Different aspects of Rig design of traditional ships.

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1. Introduction incl. Agenda

Good morning ladies and gentlemen. My name is Klaas Huizinga.
I'm 54 years old and a selfemployed Naval Architect since 1987. Since then I was involved in the design and engineering of rigs of various large sailing vessels.
Some examples are Star Flyer/Clipper, Oosterschelde, Swan fan Makkum, Urania, Caledonia and most recently Gulden Leeuw.

I want to discuss with you the different aspects of the design of the sailing rig, with special attention to modern materials and easy maintainance.
To structure my talks, I have devided it into the following parts:

- Understanding the design criteria a rig should comply to.
- Use and characteristics of different materials and their effects on the design
- Practical solutions for a number of rig components
- Questions and discussion

When you want to re-read my speech, you can find it within a couple of days on my website **www.khmb.nl**
So, first of all: the design criteria.

2. Understanding the design criteria a rig should comply to

A first 'common sence design criteria' is that a rig should withstand the forces which nature practises onto her. This is also the starting point of the classification society which have their own criteria the ship have to comply too.

That is all good and well, but during the centuries the sailing ship was the main form of transport some mariners had quit different thoughts about that issue. These men could be pleased when a topgallant mast broke away, saving the ship and/or the rest of the rig during unforeseen situations. Anyway, with a pole mast or metal topgallant mast it is not an enviable situation, but when it saves the ship (and possibly the crew) …..........

To determine the actual forces acting on a rig is very complicated as we will see.
In fact the mathematic equilibrium of a sailing yacht or ship is known to be more complicated then a plane flying in the air.
This is mostly caused by the fact, that a ship moves through air and water at the same time, the moving air being the energy, converted into speed and heel by the sails and with the water moving, potential, in all directions, with reaction movements of the ship.

The key question is :
What are the forces in the sails, to be more precies in the halliard, sheet etc. which have to be restrained by the stays, shrouds and spars in different weather, with different sea states.

With the present knowledge and calculation power of computers with CFD (Computational Fluid Dynamics) software it should be possible to estimate the forces acting on the sails and rig of traditional rigged ships.
The essence of this method is, that a precise virtual 3D model of hull, rig and sails, floating in seawater, is exposed to a specific windforce and direction. The software then calculates speed, angle of heel, wave patterns, resistance, leeway and so on.
However, these techniques are state of the art and intensified for light weight sailing hulls with small and deep swing keels and in use in the Sail-race world as Volvo Ocean, Imoca, America's cup, etc. were every ounce or kilogram counts and the budgets are large.

Another approach is to make a model of the hull and rig and test it in a wind tunnel in for instance the Southampton windtunnels. Again, this is costly and, moreover, has some disagreeable scale effects.

So, one of the most practical- and generally accepted way of calculating the forces acting on a sailing ship, is to assume that a certain angle of heel is caused by a certain amount of sails and counteract, and is in balance with, the righting moment. This righting moment is a hydrostatic value, known as an estimation or an assumption in an early stage of the design process.
For yachts normally 30 degrees angle of heel is assumed, together with full sail. (close hauled)
For traditional (large) ships an angle of heel of 20- or 25 degrees is found to be acceptable, together with full- or standard sail.
In this approach it is assumed, that the angle of heel is caused by the sails only, and that hull, roundhouses and forces on the underwaterbody have no effect on the angle of heel, which of course is not really accurate for a sailing ship. Consequently the outcome is more conservative as needed, when sailing in still water.
The specific angle of heel and sail area is dictated by the class society, or are consencus values between the architect and class society.
Together with an acceptable safety factor of normally 3,5 this is the basis of the calculation of the dimensions of the rig components.

To come to actual dimensions it is needed to look more detailed into the different effects of some sails. It is most striking that normative forces are introduced by the staysails and jibs, together with their (running) backstays. Since a wire or rope can not transfer bending moments, they give a pulling force when loaded by a sail because of the deflection of the wire or rope.
The interesting effect is, that the weaker the wire is, the bigger the deflection- and the lower the pulling force is. The opposite is also true: the stronger the wire, the lesser the deflection and the higher the pulling force. It is a sort of self regulating phenomena, with lower and upper borders. The lower border given by the given stretch/strength relationship of the wire itself and the upper border by the angle and effectiveness of the (running) backstays and strength of the mast/topmast, where the stays and halliard are attached to.
A small deflection, even under large stress is found to be effective for the generated sailforce.
So it is in the interest of the architect and shipowner and/or captain to optimize the staysail- and jibstaydiametres without overkilling it.

