MaRSoft: Automated Yacht Mast and Rigging System Design and Analysis

Dylan Soares de Melo
CENTEC, Instituto Superior Técnico, Avenida Rovisco Pais, 1, 1049-001 Lisboa, Portugal.
dylan.melo@ist.utl.pt

Abstract

While structural dynamics is explicitly considered in the design of hull and deck scantlings, it is surprising to find that empiricism and traditional analytical computation is still widely adopted in mast and rigging system design at this present time. The design tools required to carry out such explicit analyses are available through commercial numerical software, and with basic programming, efficient design specific tools can be developed.

This paper describes the development of MaRSoft, an automated parametric yacht mast and rigging system design tool developed utilising commercially available software, whereby multiple mast and rigging system configurations of finite-element models can be designed, tuned and structurally analysed. These configurations of finite-element models are to be extended to handle tension-only cable elements, as well as composite orthotropic materials, and are to be analysed utilising static non-linear finite element analysis techniques. The obtained results are to be well structured for efficient post-processing, making for clear differentiation of the specified mast and rigging system configurations. Comparing these results, one can determine which configuration best suits the designers requirements, and consolidate a vast amount of design input for further detailed engineering.

Keywords

1. INTRODUCTION

A Yacht Mast and Rigging System (MaRS) form an essential part of the overall design and specification of a yacht, with the geometry and the scantlings having a significant impact on the yachts performance and handling characteristics. Typical MaRS design is executed analytically utilising empirically derived values that approximately match the hydrostatic specification of the defined hull form on which it will operate. Utilising this analytical design approach inevitably leads to over designed scantlings and geometry, and is therefore not the most efficient nor robust design solution. Furthermore, it is imperative to have a structurally sound MaRS for the safety of the yacht, as failure can lead to catastrophic consequences and in the worst case scenario, dismasting and sinking.

Nowadays, the technological advancements in materials, Computer Aided Engineering (CAE) and Computer Aided Design (CAD) have introduced the possibility to offer highly complex, and innovative MaRS design solutions. One of the driving forces behind this innovation was the Americas Cup, its competitive nature and the huge budgets enabled leading engineers in their fields to push the limits of MaRS design. This innovation, has lead yacht MaRS design to become a highly skilled and sought after profession, with collaboration of naval architects, structural engineers, materials engineers, sail makers and aerodynamicists.

It is clear, due to the diverse skill sets required to design a yacht MaRS, that obtaining the exact solution is not as straight forward as one would imagine. On the structural side alone, multiple load cases covering all imaginable sailing conditions need to be closely analysed, requiring a great depth of knowledge on the topic, as well as a large time investment. This process is extremely difficult to analyse analytically, as multiple iterations and configurations of the MaRS have to be considered, hence the need for numerical solutions is almost a necessity in order to obtain a robust design. It is for this reason that the key suppliers of high performance yacht mast and rigging systems develop complex in-house design tools. These design tools offer a generic solution to the challenging process of designing a specific yacht mast and rigging system while providing solutions that are reliable.

1 All commercial software specified is used for educational purposes only with no intent on infringement of licensing or copyright.
Typically, only high-tech racing yachts and large leisure yachts have the budget to invest in advanced numerical analysis involving finite element method to assess and optimise the structural behaviour of a yacht MaRS. The focus of MaRSoft is to try to eradicate the notion of the large time and knowledge investments required to set-up, analyse and optimise the structural behaviour of a yacht MaRS by demonstrating how utilising commercially available CAE and CAD software, a parametric design tool can be developed to carry out complex simulations.

2. Motivation of Study

With the ever-increasing demand for quick turnover time for designing and manufacturing complex, lightweight mast structures and rigging systems, the need for a design solution to handle the complex numerical computations is apparent. There are currently Classification Society Rules, as well as commercially available software which offer a solution to yacht MaRS design, however not at a level providing fully parametric MaRS design utilising three dimensional (3D) modelling and finite element method (FEM).

