Best Mast: a new way to design a rig

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Abstract

One of the most difficult tasks for a rig designer is to estimate the maximum loading condition for a rig. These loads determine the mast tube dimensions such as wall thickness and the stay diameters. The loads basically determine the total weight of a rig. The constant drive for better sailing performance pushes the design to the limits, even for cruising yachts. In combination with the growing use of composite materials for mast and rigging, this asks for a new way of rig design.

Best Mast is a generic rig design tool developed for the Dutch spar manufacturer Nirvana Spars® B.V. The tool consists of a new developed force prediction model, estimating the external forces acting on the rig during a specific sailing situation. Subsequently these forces are used in a finite element analyses to determine the structural behaviour of the rig. In several analyses steps the rig can be optimised. Due to the generic set up of the tool, different rig configurations can easily be compared.

This paper describes the development of the Best Mast design tool with special attention to the underlying load model and the finite element model.

Introduction

Nirvana Spars is a Dutch spar manufacturer specialized in building aluminium masts for cruising yachts from 60ft up to 160 ft. Apart from masts the company also manufactures carbon furling booms, poles and deck hatches. Almost all the yachts of the well known Dutch shipyard Jongert are equipped with Nirvana Spars masts. The market for cruising yachts asks more and more for better sailing performance and lighter yachts, but without reducing the luxury. This means a lot of weight saving is required on both yacht structure and rig. As a result complete carbon fibre rigs are slowly becoming the standard for super yachts. On the other hand, the quality and reliability needs to remain high while insurance companies are asking for certainties while they receive more and more claims for broken rigs.

A sailing yacht rig might seem a very simple structure but in reality it is not. It behaves in a very complex manner. The current design methods described in literature and the one used by Nirvana Spars are based on analytical approaches. In these methods various, relatively high and often also inexplicable safety factors are used to take into account design uncertainties. By using more sophisticated models it is possible to reduce the various safety factors. This results in either lighter or more reliable rigs. More knowledge is also necessary to make fully use of the benefits of new materials such as carbon fibre for the masts and aramid fibres for the standing rigging. An alternative for the current analytical approach is the use of a finite element analyses (FEA) program. These powerful tools are very useful to analyse the non linear behaviour of rigs, but their reliability heavily depends on the analyses method and the accuracy of the loading input. With respect to the loading of the rig from the sails there is not so much known.

The overall aim of Nirvana Spars is to design rigs in a more scientific way and specifically to be able to design high quality aluminium and carbon fibre masts. To achieve this, the company has set up the Best Mast project together with the Centre of Lightweight Structures TUD-TNO (CLS), MARIN, MSC Software Benelux B.V. and Van Oossanen & Associates B.V. The result is a tool based on the finite element analyses program MSC.Marc® Mentat® and a newly developed Force Prediction Program (FPP).

Finite element analyses programs are often very difficult to use due to the large number of features that are not all of interest for a structural engineer like a mast builder. To standardize the design process, MSC Software developed a user interface and a model generator procedure especially for the definition of a rig. The role of the Centre of Lightweight Structures was to develop a load analyses method to determine the loads for the finite element module. The resulting FPP consists of a Velocity Prediction Program module (VPP), mainly based on the International Measurement System (IMS) approach and a Rigging Load Program module (RLP). The VPP determines the forces generated by each sail individually for a certain load case. These forces are subsequently transformed by the RLP to forces acting on the rig. Figure 1 shows a diagram of the Best Mast tool.

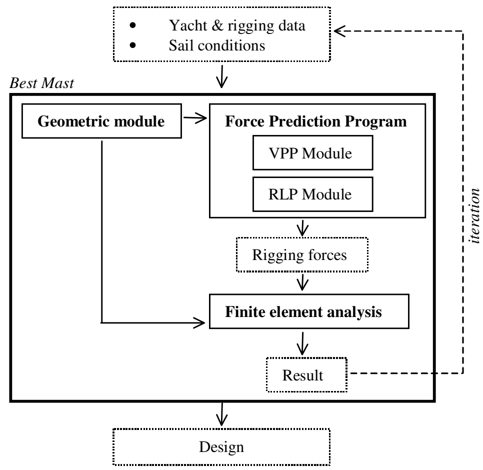

Figure 1: scheme of the Best Mast design tool

The Best Mast program is validated with results of full scale measurements performed on the 97 foot Jongert yacht “Flying Magic”. MARIN equipped this yacht with a measurement system that collects 82 data signals full time and they analysed the collected data. Strain gauges were installed on the different panels of the four spreader aluminium rig as well as on the various transverse and longitudinal stays. The performance of the yacht and the dynamic motions are constantly registered a well. At the end of 2003 a series of measurements were performed to collect data for very specific predefined semi static sailing situations. During these trials the sail settings were registered as well. The yacht was also monitored during a transatlantic passage. The collected data gives insight in the dynamical aspects of the rig. After 2 years time the system is still working and is still collecting valuable data.

In this paper the development of the Best Mast tool is explained with focus on the FPP. The next chapter deals with the state of the art design method. This explains the relevancy of the definition of a new design tool. Subsequently the background of the FPP is explained and finally some of the possibilities with the Best Mast tool are shown.

At this stage the tool can evaluate the structural response on static forces from the sails. A future step is to develop a structural model for the response on the dynamic behaviour of the yacht. Until then safety factors are used derived from the comparison of the static results from the design tool with the dynamic and static measurements on the test yacht.

The Centre of Lightweight Structures is a cooperation between TNO, a contract research organisation, and the Faculty of Aerospace Engineering of the Delft university of Technology. The group is specialised in the field of lightweight structures and especially composite materials. They are active in structural design, implementation and optimisation of production processes, testing of materials and fundamental research. Apart from the marine industry they perform projects for the aerospace, automotive and civil engineering industries.

State of the art

The function of a sailing yacht rig is to support the sails used to propel the yacht. To maximise the yachts stability and its sail carrying capacity, the rig should be as light as possible, with the centre of gravity as low as possible. At the same time the windage has to be minimized to reduce drag and the disturbance on the airflow around the sails. On the other hand the rig should have a certain ability to deform in a controllable manner, to trim the sails without losing the load carrying ability. These requirements make the design of a rig a very interesting challenge. In this chapter the design procedures as found in literature ([1], [2]) and as used by Nirvana Spars are explained. This will explain the need for a new design approach.