Another 'special effect' comes with pretensioning the rig. Pretensioning is an efficient measure against unwanted movements of the masts and components. There is almost always a certain amount of pretensioning, also in a traditional rig, otherwise the staysail- and jibstays are hanging with unacceptable deflections at there eyeplates. But to really pretension the rig, a lot of power is needed to turn the turnbuckles. Another practise, which is common nowadays in racing yachts is to jack the mast up with hydraulic power. Now the special effect:
As you can see, when both shrouds are in tension, the mast or topmast is in compression.
When we introduce a sideway force, the top of the mast will slightly move in the direction of the sideway force, giving less tension in the lee- shroud and more tension in the windward shroud. The effect on the compression in the mast is …..zero. This is called a 'compression zone'. Besides the fewer movements of the rig, the mast is not so liable to fluctuating compression, which give less fatique.

Most of the time simplifications are made by assuming that the masts and bowsprit are loaded with buckling forces only, which for the bowsprit is almost true. For masts, certainly when (partly) square rigged, obviously there is also a lot of bending involved.

When a finite elements model is used together with FEA software such simplifications are normally not neccessary. To find a balanced distribution of the forces is, finite elements model or not, still a challenge. After all, the (calculated) result is as good as the input is.

Typical for the design process is, that before any dimensions can be calculated, it is needed to assume values for most properties (incl. dimensions). This is the case for the state of the art CFD calculations as well as for the scale model windtunnel approach, as well as for the righting moment based calculations.
The side effect of this is, that when the calculations show a significant different rig as earlier assumed, the calculations should be repeated with as an input another righting moment as a result of the weight difference of the rig, to come to more precise values.
It is a process called 'iteration' which should be repeated until an acceptable difference between the assumed and the calculated rig is achieved.

At last, another very fast way of determine the dimensions of rig components is to use the past and present tables. For instance those which are presented in the book of Middendorf – Bemastung und takelung der Schiffe or Sailing ships rigs & rigging of Harold A. Underhill or, more actual, but unfortunately based upon only wooden spars: Register Holland bv – Voorschriften Zeevaart (White rules).
In general, the dimensions given by Middendorf and Underhill are in my view more or less too conservative. The reason is, that the ships in these times were cargo ships and had larger righting moments as the trainees- and chartersships nowadays, basicly because they were heavier and consequently needed a heavier rig to whitstand these forces.
Nevertheless these tables can be very practicle and useful and can act as a global check on the calculated dimensions, when intepretated with common sense.

3. Use and characteristics of different materials and their effects on the design

The following types of components are recognised:
- Spars
- Axes, bearings, pivots
- Standing rigging
- Running rigging
- Deck equipment

For the Spars:
- Wood (Oregon pine)
- Steel (Grade A)
- Aluminium (5083 or 6082 alloy)
  We exclude exotic materials such as Carbon because of budget reasons.

For the Axes and bearings:
- Stainless steel (Aisi 316L)
- Steel (Grade A)
- Aluminium (6082)
- Bronze
- P.O.M. which is a high grade plastic

For Standing rigging:
- Different wire constructions
- Different end connections
- Different tensioners or turnbuckles

For Running rigging and winches:
- Different rope materials

Spars
As mentioned before, not only should the rig be strong enough, but it should also be stiff to ensure a reasonable constant stress and deflection in the staysail and jib stays and to prevent unwanted movements, which is unpleasant and even dangerous with crew going aloft.
Another important factor is weight. To reduce weight in the rig proves to be very effective to improve the stability and therefore the sail capacity (power) of the ship. Furthermore the (intact and damage) stability criteria the ship has to comply to, can sometimes leaves the owner and architect no choice as only to reduce the total rig- and sailarea.
Especially for the spars which are moving, such as booms, gaffs and yards and/or hoistable, such as a gaff or yard, a low weight is a great advantage for other obvious reasons:
There is less power needed to control them, but maybe even more important, the forces caused by the movements of these lighter spars are remarkably less, which of course have a positive effect on all the parts involved.

