Part 25: The Lug Rig – 2

Having discussed the variations of the lug rig in w167, Moray MacPhail now asks: How strong do unstayed masts need to be?

Most assumptions are wrong, wrote Albert Einstein and he hadn't read mine in W145. My assumption was that the unstayed mast needed to be strong enough to cope with the loads from the sail as if the mast were fixed at its base. Not a bad assumption for a ballasted boat but maybe/probably wrong for unballasted sailing dinghies.

For them, the maximum bending moment on the mast at the deck may come from the weight of the crew sitting to windward. If conditions require it, the sheet can be eased or the sail reefed. Though there will be a contribution from the hull being heeled, dinghies are usually best sailed upright or nearly so, so that won't be much. I hope the examples in Table 1 across the page are helpful.

The Laser dinghy is designed for racing and exciting sailing. There is no way that the helm can get their centre of gravity to a point over 2m (6'6") from the centreline. Plus the sail can't be reefed, so the sheet will have to be eased upwind. A better design load for the mast, assuming hard hiking, would be about 1000Nm (737.6ft/lb) as opposed to 1700Nm (1254ft/lb) or so from the sail force alone. But that larger sail area makes for much faster progress downwind where the mast stresses are lower.

The Goat Island Skiff – see W144 & W164 – is also designed for racing and exciting sailing but again a singlehander could not position

Table 1 – Bending Moment assumptions – a few instances				
			Position of crew from centreline to balance sail force – assumed 80kg each	
Boat	Moment at deck from sail force (Nm)	Half beam (m)	Single handed	Double handed
Laser	1728	0.69	2.16	
Goat Island	1934	0.76	2.4	1.2
May	965	0.71	1.2	0.6
(from W145. Moment is estimated as sail force x mast length x 0.5)				

themselves 2.4m (8') from the centreline. Two up and hiking hard you might just get all the weight out to 1.2m (4'). But this rig is amenable to being reefed and if life is getting too exciting or wet, that is an option. As a design moment for the mast, you might safely reduce to about 1500 Nm (1106ft/lb).

May is my own little canoe yawl only intended for cruising. One up I could sit her out, two up sitting on the side decks would create at least as much moment as the sail. And she is easily reefed. So I'll stay with the 1000Nm (737.6ft/lb) bending moment to gauge the strength of the mast.

For a dinghy then, you take the lesser of the two estimated moments – one being the crew weight times their distance from the centreline, the other being derived from the sail force as in W145. Why the lesser? Well, if the sail moment is more than the hiking moment, you either luff up, ease sheets or capsize.

You can assess the strength of the mast using:

$$\sigma_{max} = \frac{M \cdot y}{I}$$

Where:

- σ max is maximum stress, compressive for wood. This is a known factor; see W143 for some examples.
- M is the bending moment at the deck either from the sums in W145 or from the hiking moment as above.
- y is the distance of the surface of the spar from the neutral axis, which is the radius for circular sections.
- I is the moment of inertia which is also known for a given configuration – see W142. So that is how you can check the strength.

What about stiffness?

My second mistake. All the sums for the re-masting of my canoe yawl in W158 went clean out of the window when the irresistible opportunity to get some cheap secondhand carbon windsurfer masts arose. Though there was no question that they would be strong enough, I realised they wouldn't be as stiff as my original design. But the mast was so bendy that the boom came low enough to swipe my hat off during the first outing which was irritating. And the sail wouldn't hold a decent shape. To reduce future expenditure on hats, I stiffened the mast using successive

Facing: *Michael Storey's 15'6" (4.73m) Goat Island Skiff design, built and sailed by Joost Engelen. Photo: Kathy Mansfield.* **Below:** *The author's canoe yawl* May, *a Selway-Fisher 15' (4.6m) Lillie design – see W157 – re-rigged with carbon fibre spars.*

Table 2 – 4m mast bend, assuming circular arc and constant mast section	
Deflection at masthead	Difference between straight line and arc
200 mm – 5% bend	1.7 mm – 0.04%
400 mm – 10% bend	6.7 mm – 0.16%
600 mm – 15% bend	15 mm – 0.38%
800 mm – 20% bend	27 mm – 0.68%

layers of carbon sleeve.

Which raised the question of how stiff an unstayed mast for a lug rig should be. Please note that this is a very different question to how bendy the mast on an unstayed Bermudan rigged dinghy needs to be. Nor does it apply to stayed masts.

The relevant sum for a load P at the end of a mast length L of constant section goes as follows:

$$Dmax = \frac{PL^3}{3EI}$$

For a given mast length and sail, the stiffer the material (E) and bigger the section (I) the less the movement D. To get a feel for the practicalities I imagined a 4m (13') long mast with deflections at the masthead of 200, 400, 600 and 800 mm (8", 16", 24", 32"). As it bends, the mast goes around a curve, while the halyard and sail luff stay straight. The relative lengths of the straight line versus curve gives a percentage difference which is the reduction of strain on the halyard, and hence an estimate how much the halyard tension will reduce. For the initial tension I have assumed a 20kg (44lb) pull on a 4:1 purchase to load the halyard to 80kg (176lbs).