A rig can be divided in a mast tube and standing rigging supporting the mast. The rigging consists of longitudinal and transverse stays. The whole structure is loaded in the following ways:

- Distributed forces and point loads from the sails are acting on the mast and forestay.
- Point loads are acting on the mast at the attachments of stays, spreaders, boom, pole and other equipment.
- The dynamic behaviour of the yacht causes inertia forces.

The behaviour of a rig depends on all these loads that vary for the different sail conditions.

All rig design calculation procedures found in literature are more or less based on the Skene method. Also the current design procedure of Nirvana Spars is based on this method although a lot of experience is implemented in the form of additional coefficients. Starting point of the Skene method is the transverse stability of a yacht expressed in a righting moment. Figure 2 shows a typical stability curve of a yacht.

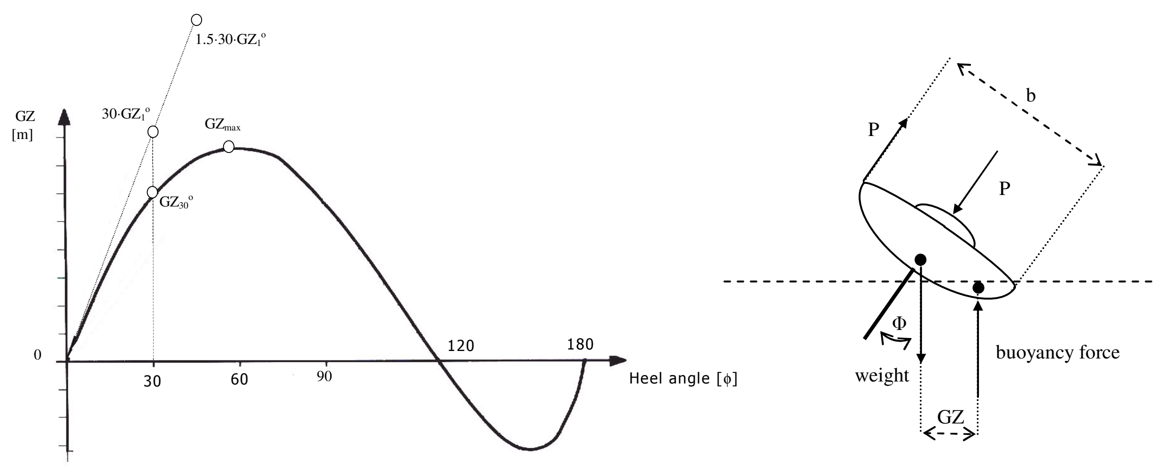

Figure 2: on the left a typical stability curve and on the right the forces on a yacht responsible for the heeling and righting moment.

Based on the stability at a 30º heel angle the Skene method estimates the maximum compression force that can occur at the base of the mast with the following formula:

$$P = 1.85 \cdot \frac{1.5 \cdot GZ_{30^\circ} \cdot \Delta \cdot g}{b/2} = 1.85 \cdot \frac{1.5 \cdot RM_{30^\circ}}{b/2}$$

P	=	mast compression force [N]
Δ	=	weight displacement [kg]
g	=	gravitational acceleration [m/s^2]
b	=	chain plate width [m]
GZ_{30°	=	righting moment arm at 30º heel [m]
RM_{30°	=	righting moment 30º heel [Nm]
1.5	=	coefficient taking into account heel angles greater than 30º
1.85	=	coefficient for stays, sheeting and halyard loads

In general mast designers don't get to know the actual stability but only the one at a 1º heel angle. In such cases this value is multiplied by 30 assuming the first part of the stability curve to be more or less linear. As can be seen in Figure 2 this may heavily overestimate the righting moment. Apart from the factor for the extra loading for stays, sheets and halyard loads, the formula represents moment equilibrium in the transverse direction, as shown in Figure 2. The assumption is that the leeward shrouds are slack at this heel angle.

The maximum compression force in the lower mast panel and the tensile force in the windward stay, both equal in magnitude, are used to determine the required stay dimensions and the panel bending stiffness (EI), in both the transverse and longitudinal direction. The general method for the bending stiffness is to use the Euler buckling formula. A distinction must be made between the transverse and longitudinal direction due to the different support lengths.

$$P_{cr} = \frac{\pi^2 \cdot E \cdot I}{k^2 \cdot L^2} \qquad E \cdot I = \frac{k^2 \cdot P_{cr} \cdot L^2}{\pi^2}$$

P_{cr}	=	Euler buckling load for the panel [N]
E	=	modulus of elasticity in axial direction of the panel [Pa]
I	=	moment of inertia in long. or transverse direction [m^4]
L	=	length of the panel between the supports [m]
k	=	support factor

An important remark is that the Euler buckling method is a linear representation of a non linear phenomenon. The formula is a theoretical approach of the buckling or instability load of a compression column. It is only valid for ideal undisturbed structures under a pure compression force. The resulting bending stiffness EI heavily depends on the type of support, expressed in the k factor. Figure 3 shows five different support types for a column with the belonging k factor. The column carries a compression load up to a certain maximum, the bifurcation point. At that moment buckling theoretically occurs, see Figure 3 curve A.

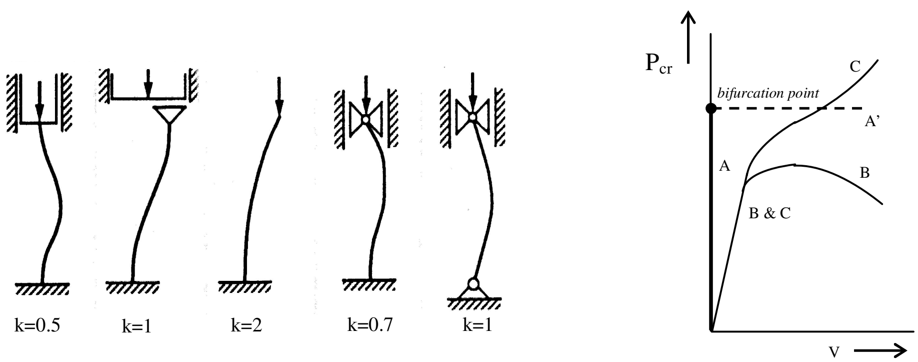

Figure 3: on the left five different types of support with the belonging k factor. On the right the force to axial displacement curve for a column under compression, theoretically (A) and actual (B &C).