Within this framework hereby a comparison of the following characteristics of the 3 different spar materials, namely wood, steel and aluminium:

	Weight	Strength	Stiffness
	density (ton/m^3)	tensile strength (T) (kN/cm^2)	elasticity modulus (E) (kN/cm^2)
Wood	0,50	4,7 *1	1250
Steel	7,85	40	21000
Aluminium	2,70	27,5 – 30,5*2	7000

*1 parallel to the fibre in compression
*2 variation between 5083 W28 and H116 alloy

The relationship between these materials are, based upon the above figures, the following:

For the density:	wood:steel:aluminium = 1 : 15,7 : 5,4
For the tensile strength:	wood:steel:aluminium = 1 : 8,5 : 5,9 – 6,5
For the stiffness:	wood:steel:aluminium = 1 : 16,8 : 5,6

Looking at the figures, wood seems a competitive material: superior or equal strength and practically the same stiffness for a given weight. In practice however, wooden spars are most of the time massive roundwoods, while steel and aluminium spars are tubes with a certain wall thickness, and in that configuration wood looses some advantage over steel.
Hollow bonded wooden spars are very weight/strength/stiffness efficient, but are expensive in purchase and moreover need more craftmanship and time when it comes to maintainance.
On top of that wood in general is more vulnerable in use then the other materials.

For a direct comparison between steel and aluminium hereby the Yield strength as an extra parameter to compare. Where the tensile strength is the stress value were the material breaks or cracks, the yield strength is the value were the material begins to deform permanently, but does not breaks down.

	Yield strength (Y) (kN/cm²)
Aluminium	12,5 – 21,5 kN/cm² *
Steel	27,5 kN/cm²

* Depending on hardness of the material, 5083, W28 has a yield strength of 12,5 kN/cm², 5083, H116 and H321 have a yield strength of 21,5 kN/cm². However when welded, in the welding area the material's yield strength will degrade to a minimum value of 12,5 kN/cm².

For the density:	aluminium : steel = 1 : 2,91
For the Yield strength:	aluminium : steel = 1 : 2,20 – 1,28
For the tensile strength:	aluminium : steel = 1 : 1,45
For the stiffness:	aluminium : steel = 1 : 3

An example:
For a wooden gaff of 10,00 metres long and with a diameter of 200 mm, I searched for standard profiles in steel and aluminium as an alternative with the same strength.
In steel a standard tube of 193,7x4,0 qualifies.
In aluminium a standard tube of 200x6 qualifies.

	Wood	Steel	Aluminium
Weight (kg):	157	187	100
Strength (T*W):	3690	3400	3657
Stiffness (E*I)/1000:	9818	22512	12054

W = Statical moment
I = Moment of inertia

As you can see the outside dimensions are practical the same.
The weight and the stiffness however are not:
Aluminium has ≈30% less weight then wood, steel ≈20% more.
Aluminium is ≈23% stiffer then wood, steel ≈129% (!).

As a result you can say that aluminium wins the 'battle', moreover when we look at the resistant against corrosion, with it, a low level of maintainance needed.

Aluminium however has also a number of disadvantages:

- It is a more costly material / product.
- Craftmanship on a high level needed by processing the material, especially when welding and deforming.
- Special attention have to be paid to insulation to other (metal) material(s).
- The aluminium surface is more vulnarable then steel is.

Therefore some practical points of attention are needed during the engineering and construction:

- When engineering, take into account that the less welding is needed, the better.
- Try to put the welds in the construction where the lowest stress levels are.
- All (aluminium) eyeplates, when welded, should run through the profile and be (slot)welded on the other end or,
  are 'hooked in' (and welded) in a thicker- or double plate.
- Eyeplates which are heavy loaded and connected to (steel) shackles have to be protected. There are a couple of possibilities, two of them are:
  - Anodising the eyplate (before welding it in) and then press a stainless steel bush in the hole.
  - Protecting the hole with a high-grade plastic bush first and then press a stainless steel bush in the plastic bush.
- All locations where stays, halliards and other lines will possibly touch the aluminium spar, should be protected with some kind of covering.
- All 'closed' constructions preferably provided with one or more expansion/drain holes on the underside. To avoid pollution and insects inside the the tube(s) these holes to be closed with a plastic plug.