I don't know and haven't measured how much stretch there is in a sail luff, which will make up nearly a half of the total length in question. I'd be interested to find out how much, but in the meantime, what emerges from these numbers is:

- The stiffer your halyard and sail combination, the more sensitive it will be to mast bend. Just assuming – without much basis! – that the luff of a polyester sail is about as stiff as braided polyester line, then your fairly brutal tension of 80kg (176lbs) will induce a strain of about 1%.

Because the maths is very difficult, I will ignore the effect of halyard tension bending the mast. But a 10% deflection of 400mm (16") at the masthead would reduce tension by 0.16% over the 8m (26') halyard. That's the equivalent of slacking off the halyard by around 12mm (½") in real life; which is, I suggest, something we can live with.

- Alternatively, we might use high modulus halyards and exotic sailcloth on that same mast. As before that deflection of 400mm at the masthead represents at least a 0.16% reduction in length, which would almost entirely slacken the higher tech halyard whose strain was only 0.2% under the assumed load of 80kg.

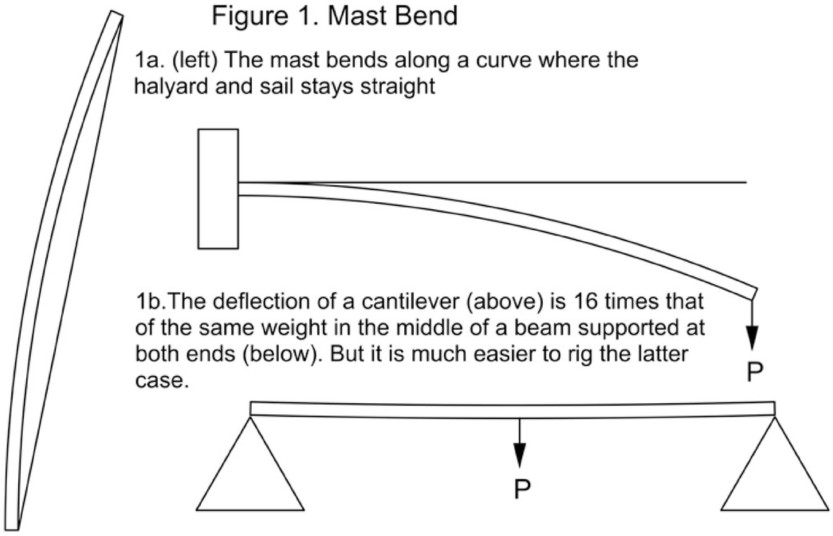
So any upgrades to the halyard or sail specification may prove to be counterproductive unless your mast is also stiffened.

So how stiff is your mast?

Though quite hard to do in practice, you could create a rig which holds the foot rigid, hang a weight from the end and measure the movement. Much easier is to support the mast

Table 3 – Rope behaviour – from data in W164 – assume 80 kg luff tension		
Rope type	Max load (kg)	Strain at 80 kg
3 strand polyester 5mm dia	708	1.5%
Braided polyester 5mm dia	854	1.0%
HMPE 4mm dia	800	0.2%

on trestles positioned at masthead and deck level – as in my picture – hang that same weight from the midpoint, and measure the movement there. To get the masthead movement multiply by 16. The difficulty here is that any errors are multiplied 16-fold.



How heavy should the weight be? Well the design weight in kg would be the lesser of:

- Sail area in square metres x 4.5, *or*
- Crew weight (kg) x crew lever (kg) divided by mast length, deck to masthead (m). It may be more practical to use a smaller weight and factor the result.

For *May's* old 76 mm (3") diameter Douglas fir mast, the movement at the masthead is 225mm (9"). On the length of 3500mm (11'6") this represents 6.5% bend, which means my halyard would slacken by 0.08%; not enough to worry about. But the wooden mast weighs 10kg (22lb).

The new carbon mast is 54mm (2 1/8") in diameter, with tapering section and wall thickness. Though it weighs less than half as much at 4.4kg (9.7lbs), it bends twice as much. This is about a strain of 0.18%. On an HMPE halyard and exotic sail, the whole thing would go limp. On my polyester rig, it's the equivalent of slacking off the halyard by about 20mm (3/4"). I'll have to see how much this matters in practice. Nonetheless it was a mistake to neglect this whole issue from the start by concentrating on strength rather than stiffness.

The question left unanswered – you will have noticed – is how stiff a mast should be. The idea that a mast shouldn't bend at all is unachievable because everything bends. Clearly my first try, with a bend about 25% of the mast length, was hopeless. The original mast's 6% was OK. But is 3% much better or 12% acceptable? The stiffer you go, the more weight or windage or cost, so what is the optimum trade-off? I don't know.

Next time we'll look at the yard and boom to apply some more ignorance. It seems to work.
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Table 4 – Mast deflections using existing masts								
Mast	Length (m)	Sail area (m2)	Sail Load (kg)	Hiking force (kg)	Number used (kg)	Weight used (kg)	Measured (cantilever) (mm)	Predicted (cantilever (mm)
Old	3.5	8	36	29	30	20	225	222
New MkI	3.5	8	36	29	-	-	-	652
New MkII	3.5	6.4	29	29	29	20	420	326