In practise, like in case of a sailing yacht rig, this ideal situation never occurs. A distributed force of the mainsail or point loads from boom or stays make that a mast is never in a pure compression state. Right from the beginning there is a certain bending and an axial displacement as shown by curve B in Figure 3. As a result the actual bifurcation point will be below the theoretical value. Whether the structure is able to carry more load after that point, like curve C, depends on the post buckling properties of the column. This so called global buckling does not automatically mean that the structure will collapse.

For the dimensioning of the rest of the rig, mast and windward rigging, it is considered as a static determined structure. The heeling moment at deck level is the result of heeling forces acting at the hinges between panels and spreaders. Distributed forces as from the mainsail and forces acting between panels need to be translated to forces acting at the hinges as shown in Figure 4. With equilibrium equations the transverse stay and panel forces can now be determined and so the required dimensions. The dimensioning of the longitudinal stays is also based on the transverse stability.

The Skene method is a rig design method solely based on the transverse yacht stability and using analytical formulas. In literature many variations on this method exist with the main differences in the various factors to take into account the modelling assumptions and effects as distributed forces from sails, halyard forces, and longitudinal forces from stays. The background of these factors is often not clear making optimization of the structure very difficult.

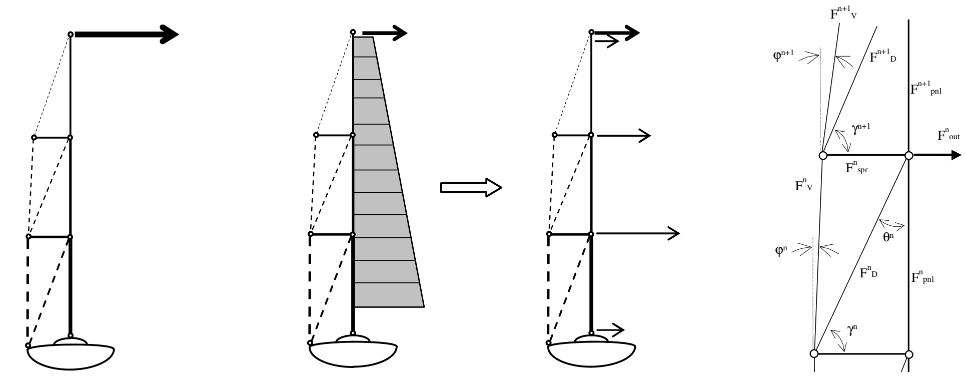

Figure 4: the force of the sails is translated to forces acting at the spreader heights, on the right a static determined mast structure

Due to this approach it is not possible to examine for example local buckling or the effects of variations in the pre loading, interactions due to swept back spreaders, fore and aft D1 stays, jumpers, etc. It is also not possible to determine the general behaviour of a rig, for example bending and deformation under normal sailing situations. It requires a non linear analyses on a three dimensional model to do so.

These considerations lead to the development of a generic design tool with a finite element analyses program and a new developed load model to determine the sail loads acting on the mast.

Development of the Force Prediction Program module

To determine the sail loads on the rig, a load model is developed based on the performance of a yacht. In a static sailing situation the forces generated by the sails are in equilibrium with the hydrodynamic forces. These sail forces are transferred to the yacht at the connection points of sail and yacht or rig. The FPP module translates the sailing situation into rig loads.

The FPP consists of a Velocity Prediction Program module (VPP) mainly based on the IMS approach and a Rigging Load Program (RLP). The VPP predicts for a particular sailing situation the driving and heeling forces generated by each sail. The RLP translates these sail forces to forces acting on the rig. Input for the FPP is yacht, rig and sail data plus data for a particular sail situation. The result is a set of loads acting on the rig which is used as input for the finite element analyses program, see Figure 5.

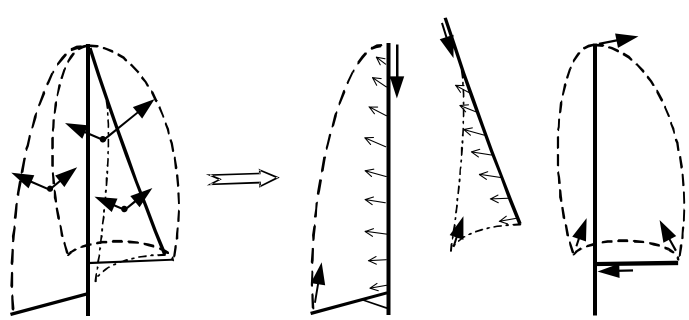

Figure 5: total forces generated per sail as determined by the VPP module are translated by the RLP module to forces acting on the rig.

The velocity prediction module

Common velocity prediction programs are used to predict the sail performance under various sailing situations. The Best Mast VPP predicts the driving and heeling force generated by each sail individually.

The belonging speed of the yacht is not of interest for the analysis. Formulas derived from the Delft Systematic Yacht Hull Series (DSYHS) as available in literature ([3]) were used to develop the velocity prediction program from scratch.