The current commercially available CAE and CAD software allows the possibility to control and “drive” input parameters through macros and other forms of computer programming. This makes it possible to set-up design tools utilising a simple graphics user interface (GUI). This “controlling” of CAE and CAD software through a GUI lends itself to design procedures whereby multiple configurations need to be analysed, such as that of a yacht MaRS.

Progressing from one dimensional (1D) analytical and numerical solutions to complex 3D non-linear numerical simulations requires in-depth knowledge of FEM theory and an in-depth knowledge of 3D CAD and CAE software. Furthermore, FEM software needs to used with great caution, as it is a tool that if not fully understood, can lead to a misinterpretation of results, and false validation of the problem. This highlights the significance of a design tool, that if well developed, “de-bugged” and tested to validate the numerical model, can remove a great amount of risk involved in the setting up of a complex “one-off” finite element analyses.

3. Objectives

The objective of this paper is to provide an overview of MaRSoft and the scope of its development.

MaRSoft is a basic, efficient design tool capable of parametric design, tuning and analyses of sloop type rigs. At the core of MaRSoft is a fully developed finite element model that has the possibility to carry out static linear, modal (vibration), linear buckling and static non-linear finite element analyses. It is to be built utilising commercially available software, with coded Microsoft Visual Basic Applications (VBA) macros simplifying design input from a GUI. All the actions required to perform and fulfil a complete finite element analysis of the mast and rigging system structure are to be fully automated using each of the secondary software’s coding language, and are to be wholly controlled through the GUI with no direct input into any of the secondary software.

MaRSoft shall be sufficiently developed to structurally analyse the mast tube. In order to set-up an accurate simulation of the mast tube, the mast and rigging system will be modelled in its entirety, including rigging and spreaders, however the structural analysis of these rigging and spreaders will not be considered in this paper. To simplify the design tool further, the number of spreaders will be constrained to a maximum possible selection of three spreaders, and the rigging will be constrained to a single forestay, a single backstay and typical “linked” lateral rigging. Due to the high level of non-linearity in the rigging cables, with the capacity to sag when in compression, the FE model is to be extended to handle tension-only cable elements. These tension only cables are to be simplified in the static linear analysis to become “bar” type elements that resist load in compression, and completely removed in the linear buckling analysis. The reasoning for this, is that the function of the static linear analysis is not to structurally analyse the mast tube itself, but is used to set-up and modify the geometry with quick results of parameters such as the section modulus, vertical centre of gravity, and mast tube weight. Similarly, the function of the linear buckling analysis is not to structurally analyse the mast tube, but to understand how the mast tube reacts in compression, and to obtain the first modes and eigenvalues of a simplified system. Using the results obtained and knowledge gained from the linear buckling as well as the conservative values of deformation obtained from the linear static analysis, a non-linear analysis of the MaRS can commence with a greater understanding of the prerequisite design values needed to carry out an efficient, and accurate analysis.
All results obtained from the simulation are to be easily comparable through both visual means, utilising contour plots and graphical plots, as well as through numerical means. The available options in which results can be formatted and displayed in typical commercial FEA post processing are endless, and therefore to simply illustrate the effects of any changes made to the finite-element modal, a force versus displacement graphical plot will be generated at selected critical points. Contour plots such as equivalent stress, equivalent strain, displacement sum, and rotational sum will also be produced and reported, as well as graphical plots of displacement and equivalent stress along a vertical path up the aft edge of the mast tube. The numerical results will be available through the output file generated by the FEM software, and easily accessible through the GUI.

4. State of the Art

The calculation procedures for MaRS design referred to in literature ([1], [2], [3]) are based on Skene’s Method. This is an analytical method still widely used in mast design, and is based solely on the transverse stability of the yacht. Skene’s method has however evolved, and there are many variations to the method, with the evolution coming from coefficients applied to the formulae, obtained through practice.

