Rigging Loads

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Rigging Loads - or a tale of scientific progress?

In which your hero tries to work out the starting point for the design of rigs

Those of you not already acquainted with the work of Douglas Phillips-Birt could do worse than visit your nearest second-hand bookshop to rectify the situation. Written some 40 odd years ago, his books have inevitably dated, but still have a remarkably high nugget to dross ratio. For example "Masts are tricky things. It is not for nothing that Lloyd's, which is ready to specify the scantlings of nearly every other part of a yacht, washes its hands of them altogether and plants the responsibility for their size and shape squarely on the designer's shoulders; then, as a happy afterthought, advises him to fit lightning conductors. The advice is good; but it leaves the part between the lightning conductor and the step open to various interpretations. The fact that Lloyd's, with its vast collection of data on wooden yachts, feels like this about masts, suggests that masts are perhaps a little beyond rational analysis.[1]" As true now as 45 years ago, though it is yachts as a whole which defy complete analysis, not just their masts. The purpose of this article is to explore some of those "various interpretations". Depending on your viewpoint, it is either a triumph of experience over science, or.....

A study in ignorance

As a working example, I'm going to look at a number of possible ways of sizing the mast and shrouds for a 30 foot gaff cutter which displaces 8 tonnes, with one cap and two lower shrouds. I'll point out as we go the implicit or explicit assumptions being made. The crudest rule of thumb which I have come across - I don't know its origin - is the idea that the shroud set should break at a load equal to the weight of the boat. So each shroud needs to be able to stand 2.66 tonnes, i.e. 8 tonnes displacement divided by 3 shrouds per side. As we saw in the last article, the maximum compression in the mast is in the lower section, and is roughly equal to the combined tension in the shrouds, so that means the lower panel of the mast needs to be able to stand 8 tonnes. For all its crudeness, this rule at least recognises that the strength of rigging relates more to the size of boat rather than the size of the rig. A steadying sail on a trawler may be no bigger than the mainsail of a 12 foot dinghy, but because of the relatively huge inertia of the trawler's hull, the forces transmitted into the rigging and mast of the sail by a gust of wind will be very different. The rule also implies that factors such as ballast ratio, stability, rig shape and size, and beam/length ratio are "normal". It might get you into the right area, but the limitations of such a guideline might be misleading.

One level up, and despite his quote above, Phillips-Birt offers an empirical rule which runs as follows:

Mast Scantling Criteria = B + M + H + 2cos4A. B is the ballast ratio, here used as a measure of stability in conjunction with M, which is the metacentric height as a proportion of the waterline beam. H is the foretriangle height as a proportion of the upper half of the mast(!), and A is the shroud angle. You can see that these factors will bear on the issue, but the more you look at it, the less you can understand why they are combined in the way they are. Why not B times M, what has the cosine of four times the shroud angle got to do with it, and so on. With a method so opaque in its assumptions, you never know what the range of validity is in terms of rig type, or arrangement of stays. It might have been a useful guide for yachts 40 years ago, but you can't tell whether it might apply to yours. Besides it gives no clue to shroud sizing.

At least the assumptions in Skene are more overt, which means that they are there to disagree with if you wish! He offers two approaches to mast and shroud sizing. The "short method" is based on the righting moment of the hull at 30 degrees of heel - fudge factor 1, why 30?. If you don't happen to have that information, he provides a chart to give you a good guess - fudge factor 1a, to what sort of yachts does this reasonably apply? The mainmast maximum compressive load is 2.78 times the moment divided by the half beam - fudge factor 2, why 2.78? You then derive the panel sections by doing a sum about buckling, adding 50% more for a deck-stepped mast. By reference to a table apportioning the shroud loads depending on the rig, number of spreaders and lowers, you then work out the shroud loads and add a further factor of safety of between 1.5 and 3, depending on which wire you are considering - fudge factors 3 & 4.

Well that is a bit more scientific; at least here there is some recognition of the staying geometry.