Only four of the total six degrees of freedom are taken into account for the sake of simplicity, see Figure 6.

$$\sum F_{Vert} \vdots \quad \text{Displ} + F_{buoyancy} = 0$$
$$\sum M_{Heel} \vdots \quad \text{Displ} \cdot \text{GZ} + F_{hl} \cdot heeling\ arm = 0$$
$$\sum F_{Long} \vdots \quad F_{drive} + R_{tot} = 0$$
$$\sum F_{Trans} \vdots \quad F_{hl} + F_{heel} = 0$$

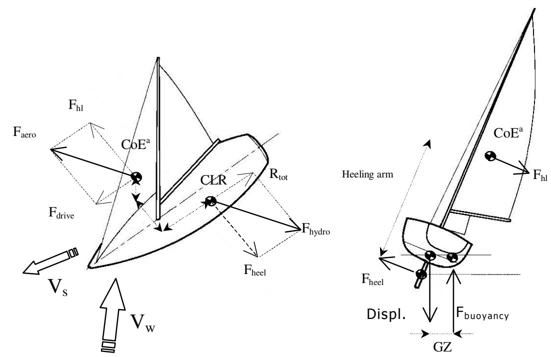

Figure 6: four degrees of freedom are solved in the Best Mast VPP. The figure on the right shows the longitudinal and transverse forces plus the vertical forces, the heeling and righting moment.

The total hydrodynamic drag is based on the viscous drag of hull, keel and rudder plus the upright and heeled residuary drag for the hull keel combination plus the induced drag. For the rudder only the viscous drag is taken into account, the induced drag is based only on the heeling force generated by the keel. Effects of longitudinal trim and added drag for sailing through waves are not taken into account in this VPP module.

The hydrodynamic heeling force is assumed to be generated by only the keel and rudder, not by the hull. The heeling force of the rudder is determined by the extended keel method ([4])with a rudder angle of 2° for true wind speeds up to 5 knots and 6° for wind speeds above 20 knots while sailing upwind. For increasing apparent wind angles the rudder angle is reduced.

The aerodynamic forces are based on the lift and drag coefficients, C_l and C_{dp}, as used by the IMS VPP. Based on the series of 9 lift and profile drag coefficients, continuous curves are created as a function of the apparent wind angle for mainsail, jib and spinnaker, see Figure 7. In the Best Mast VPP four different sail types are distinguished: mainsail, jib, spinnaker and gennaker. The curves for a gennaker are created by manipulating the spinnaker curves.

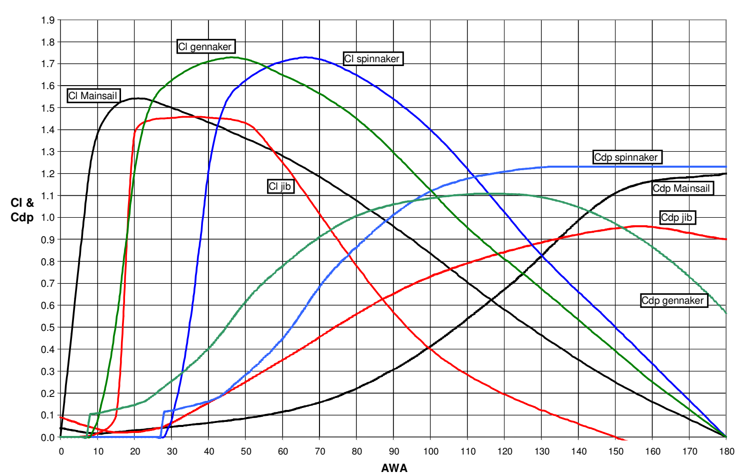

Figure 7: the Cl and Cdp curves for mainsail, jib, spinnaker and gennaker based on the IMS coefficients.

The IMS values assume an optimum setting regarding sail combination and sail trim (profile shape, trim angle and twist). By introducing reduction factors the VPP can also be used for single sail settings. The heeling arm per sail, the vertical distance between the centre of lateral resistance (CLR) and the

aerodynamic centre of effort (CoE^a) is based on the relative positions of the CoE^a per sail as shown in Table 1. For the mainsail it is a fraction of the luff length with respect to the boom and for the other sails a fraction of the I height above the deck.

Table 1: the position of the CoE^a for the different sail types.

Mainsails	0.40	$\cdot$ P
Jib or Staysail	0.39	$\cdot I_{top\text{-}jib}$
Gennaker	0.60	$\cdot I_{top\text{-}gen}$
Spinnaker	0.60	$\cdot I_{top\text{-}spi}$

The measurements performed on the “Flying Magic” yacht were used to validate the results of the VPP as boat speed and heel angle. For this particular yacht the VPP slightly overestimates the performance. The set up of the VPP is such that it is possible to use more accurate data for a specific yacht if available from tank and wind tunnel tests.

The RLP module

The total driving and heeling force acting at the centre of effort of a sail is the result of a pressure difference between the windward and leeward side of the sail. The sails can also generate vertical forces; however these are not taken into account. In a state of equilibrium the three resulting forces are counteracted by forces from the rig and sheets acting on the sail. The Rigging Load Program determines these forces for the different sail types ([5]). Starting point is the fact that sails are made from cloth that can only transfer tensile forces. Just like a rope the orientation indicates the direction of the force. Due to the different supports the RLP uses different methods for fixed sails like mainsail and jib and for the free flying sails as spinnaker and gennaker.

Mainsail and jib

In the RLP these sails are divided in triangles running from the clew to the luff of the sail as shown in Figure 8. Each triangle carries part of the total generated force; this is assumed to occur as a distributed force along the diagonal running from the clew to the luff of the sail. This distributed force is in a state of equilibrium with the reaction forces acting in the directions of the diagonal at the clew and leech. The angles are different for each diagonal and are a function of the shape and twist of the sail.

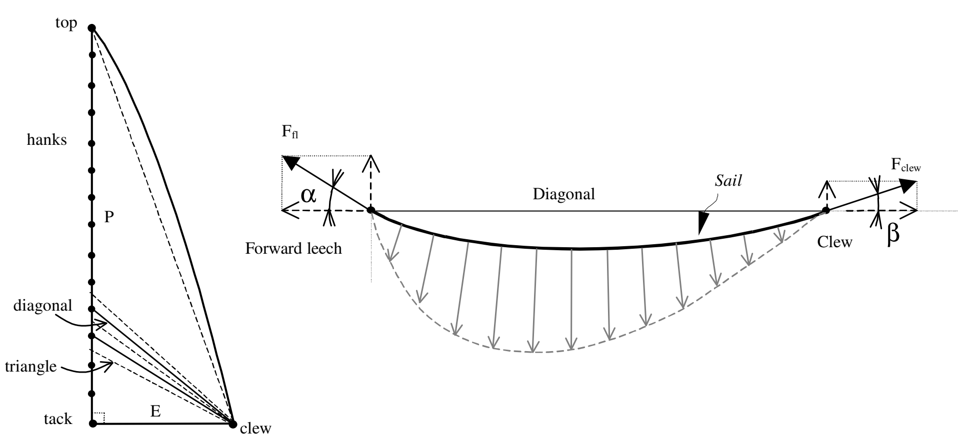

Figure 8: division of the mainsail in triangles. The force on each triangle is transferred to the rig by a diagonal.