The starting point for Skene’s method is to consider the mast stability in compression, from which the cross-section dimensions of the mast can be calculated. The stability in compression is based on the righting moment (RM) of the yacht, typically taken at 30°. This angle corresponds to a reasonably high wind strength with the sails generating high loads, and the yacht making good speed through the water. The first estimate of maximum compression at the mast base is obtained using the moment balance of the form:

\[ P = \frac{RM_{30\circ}}{b^2} \]  \hspace{1cm} (1)

where \( P \) is the mast compression force, \( b \) the chain plate width and \( RM_{30\circ} \) is the righting moment at 30° heel.

Over time, this equation has been optimised using coefficients to take into account the modelling assumptions and effects of distributed forces from sails, halyard forces, and longitudinal forces from stays, and the most common form used at present is:

\[ P = 1.85 \cdot \frac{1.5 \cdot RM_{30\circ}}{b^2} \]

\[ P = 1.85 \cdot \frac{1.5 \cdot GZ_{30\circ} \cdot \Delta \cdot g}{b^2} \]  \hspace{1cm} (2)

where \( GZ_{30\circ} \) is the righting moment arm at 30° heel, \( \Delta \) weight displacement, \( g \) acceleration due to gravity and the coefficients 1.5 and 1.85 take into account the heel angles greater than 30° and the coefficient for stays, sheeting and halyard loads respectively.

Since the designer is making use of an equation with no understanding of where, or how the coefficients have come about, it is not possible to optimise the design. In essence the MaRS under consideration is a replica of what has already been built. Moreover, the RM of the yacht is often only known at 1° from the hull’s upright hydrostatics, and it is therefore assumed the first part of the static stability curve (see Figure 1) is linear, and the value is multiplied by 30. This is clearly not the case, as the curve is not linear which leads to a much higher RM value, and therefore a much greater compression force, and ultimately heavier scantlings.

![Figure 1: Static Stability Curve [5].](image)

With the empirically calculated mast compression force obtained, the required second moment of area, \( (I) \) to resist buckling can be calculated using Euler’s buckling equation for long slender columns:

\[ P_{cr} = \frac{\pi^2 EI}{k^2 L^2} \Rightarrow EI = \frac{k^2 P_{cr} L^2}{\pi^2} \]  \hspace{1cm} (3)

where \( P_{cr} \) is Euler’s critical buckling load, \( E \) is the modulus of elasticity, \( I \) second moment of area, \( L \) is the length of support and \( k \) is Euler’s support coefficient.

The length of support, \( L \), in equation (3) represents the panel length of of an unsupported mast
between any two supports. The value of the coefficient is dependant on how the mast panel is supported, which is related to the panel location on the mast, whether it is supported by spreaders, or if it is a fore-aft panel or aftwartship panel. For this reason, it is necessary to distinguish the second moment of area between the transverse, and longitudinal direction as the support lengths, as well as the coefficients change. It must be noted that a typical mast does not conform to the constraints to which Euler’s buckling formula was developed, as it is a tapered column with multiple fixivity, and subject to both bending and torsion.

To calculate the required rigging strengths, multiple loads pertaining to each loading system are taken into account. The loading systems are made up of the pre-tensioning of the rig, transverse sail forces, self-weight forces and extreme loads [1]. Pre-tensioning of the rig, self weight-forces, and the extreme loads are considered as a separate case, and are configuration dependant, and do not have empirical formulae to follow.

The transverse sail forces are also determined from the righting moment of the yacht. Each sail’s contribution to the resultant heeling moment is assumed to be proportional to the sail’s area and the distance of its centre of effort above the underwater body’s centre of lateral resistance (see Figure 2).