Axes and bearings
To make maintainance as efficent and as less time consuming as possible I have a strong preference for stainless steel for the (heavy loaded) axes and (high grades) plastic for the bearings. With these materials, greasenipples and grease, which is needed when using normal steel for the axis and bronze for the bearing are practices from the past.
Only a bit of Teflonspray will do the job.
For the high grade plastic bearings special attention is asked for the tolerance between the axis and the bearing. Plastics have the tendency to expand, because the material absorbs water during its lifetime. Especially Nylon is known for this. P.O.M (tradename Delrin) is better.

Aluminium can also be used as an axis, but needs lubrication on a regular basis, when used in combination with plastic bearings. Dimensions of those parts will of course be bigger, than with Stainless- or normal steel axis because of the lower mechanical properties of aluminium.

Five last things about stainless steel.

- Type Aisi 304 is not seawater resistant and will rust ! Aisi 316 (L) is seawateresistant.
- Tools which are used with normal steel should not be used to treat stainless steel. Small particals of normal steel will stick to the stainless steel and will weaken it.
- Stainless steel Aisi 316 L is weaker then Grade A steel.
- Stainless steel is more sensitive for fatique then Grade A-steel.
- Because of the lack of corrosion, the tendency is to check stainless steel components less regular as other components. That of course, is not sensible.

Standing rigging

Wires

The desired properties for the standing rigging are:

- Low weight
- Great resistant against stretch
- Excellent corrosion resistancy
- Not treated with grease (!)
- Less sensitivity for fatique.

In general we can say that the less strains a wire has, the stronger the wire is for a given diametre, the more resistant the wire is against stretch and the more sensitive for fatique. Because the total surface area of a wire is less with less strains, the corrosion resistancy is less critical also.

The products on the market which are applicable for the job are:
Galvanised steel wire, construction 6x36
Galvanised steel wire, construction 7x7
Galvanised steel wire, construction 1x19
Galvanised steel wire, construction 1x37 (for bigger diametres)

Above products are to purchase in different qualities:
The tensile strength of the material varies from 1570– to 1960 N/mm² or even higher.
The drawback of the higher tensile strength is that the steel becomes more sensitive for fatique.
The quality (thickness) of the galvanisation can be purchased in Class A and Class B galvanisation, where Class A has the most protective (thicker) galvanisation.

Smooth concrete reinforcement bars can also be used for the non-sail carrying stays..... Mechanical properties are much less then those for the wires, so a bigger diametre is needed and therefore a lot of weight is added. Special attention is needed for conservation and the end-connections and their weldings. How the classification societies look at such a solution, I do not know. If they are willing to accept, I presume that a destructive test of the whole construction, so including the end connections, is required.

Stainless steel products for this purpose are:
Stainless steel wire, construction 6 of 7x19
Stainless steel wire, construction 7x7
Stainless steel wire, construction 1x19
Stainless steel wire, construction 1x19 Dyform
Stainless steel wire, construction 1 x37 (for bigger diametres)

It is recommanded to use the highest grade of corrosion protection for the bobstays, bowsprit guys, martingale wires, foremast jib- and staysailstays and maybe even the foremast shrouds, when using normal steel wires. These wires are the most exposed wires and vulnerable for corrosion.
Of course is the use of stainless steel in these areas an alternative. Unfortunately this material is expensive, which is even more true for the end connections. Moreover these stays are often the most heaviest of the total rig. Nevertheless stainless steel wires are used on a regular basis for staysail and jibstays, because of the wear of the galvanise layer caused by hoisting and lowering these sails, when using galvanised wires.

To avoid damage when gaffs, booms and yards interacting with the standing rigging, it is common practice to 'protect' the spar by winding a small diametre rope around the shroud or stay. Depending how much and how long water the winding can contain, the conditions look ideal for corrosion. A regular check of these spots is therefore recommendable.

End connections
The type of end connections depends very often on the taste of the owner/principal.
These connections are very visible on deck/bulwark level, so they are, in a way, qualifying.
When a classic look is wanted a couple of solutions are on hand:

– Splicing with an eye or dead eye*
– Bindings with an eye or dead eye*
  * dead eye in combination with lanyard

For a lanyard, in my view a steel wire (of relatively small diametre) or high grade rope should be used to keep the rig under tension during a longer period of time.