The "long method" is based on sail loading. Good Heavens! That is the first time it has been mentioned, which considering that it is the sails which load the rig must be an improvement. Don't get too excited though. "How much is the mast loaded and where? The answer is that nobody really knows. There are theories on the subject, however, and the best of them seem to be these: For a mainmast, assume a wind pressure of one pound per square foot of sail area...It seems to work well if we assume that the load (of the mainsail) is evenly distributed along the mast, regardless of the fact that most sails are triangular.[2]" Fudge factors 5 & 6. Now triangulate for shroud tensions, and add a factor of safety of 4 - fudge factor 7, it was 1.5 to 3 last time! Then resolve back for mast loadings, add some extra for weight of sail, boom, tension of halyards, and multiply by a factor between 2.7 and 4. I think I've lost count. Anyway it is time to bring ourselves up to date with one of the most recent books on the subject - "Principles of Yacht Design", first printed in 1994.

Turning to the chapter headed Rig Construction, we find that Lloyd's (and ABS) continue to wash their hands of masts and spars, but the Nordic Boat Standard does provide a design guide. "The starting point when dimensioning the rig is to calculate the righting moment. It is commonly agreed that a heel angle of 30^o is a good design angle. This corresponds to a reasonably high wind strength with the sails still generating high loads and the boat making good speed through the water. Letting the boat heel over more....in reality means a slower boat owing to increased resistance, with a correspondingly smaller dynamic force.[3]" So that is why 30^o is a good angle. Hrrrumph. Sorry about this, but it is time for a digression. Calculation of the righting moment is based on a stationary boat in still water. It has precious little, nothing actually, to do with boatspeed, dynamic forces, wind strength, resistance or anything except a calculation, verifiable by experiment in suitable conditions, of the stability of a yacht. It provides, then, not a real life start point for some rigorous analysis, but a common assumption which can be used to compare craft with each other and/or with empirical data. You could start with the righting moment at 1, 5, 10, 17.386 or any other number of degrees and get to the same answers by changing the various factors applied to the moment. To try to rationalise an assumption like this is at best pretentious - an attempt to ennoble guess-work, at worst dangerous - someone might believe it.

Meanwhile, back to the Nordic Boat Standard. Starting with the righting moment, you add some correction for the crew sitting to windward. Old Gaffers might safely ignore that bit! The method is then based on the most severe of two load cases, the first under full working headsail only, the second under reefed main, using not sail area, but a function of the righting moment. The loads are apportioned to the masthead, hounds, and gooseneck, and with suitable application of trigonometry the shroud loads are determined before multiplying by 2.5 to 3. Similarly, the mast compression is based on the righting moment, with factors for keel or deck stepped masts and times by 1.5 "to handle the dynamic factors".

You may be getting the impression that this is not much advance on earlier efforts. To an extent that is true, though as we'll see later, that can be a source of comfort. But the NBS is to my knowledge the most carefully codified approach to a variety of rigs - all Bermudan, of course - and for the first time begins to provide the flexibility to extend the analysis across different types of monohull, or a variety of materials for the rig and stays. And whatever the relation of the various assumptions to real life, they are at least quite clear.

And the answer is.....

Table 1 - Loads in mast and shrouds

Base Design: 30 feet Length on deck, 8 tonnes displacement, keel stepped mast, 2 lower shrouds, 1 cap shroud over spreader .76m long.

	Mast Load	Mast diameter[1]	Lower Shroud load (each)	Cap shroud load
Crude Rule-of-Thumb	8 t	135mm	2.67t	2.67t
Phillips-Birt	not calculated	183mm	not calculated	not calculated
Skene (short)	6.75t	171mm	2.02t	3.03t
Skene (long)	6.62t	160 to 165mm	2.4t	2.97t
NBS[2]	not calculated[3]	141mm	4.49t	3.12t

1. Based on solid round Douglas Fir mast, converted where necessary by matching section inertias

2. Because this method takes account of spreader length, it is possible to vary the shroud loads considerably by varying the spreader length. For example, omitting the spreader changes the loads to 2.9t in the lowers, and 6.8t in the caps. It is reassuring, compared with Skene, to note that with a spreader the lowers are more highly stressed than the caps, which is what you would expect.

