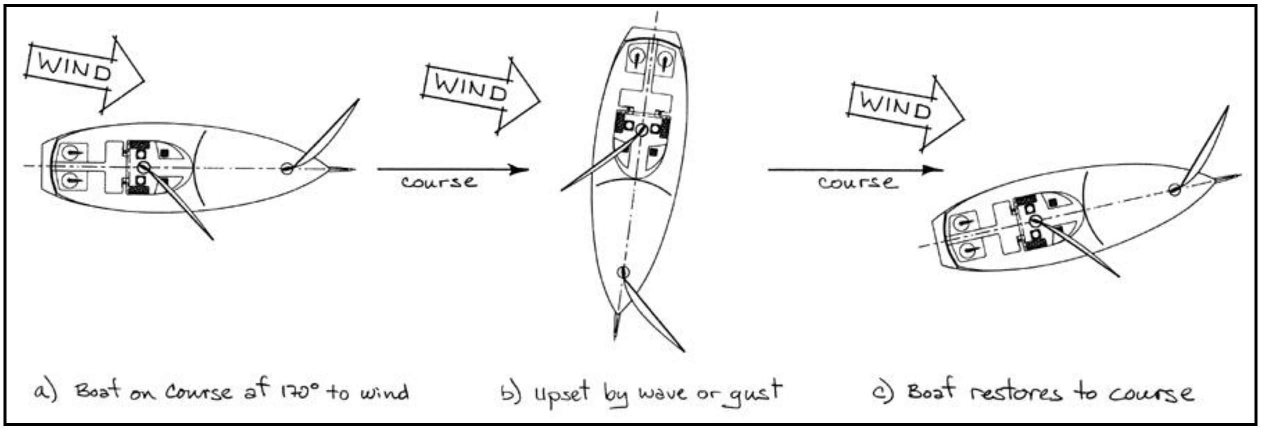
Off the wind, the mainsail on a stayed rig sets off the side of the mast because the mast can’t rotate. The leading edge shape--the most important part of the rig for generating power--is awful. The airflow quickly separates off the mast. To recover some lift, the sailmaker has to build enough camber into the sail to fool the airflow into reattaching.

Then, when you go even further downwind, you lose lift altogether and drag is the only component left to make you go. Most people will say that the more downwind you go, the more pure drag you want anyway, to push you downwind. They obviously have not felt the adrenaline rush of acceleration and speed caused by *pure lift* from a properly designed and rotated wingmast rig. Get rid of the wires, and full mast rotation is possible. Rotate the mast, and all the aerodynamics change. Even downwind--especially downwind--pure lift is much more powerful than pure drag. The boat is considerably faster because so much more power is harnessed from the wind. This has been proven a number of times in actual sailing trials between stayed rig boats and boats with free-standing, rotating masts. The free-standing rig boats just run away from their stayed counterparts when sailing off the wind.



When sailing on the wind (a), the airflow on the back side of the mast is well-attached. Off the wind (b), the flow separates easily on the back side of a non-rotating mast, producing almost pure drag. By allowing the mast to rotate into the wind (c) the airflow remains attached and generates considerable lift.

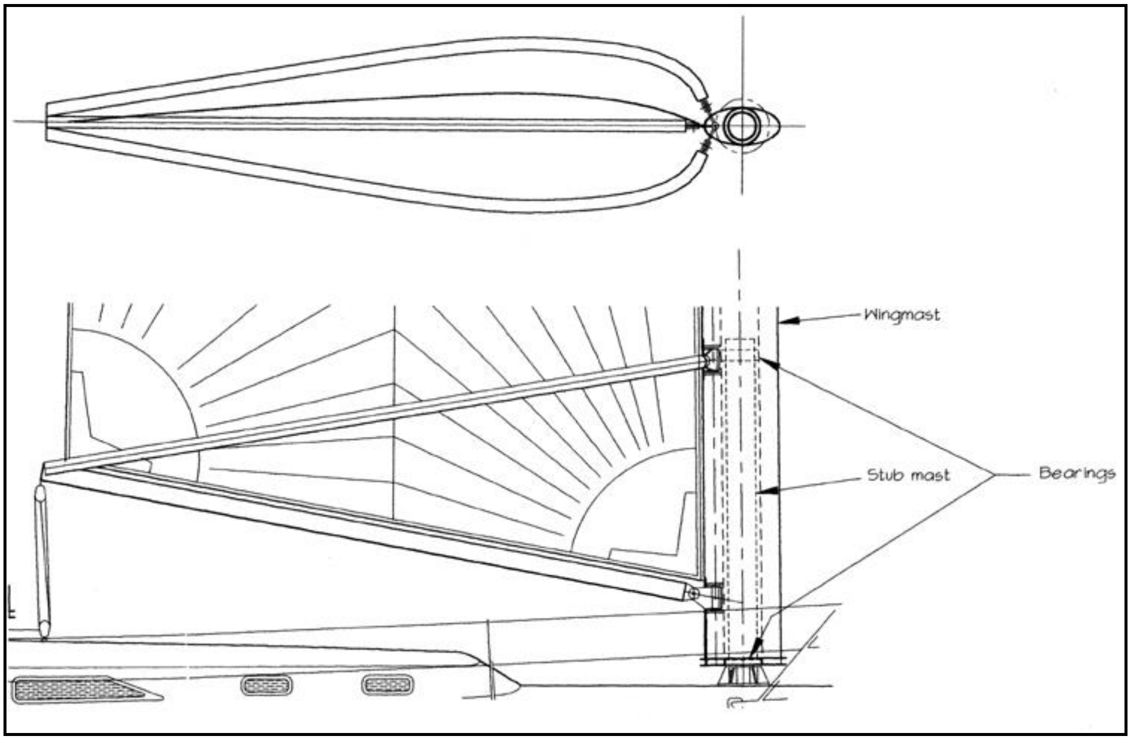
Another benefit of eliminating the wires is that a boat is much more directionally stable and more resistant to gybing. A boat with a stayed rig can sail perhaps ten degrees by the lee before the mainsail gybes. If not properly controlled, the boom will swing violently to the other side and crash against the lower shroud, perhaps breaking the shroud or itself. The boat may also broach if the seas are running fairly high. If something breaks or the boat broaches, the boat is instantaneously in danger of losing its rig and getting rolled over.