For all of these possibilities only the wires consisting of a lot of small strains qualifies; 6x36, 6 or 7x19 and the 7x7 wire construction can be used.

These wire constructions can also be used when loops around the mast at the upper end of the shroud or stay are employed.

Other, more modern end connections, are:

– pressed Talurit, only to be used on wires with a lot of small strains
– pressed terminal' available as a gaff- or eye and
– the 'pour-sockets', a construction where the end of the wire is 'folded open', which with melted sinc or an epoxy resin will form a wedge for fixation of the socket on the wire. These sockets are also available as a gaff or eye.

The more modern end connection can be used in practice for all mentioned type of wires.
Classification normally is no problem, because these products are in use with hoisting cranes etc.

The drawback of splicing and bindings is, that it takes much more time to make then a talurit- or terminal end connection. A little bit more favourable are the 'pour sockets', but they still need more time to make then a talurit or a terminal.

Turnbuckles
When no lanyards are used, there are different other means of tensioning the rig:

– No tensioner at all, the tension in the relevant wire is caused by one or more other compensation shrouds or stays with an available tensioner.
– No tensioner at all in combination with a hydr. jack and/or other compensation shrouds or stays with an available tensioner.
– A bottle screw tensioner. This tensioner has a closed body are available with metric-, UNC and trapezoide thread. The last one normally used for wires which needed to be tensioned and un-tensioned on a regular base.
– Open body tensioner.

All the tensioners are available with eyes, gaffs and even hooks.
Very important of course is the degree of conservation.

Drawback of the closed body tensioner is that when no precautions are taken, the 'bottle' fills itself with water and causes corrosion so that the 'bottle' is stucked to the thread, and the strength, in time, can not longer be guaranteed.
A solution is to fill the bottle with (heavy) grease and wrap up the bottle to avoid leakage of the grease when temperatures are high. It's all rather time consuming.

The open body tensioners can, if needed, be made more attractive.
Because of the low maintainance level of this tensioner and the open structure, so that 'you can see what you have', I'm a supporter of this kind of tensioner.

Special attention is needed for locking the tensioners. The 'wire side' and the turnbuckle's body needs a locking device.

To keep the tensioners working and to avoid bending and premature damage on both, tensioners and wire/end connection the wire or tensioner should be connected to the eyeplate with a 'toggle'. For the Stainless steel end connection special component are available.
It can be simply attained by putting an extra shackle in between the end connection or turnbuckle and eyeplate. The toggle is obviously even more important for sail carrying stays. Only for stays which eyeplates are really 'in line' such as for a bobstay, the toggle can be left out.

Another important matter is to keep the hole-diametre of the eyeplate just 1 mm bigger then the pin of the shackle or tensioner and the thickness of the eyeplates just a little bit smaller than the width of the shackle or tensioner. In most cases this will avoid bending the pin or damage of the eyeplate hole.

For the running backstays the use of high grade (aramide) ropes have a big advantage. These can be handled very easy (because of the weight) in contrast with (stainless) steel wires, which need an extra line to control them when not in use. Moreover, because of the mass of the steel wire, the movement of the leeboard stay is very hard to control in heavy seas.
2 Extra 2 sheaves violin blocks, one with a hook and a serious winch are enough to tension the runner.
Another more modern solution for tensioning the runners is to use (manual) operated hydraulic cylinders. When well choosen, the winch and extra blocks are in this case not neccessary.

<u>Running rigging</u>
A very principal choice is to be made in an early stage of the design in connection and that is to which level the rig should be able to be handled manual and without winches. This choice has its effect on almost everything which has to do with the rig.
For instance, when an owner decides for whatever reason, that the sheets and halliards should be handled without winches, limits the size of the sails immediately and no, often welded, winch foundations are needed. At the same time the total numbers of blocks and the total length of ropes for the running rigging will grow considerable.

Do you remember the nice smell of manilla ropes ? I'm glad that we can buy something much beter, although I do miss the smell.
Nowadays in fact all high quality lines such as tasmania, cup sheet, aramide etc. can be purchased in the color wanted, so it has the looks of a classic rope, but are in fact high graded. This is also true for the more common used cheaper plastic lines.