At the luff the sail can slide along either the mast or forestay. The components of the diagonal forces in the leech direction are transferred to the top of the sail and are counteracted by the halyard. For a jib a small part will be transferred to the tack of the sail. The force components perpendicular to the mast and forestay result in a distributed force along mast or forestay. At the clew the forces of the diagonals are

summed to components in the three main directions acting at the outboard end of the boom, or on the jib sheet. These forces are counteracted by the outhaul and clew tie down for the mainsail or by the jib sheet.

While sailing upwind the driving force of the main and jib is transferred to the yacht by the outhaul and the jib sheet. The forces at the mast and forestay tend to heel the yacht and pull it backwards. At higher apparent wind angles the driving force of the mainsail is transferred more and more by the sheet. The mainsail and jib are assumed not to generate a vertical force so the vertical components of the halyard and sheet counteract each other.

The mainsail shape is rather constant for the different sail angles. Only the angle of the boom relative to the yacht centre line needs to be defined as a function of the apparent wind angle. However the shape of the jib changes with sheet tension and track position. For the jib an entrance angle of the luff leech, with respect to the yacht centre line, is assumed as a function of the apparent wind angle. Together with the geometry of the sail, the jib track position and the twist define the sail shape and so the required angles of the diagonals.
Figure 9 shows the decomposition of the resulting force on the diagonal in the vertical plane, to the forces acting on sheet and forestay.

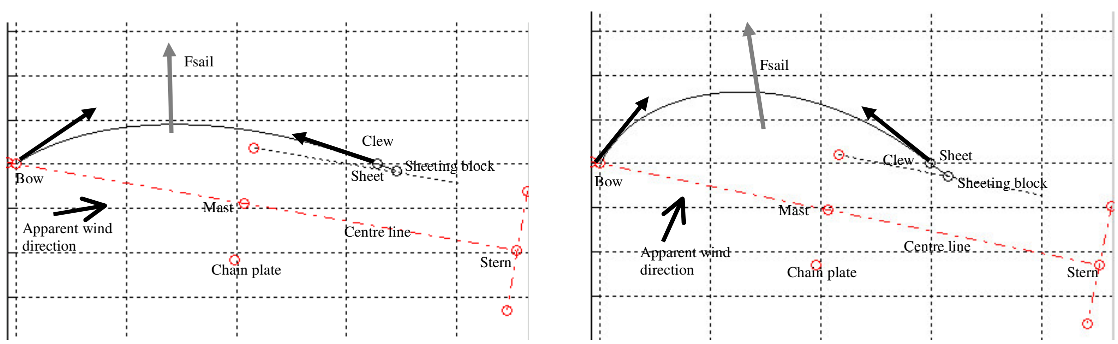

Figure 9: the left figure shows a horizontal cross section of a jib at clew height in upwind sailing condition with the various forces. The figure on the right shows a high reaching situation.

The vertical component of the mainsail tack force acting at the outboard end of the boom is mainly counteracted by the mainsheet when sailing upwind and by the vang when sailing lower courses, see Figure 10. Due to its short length and forward position the vang can cause high loads on the lower part of the mast. The RLP uses a vang factor to take into account the distribution of the vertical force between the sheet and the vang. This so called vang factor is an additional trim facility and needs to be defined for each sailing situation.

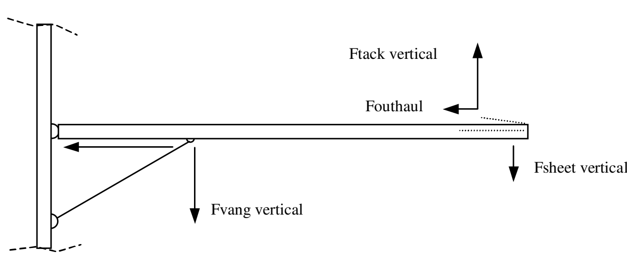

Figure 10: the vertical component of the tack force of the mainsail is counteracted by the sheet and the vang. Using the vang causes high extra loads on the lower part of the mast.

The result of the RLP for the mainsail is a distributed force along the mast in both the driving and heeling direction, a compression force on the mast due to the halyard and forces acting at the boom and vang attachments. For the jib the result is a distributed force along the forestay and also a mast compression force due to the halyard. Additionally the jib sheet force is determined.

Free flying sails

The spinnaker and gennaker are controlled by two sheets plus the halyard. The tack of the spinnaker is kept in position by the pole; especially at reaching angles the resulting pole force at the lower part of the mast can become very high. A gennaker can be set with the tack directly running to the bow or to a bowsprit or pole. Figure 11 shows for a gennaker the decomposition of the resulting sail force plus the sheet and halyard forces in the driving, heeling and vertical direction.

In a static state all forces on the sail are in equilibrium. This requires at every apparent wind angle a certain relation between the resulting sail force and the pointing direction of sheets and halyard which is dictated by the shape of the sail. In the RLP calculation procedure the sheet and halyard loads are determined by adapting the shape of the sails, within certain limits, till equilibrium is reached. The shape of the sail is defined by:

- the entrance angle of the luff with respect to the apparent wind angle.
- the angle of the boom to the yacht centre line.
- the geometry of the sail.
- the position of the sheeting block.

As starting point for the calculation a base transition is defined for both the entrance and boom angle, as a function of the apparent wind angle.