A free-standing wingmasted boat like Project Amazon, pictured here, can sail fast deep downwind with the booms set forward of abeam (a), something which no other boat with a stayed rig can do. If a gust or wave upsets the boat, even to turn it broadside to the wind (b), the sails will pull the boat back on course (c). This makes the boat naturally stable and almost totally immune to crashing gybes and broaches.

On a boat with a free-standing rig, particularly on a cat-ketch like *Project Amazon*, since there are no wires, the booms can set way forward of abeam wing-and-wing. You can sail *ninety degrees or more* by the lee without gybing. If the boat starts to round up because of a hit by a wave or gust, the sails will naturally pull the bow back downwind. And even if the boat does gybe, what happens if the boom gets away from the crew? Nothing, because there is nothing to hit—*if it is not there, it cannot break!* The sails will stop in a luff position all by themselves. It is very unlikely that the boat will broach. When the other boats crash, this one just keeps on going.

Wingmast design and construction.
My latest wingmast rig that is currently sailing is the one on *Wobegone Daze*, which you can see on this section of the website. The wingmasts are in two parts: 1) A stub mast that fits into the boat and on which are mounted two large bearings; and 2) the wingmast which slips down over the stub mast and the bearings and rotates thereon. Both mast parts are made of carbon fiber. The bearings on *Wobegone Daze* are made with aluminum bodies and Torlon roller and ball bearings. See the figure below.



The foremast on Wobegone Daze, a Freedom 38 with a custom wingmast rig.

As you can see, the cross-sectional shape of the wingmast is an ellipse. There are a couple of reasons for this. First, the leading edge of an ellipse is particularly friendly to airflow. Airflow stays attached to an elliptical shape much more easily than to a round shape.

Second, ellipses are defined by simple equations, so when I do my engineering calculations to determine wall thickness, cross-sectional area, moment of inertia, and section modulus (all geometric factors based on shape), I can do them easily with simple equations in a spreadsheet.

The trailing edge part of the wing does not have to extend into a tail; rather it can be left as an ellipse. There is little or no drag in the transition between the mast and the sail. A little bubble of air may get trapped in the joint, but it stays there, the airflow skips right over it from mast to sail, and the transition is pretty fair on all articulation angles of the wing to the sail. Keeping the wingmast totally elliptical means that the patterns for the wing are simpler to make and, therefore, easier and cheaper to build.

This rig sails pretty well, and the owner is quite happy with it, but I would like to make a few improvements on the design of the next rig. First, I would get rid of one side of the wishbone, discarding the port half and keeping only the starboard half. You don't need a two-sided wishbone when one side is sufficient to do the work. This would cut weight, complication, and cost considerably. Also, with a double-sided wishbone, you necessarily have to mount the wishbone gooseneck forward of the sail track. This limits the amount of rotation that occurs between the wishbone and the mast because, unless the wishbones are restrained with keeper lines or tackle, they will hit the sail track, bending it or breaking it. If you get rid of half the wishbone, then the gooseneck can be mounted on the side of the mast and not interfere at all with the sail track. Eliminating half the wishbone solves lots of concerns.

The next thing I would do is eliminate the lower boom. Again, with a half wishbone, you have all the boom you need, and the lower boom is not required. The only reason we have it on *Wobegone Daze* is because the owner did not like the idea of the sail being stowed only in lazyjacks, kind of in a bunch hanging below the wishbone. I have no problem with that, and so again, I would get rid of gear (and cost and complication) that I don't need.

The final thing that I would do is change the bearings to all-stainless steel. The aluminum parts of the current bearings are fine, but the Torlon balls and rollers, I think, probably compress slightly under load, and I think this makes the mast a little harder to turn while it is sailing, as we have seen. If you go with a harder material for the rollers and balls, and by that I mean at least with stainless steel, then you really have to go with stainless steel bodies as well. This jacks up the price of the bearings considerably—from about $3,000 apiece to maybe $5,000 apiece, but they would be better in the long run.

That just about covers the topic of free-standing masts and wingmasts. If you have gotten this far, I'm impressed, because it is a lot of material to absorb. But have a look on the other pages for examples of some typical free-standing rigs that have been built to my designs in the last few years.

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