3. Interesting that the NBS method does not specifically relate mast loads to shroud tensions, but starts again with the righting moment. The mast diameter goes back up to about 160mm if derived by resolving forces, but then you never know how to interpret the factors of safety used in sizing the shrouds!

Table 2 - Transverse loads

	Masthead	Hounds	Deck

Skene (long)	0.42t	0.86t	1.11t
NBS	0.88t	1.17t	0.88t

Have a quick look at Table 1 which compares the results of the various analyses. Perhaps surprisingly, the answers, except for the lower shroud design loads, come out very similar. I think that is for two main reasons. First, the craft I am looking at is a “moderate” design, so the rules which make implicit assumptions about stability etc can reasonably apply. Try to run the same series of sums for a more extreme design like an Open 60, and you would quickly find the limits of all but the NBS rule. Secondly, however numerate the rules appear, in practice they are all founded on empirical data - how else could the safety factors be determined? - and the similarity of the results confirms that the forces of wind and sea have not changed too much. Besides, masts don’t often fall down, except when designers are at the very edge of technology, for example as they struggled with the huge Bermudan rigs and new mast materials for racing yachts of the early decades of this century, or carbon sticks during the last decade. In my view the difference lies not in the answers, which don’t vary much, but in the approach. As assumptions are made more clear, it becomes possible to extend the analysis to include either a wider range of boats, or a wider range of materials for masts and stays. Given the range of designs and materials now on offer, that is very useful. Also, see from Table 2, we are getting the beginnings of an analysis of transverse loads on the mast. As you can see they are, by comparison with the compressive loads, very small. Almost suspiciously small. The loads would indicate, for example that a gooseneck pin of about 6mm diameter would be adequate for my test boat; but I think I could predict the response of the owner if I proposed such an arrangement. It would seem that the design loads on a gooseneck come from other considerations, perhaps the shock load from a gybe, or the flogging of a boom whilst reefing. Or maybe Bill Tilman was right not to worry about worn gaff saddle bolts[4]. So we are a long way from a complete picture of the loads in a rig, particularly traditional rigs. Why? For a start, the more sophisticated approaches have developed during the age of the Bermudan rig. The usual assumption that shrouds can be analysed separately from fore/backstays probably holds better for Bermudan, with fixed backstays and forestays mounted inboard, than for gaffers, where there will be a complex interplay between peak halyard, runners, mainsheet, bowsprit shrouds and so on. I don’t think anyone has attempted to resolve this yet. Another by-product of the Bermudan based analysis, is the assumption that windward work induces the highest rigging loads. I am not utterly convinced that this is true of the gaff rig, but have no ready way of finding out one way or the other. Finally, and most significantly, none of the methods derive loads from the force of the sails, which is after all what is loading the rig. Such an analysis would be fiendishly complex, but with ever more powerful tools and computers, I think it is not an unrealistic thing to attempt. It is almost certainly done for Americas Cup boats, but the results are of course not published.

So what are we left with? Well, I hope that I have shown that we can have some confidence in calculated shroud and mast loads. These can be used to size appropriate and consistent sets of equipment, i.e. shrouds, rigging screws or lashings, chainplates, tangs and so on. And I’ll bet you can’t guess what the next article will be covering.

References

1. Rigs & Rigging of Yachts D. Phillips-Birt Adlard Coles 1954

2. Skene’s Elements of Yacht Design F.S.Kinney Dodd, Mead 1981

3.Principles of Yacht Design Larsson & Eliasson Adlard Coles 1994

4. Mischief Goes South H.W.Tilman various publishers