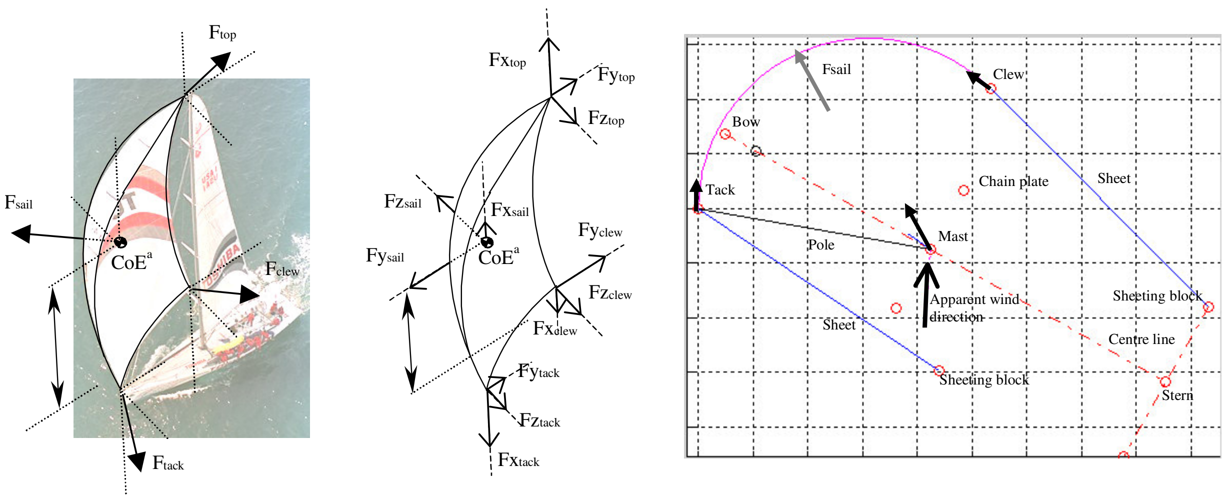

Figure 11: on the left and in the middle the resulting force generated by a gennaker and the counteracting forces of the sheets and halyard. On the right a cross section of a spinnaker at pole height.

For both the spinnaker and gennaker the following results are generated: a driving, heeling and compression force acting at the mast. When the pole is used the driving and heeling force on the mast at pole height are also determined. Additionally the sheet, tack and guy forces plus the compression force in the pole are determined.

User interface for the FPP

When using the Best Mast tool the first step is the definition of the rig geometry in the dedicated user interface built by using MSC.Marc® Mentat®, see Figure 1. When the model is generated the next step is the definition of various load cases to be analyzed. Part of the required information for the FPP follows from the geometry but additional information needs to be defined in a special FPP user interface. The following input groups are distinguished:

- Hull and appendage data required for the VPP module.
- Rig data required for the RLP module.
- Sails data required for both the VPP and RLP module.
- Load case data required for both the VPP and RLP module.

In the FPP several load cases can be defined, the result of each can subsequently be used as input for the FEA module. A load case is defined by a sailing situation with a certain wind angle and wind speed plus a combination of sails. Figure 12 shows the required input in the FPP user interface.

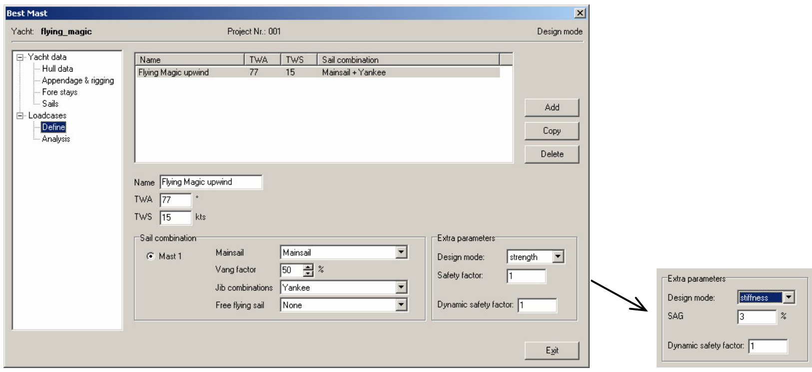

Figure 12: the load case definition window of the FPP user interface, depending on the mode, design or stiffness a safety factor or a forestay sag has to be defined.

For each load case distinction is made between the load to be used for rig strength design and rig stiffness evaluation. For rig strength design the worst case rig load should be applied. Therefore a load safety factor is used on the load predicted by the FPP to account for uncertainties. For rig stiffness evaluation the FPP loads without safety factors are used to evaluate the rig deformation under nominal sailing situations. During the design phase this enables the designer to judge for example the mast bend, the effect of the applied transverse pre load or the loads on the stays useful for fatigue analyses. It can also be used to evaluate the loads during a rig failure.

For a stiffness evaluation it is necessary to define a sag factor representing the maximum sag of the forestay as a percentage of its length. In normal sailing situations the aim is always to minimize the sag because of the negative influence on the performance. This is achieved by tightening the backstay or the runner resulting in extra loads on and deformation of the rig. In the Best Mast tool this can be simulated

Figure 13 shows the typical result of the FPP, in this case for the yacht "Flying Magic" when sailing upwind in 15 knots of wind. The VPP estimated a boat speed of 11 knots at a heel angle of 17º. The windows at the right show the results of the RLP. For both mainsail and jib the distributed forces along the mast and forestay are given in both the driving and heeling direction. Negative values indicate a force to windward or backwards.