Of course the staysails, jibs and gaffsails can be hoisted by low grade polyester or polyethylene lines. The effect is however, that these sails have to be retensioned every hour or so because of the slack in de leading edge. Therefore I'm a real supporter of more sophisticated lines for this purpose. How far an owner wants to go in this, depends where his priorities are.
These modern lines are also a lot less in weight in comparison with their predecessors, and there-fore much more efficient and easy to handle.
Another way to go is to hoist the sails with steel wires with on the deck-end a tackle or winch or a winch, which directly handles the steel wire. Disadvantage is that damaged steel wires are bad to handle and a tackle can give a lot of ropelength, which is not very efficient.

In both ways the diametre of the sheaves in the blocks should be big enough to avoid cracks and deforming. For steel wires 15 – 20 x the diametre of the wire. For cupsheet approx. 5 a 10 x diametre of the rope and for exotic ropes 10 – 15 times the diametre is found adequate.

A lot of attention should go to leading the running rigging along the yards, mast, spreaders etc. smoothly down to deck level. Especially for square rigged masts miles of ropes are coming down and they all need good leads to avoid premature damage of the lines itself and damage of the spars they pass by. A good material for leads is hardwood and with no or less maintainance, nylon. When sharp corners (above approx. 10 degrees), extra leading sheaves or blocks are needed.

4. Practical solutions for 2 rig components.

A. Deck- and keel stepped masts.
The most common way in the early days was to have the mast stepped on the keel.
The reason probably is that building a wooden support under the mast foot was not a very logical thing to do, moreover the standing rigging in those days exists of ropes.
The properties of these ropes were by far inferior in comparison with the present ropes and so all what was a help in stiffening the mast was found helpful. A keelstepped- and deck wedged mast was therefore the most logical thing to do.
Nowadays with most ships built in steel, a serious interior and high quality steel wires as standing rigging, we now have more or less a choice.

– When stepping the mast on the keel and wedging it in the deck(s) will result in a mast which can stand on his own and will stand more stiffer in comparison with a deck stepped mast. Because of the properties of a beam under buckling, this construction, when compare it with a deck stepped mast, can withstand bigger forces, a slightly smaller diametre for the mast can be tolerated and so the weight will be reduced a little. To avoid large tensions in the edges of the mast foot, it is better to reduce the mast foot diameter.
– Another possibility of placing a keel stepped mast is, to simply weld a (steel) mast into the deck(s) and on the keel. A danger is the potential high tension at the welding positions. Therefore a sinoid curved double plate at these positions is recommandable.

Disadvantage of the keel stepped mast, welded or not, are:
1. Because of the possible temperature differences between under- and above deck risk for condensation.
2. Because of the SOLAS criteria for structural fire protection, class societies can require insulation of the mast part underdeck. For the same reason class authorities can require special materials for wedging.
3. Keel stepped mast interfere with the interior lay-out, especially when insulated, they take a lot of space.
4. When not properly wedged or stepped a lot of unwanted noises during sailing in more or less severe weather can disturb the atmosphere on board.

The deck stepped mast can be:
– Bolted with a flange on deck. Very practical, but not very pleasant for the eye in my view. Again, possible high tension at flange location. Advanced double or thicker plate needed.
– With the mast foot inside a steel ring or. Keeping the space in between the ring and the mastfoot dry and rust free is a challenge.
– With the mastfoot on a foundation, the horizontal movements restricted by a strong square locker, which also act as a anti rotation device.
– With the mastfoot on a (steel) ball. An anti rotation device still needed.

B. Forestay(s) for yardrigged masts.
It is common practise to place the upper end of the forestay above the lower yard and the lower end near the stem. Because of this configuration, placing a staysail in this position is not very logical, which for the close hauled courses at higher windspeed can be very practical and efficient.
To overcome this, the forestay can be replaced by 2 babystays, of which the upper ends are placed at the height of the lower yard and at the lower end placed a couple of metres before the mast crossing with deck and a couple of meter besides the centre line.
With the (baby)stays in this position a serious staysail with or without a boom can be placed on a seperate forestay,with the upper end connected to the mast above the Lower topsail yard.
This sail/rig geometry has been chosen for the barquentines Star Flyer/Clipper and Caledonia and is working fine as far as I know.

Thank you, for your attention.

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