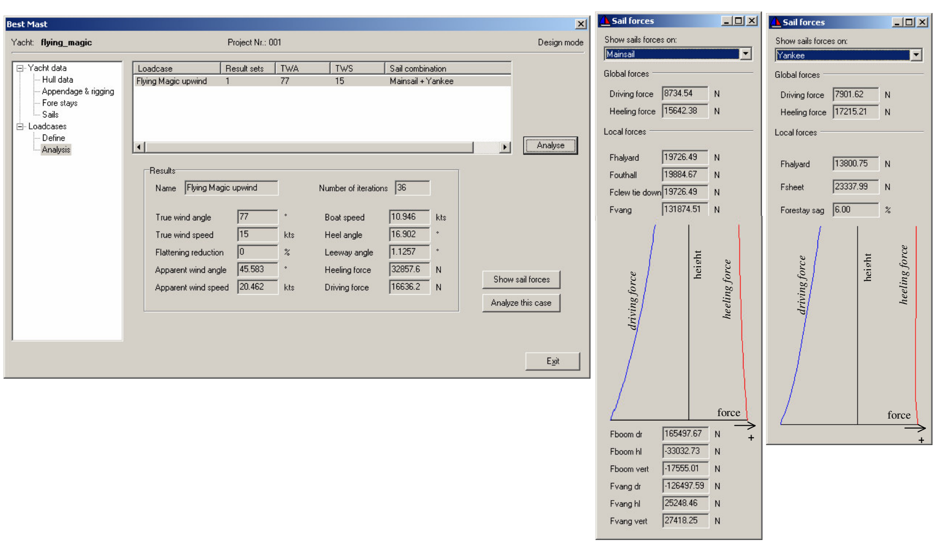

Figure 13: the results of the FPP for the yacht "Flying Magic" while sailing upwind. The window at the left shows the results of the VPP module while the two windows at the right show the resulting forces for both mainsail and jib.

Best Mast design tool

With a minimum amount of information the geometric model is defined in the dedicated MSC.Marc® Mentat® user interface. Figure 14 contains several windows of the Best Mast tool to show the required information.

The amount of spreaders, their width and height above the deck are free to choose. Stays can be selected from libraries containing properties of various stay suppliers and different materials. Also for the mast tube and spreaders a library is available for the standard Nirvana Spars profiles and materials as aluminium and carbon laminates. The total amount of pre load needs to be defined together with the distribution of the load over the different panels. It is possible to select special features as fore and aft lower diagonals, runners with or without check stay and a jumper. The first result after the definition of the model is an indication of the weight of mast and standing rigging and the belonging centre of gravity.

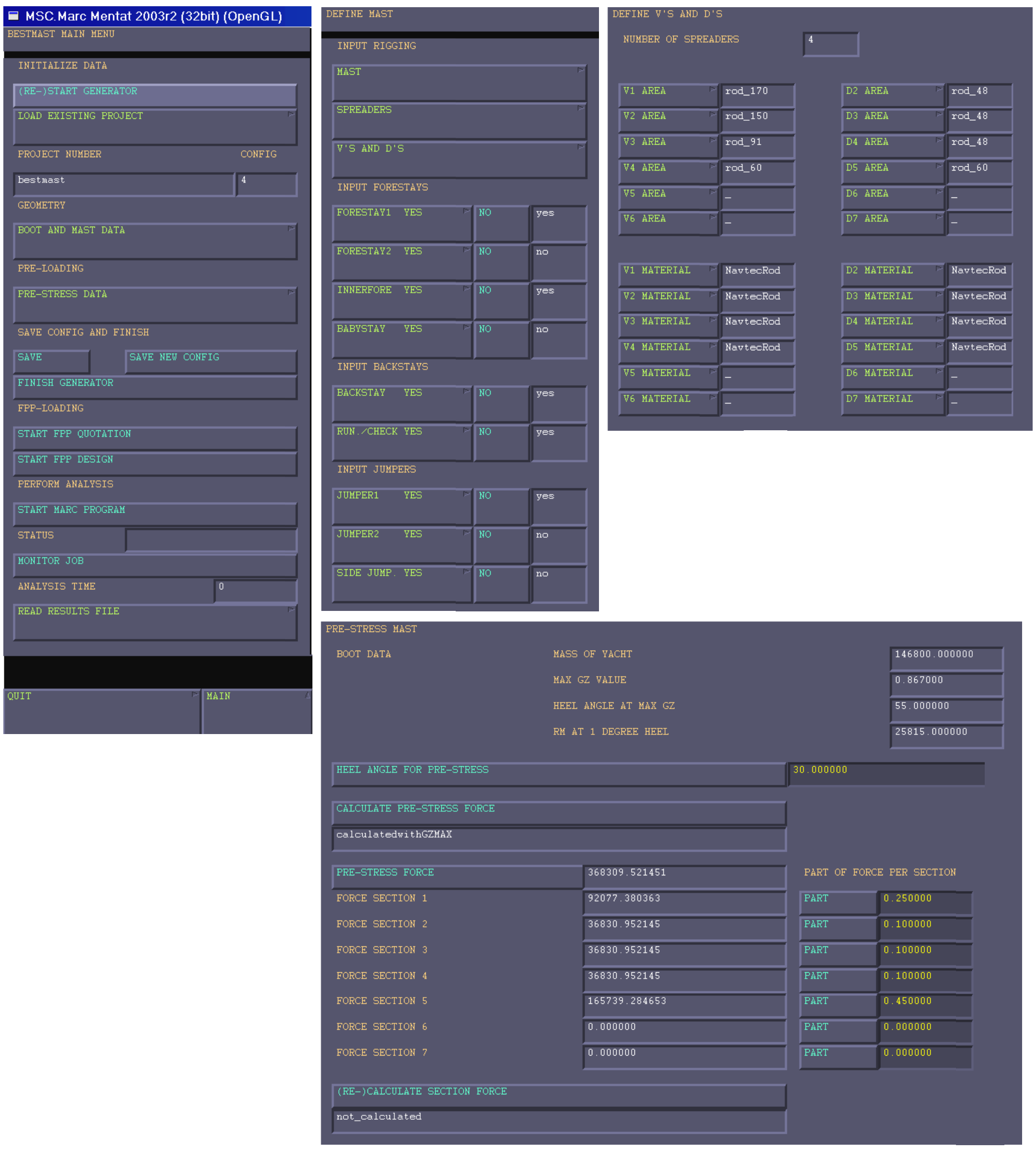

Figure 14 several screens of the MSC.Marc® Mentat® user interface showing the generic set up of the Best Mast tool.

After the definition of the geometry, the FPP module is started and the rigging loads are determined for a specific sailing condition. The finite element model is built using shell elements for the mast tube, rod elements for the transverse rigging and beam elements for the longitudinal rigging. The non linear analysis starts with the application of the transverse pre load followed by a pre bend check. If necessary the length of both fore stay and backstay is altered to achieve the required pre bend. Next the external forces are added and the load case is analysed.

The general behaviour of the rig can be monitored by monitoring the different load application steps. Figure 15 shows the geometric model and the deformed structure after the pre tension is applied. Also the final deformed structure is shown where the sag of the fore stay is clearly visible.

Figure 15: on the left the geometric model, in the middle the model under only pre tension and the final deformed structure on the right.

By examining the vertical displacement of the top of the mast as a function of the load steps global buckling can be monitored. The analyses also results in the stays forces and the stresses in the different directions of mast tube, see Figure 16. The later can be used to examine local stress concentrations and the risk for local mast wall buckling. Based on the results of several load cases the designer may decide to change some rig parameters and perform the analysis again.

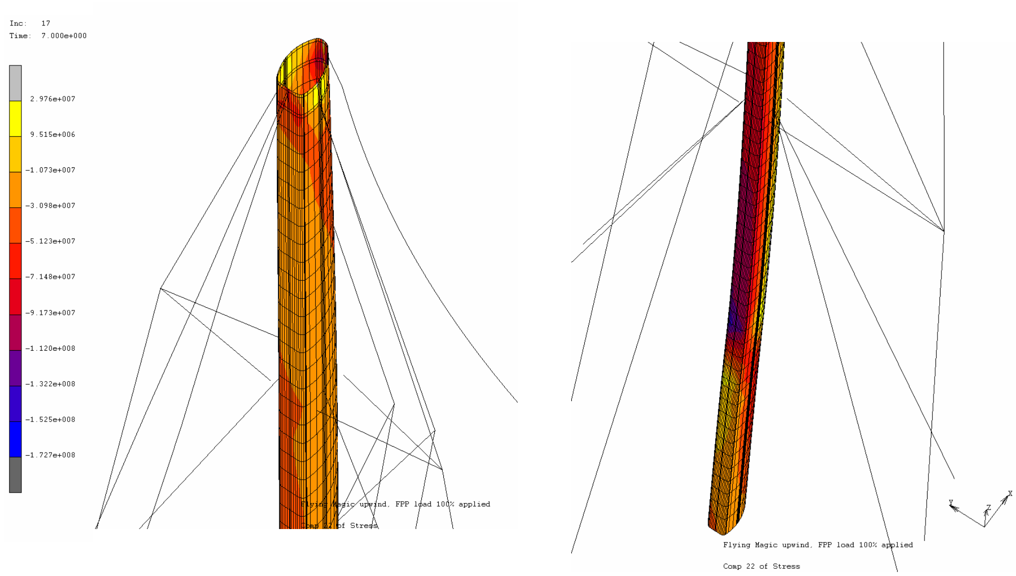

Figure 16 stresses in the mast as determined by the Best Mast tool, on the left the top of the mast and on the right the mast up till the first spreader.

The Best Mast tool is validated with the measurements obtained on the yacht "Flying Magic". As explained in the previous chapter the results of the VPP are compared to the measured boat speed and heel angle for various sailing situations. The finite element model is validated with the measurements performed during an inclination test of the yacht and the data from the pre load situation. For the semi static load cases the measurements are split in a static and a dynamic part. The static loads are used to validate the external forces as predicted by the load model. The long term measurements are used together with the dynamic part of the short term measurements to derive dynamic safety factors to be used for the different sailing situations.

At this stage the tool is capable to evaluate the structural response on static forces from the sails. A future step is to implement a model for the mast response on the dynamic behaviour of a yacht. Probably slamming and longitudinal decelerations do have a significant effect on the response where transverse linear and rotational accelerations are less dominant. Until then dynamic safety factors are used which are derived from full scale measurements in combination with the design tool.

Conclusions

In this paper the development of a new design tool for Nirvana Spars is discussed. Current design tools, as until recently used by Nirvana Spars, do not allow for further optimisation of sailing yacht rigs. This is due to the fact that they are based on a simplified statically determined model of the rig and the use of relatively high and often not traceable safety factors to take into account several design uncertainties. Lowering these factors may result in particular cases in unsafe rigs.

To be able to design lighter and reliable rigs in aluminium and carbon, a more sophisticated model for the structural behaviour of a rig is needed. Only a non linear finite element analyses can provide a prediction of this behaviour. This requires a reliable input of the external forces acting on the structure. The loads determined by the current design tools are not detailed and reliable enough for this purpose.

For Nirvana Spars a new design tool, Best Mast, has been developed. The tool consists of the finite element analysis program MSC.Marc® Mentat® and a sophisticated load model. Due to specially developed user interfaces for the input of mast and yacht data the result is a very generic rig design tool. The load model is based on a VPP and a force translation routine. The VPP determines the total driving and heeling force as generated by each sail individually. These are subsequently translated to forces acting on the rig like a distributed force on mast and fore stay, halyard loads and boom and pole loads.

At this stage the Best Mast tool can predict the response of the structure on static forces from the sails. A next step is to develop a structural model for the response on the dynamic behaviour of the yacht. Until then dynamic safety factors are used derived with full scale measurements in combination with the design tool.

References

[1] Claughton, "Sailing yacht design: theory", Addison Wesley Longman Limited, Harlow, 1998

[2] Larsson, L. & Eliasson R.E., "Principles of Yacht Design", Adlard Coles Nautical, London, 1997

[3] Keuning, J.A. & Sonnenberg, U.B., "Approximation of the hydrodynamic forces on a sailing yacht based on the 'Delft Systematic Yacht Hull Series", 15th International symposium on "yacht design and yacht construction". Amsterdam, 1998

[4] Keuning, J.A. & Vermeulen, K.J., "The yaw balance of sailing yachts upright and heeled", International journal of small craft technology, RINA transactions 2003 part B1, London, 2003

[5] Janssen, R.J., "Comparison of different rig configurations for an Open 60", Delft university of Technology, Delft, 2001