![Figure 2: Centre of Efforts on Sails [1]](image)

The sum of these heeling moments is needs to balance the previously calculated RM, and given by the following equations [1]:

\[ F_{tm} = \frac{RM_{design}}{CoE_mCLR} + \frac{A_F \cdot SFC_f}{A_m \cdot SFC_m \cdot CoE_fCLR} \]

\[ F_{tf} = \frac{A_F \cdot SFC_f}{A_m \cdot SFC_m} \cdot F_{tm} \]

\[ F_{ts} = \frac{RM_{design}}{CoE_fCLR} \]

where \( F \) is the transverse sail force, \( A \) the sail area projected laterally, \( CoE \) the centre of effort of the sail, \( CLR \) centre of lateral underwater resistance of the boat and \( m, f, s \) represent the mainsail, foresail and the spinnaker respectively.

Once the transverse sail force is known, the distribution of the loads at the sail corners with respect to the sail balance has to be performed. This is done by multiplying the transverse sail force by a factor depending on the sail type and amount of spreaders under consideration (See [1]).

![Figure 3: MainSail, Foresail and Spinnaker Load Distribution [1]](image)

Since no direct forces generated from the sails, rigging and self weight of the mast are taken into account, and the formulae are based on empiricism resulting from the yachts righting moment, it is clear that optimisation of the MaRS is very difficult.

In literature [5], [7], the determination of sail loads on the rig are explicitly determined through the development of a Force Prediction Program (FPP). The FPP is made up of a Velocity Prediction Program (VPP) which predicts the driving and heeling forces generated from each sail under a given sailing condition, and a Rigging Load Program (RLP) which translates these sail forces onto the rig. This is a great step forward in the accuracy of the load values on the rig, as the forces generated by each sail are translated numerically onto the rig. The result of the VPP is a set of loads acting on the rig which can be used as design input in a finite element analysis program, or a design tool like MaRSoft.

![Figure 4: Predicted VPP Loads Translated onto the Rig by the RLP [5]](image)

The requirements to execute a state-of-the-art design of a yacht mast and rigging system without...
utilising empirical formulae can therefore be broken down into two distinct groups.

1. Obtaining accurate loads transmitted onto the rig utilising VPP software or similar.
2. Utilising the obtained loads in a non-linear finite element analysis of the MaRS in its entirety.

MaRSsoft focuses on the second group, and does not have the ability to numerically obtain the transmitted loads. It is therefore required to be used in conjunction with software capable of obtaining these loads in order to be used to its maximum potential. This is not to say that it is not a useful design tool, as it still has the capacity to greatly optimise the mast tube structure based on measured loads from practical applications, historical data, as well as loads obtained from empirical formulae. More importantly, it can be used to accurately tune the mast pre-bend and analyse exactly what displacements each section of the mast tube will see, and to what values the rigging needs to be strained in order to achieve the displacement values.

5. Finite Element Model

The defining and development of the finite element model is of great importance and forms the backbone of MaRSsoft. Since MaRSsoft is parametric design tool, a different approach to setting up and writing the finite element code needs to be taken in order to successfully analyse multiple MaRS configurations.

ANSYS® was chosen as the commercial finite element analysis software to be used in MaRSsoft. The main reason for opting to use ANSYS is due to the ability to program through its parametric design language known as ANSYS Parametric Design Language (APDL). APDL is a scripting language that allows for automation of common tasks and one can build the finite element model based on parameters and commands. This approach suits the MaRSsoft requirements perfectly.

SOLIDWORKS® was chosen as the dedicated 3D modeller to generate the 3D finite element geometry in order to carry out the finite element analysis. SOLIDWORKS (SW) was chosen as it has a parametric kernel, and is therefore capable of fully parametric modelling, which is required in order to handle the multiple geometry configurations specified by the user through the GUI. It also has the capability of controlling and manipulating pre-set parameters through Microsoft® Excel based Design Tables, which is extremely useful for the design tool application. The FE model is generated utilising very few input parameters that “drive” a fully contained 3D mast a rigging system model. This is made possible by applying equation driven dimensions that are updated via the SW Design Table. An example of the constrained mast tube section can be seen in Figure 5, with the purple dimensions illustrating the equation driven dimensions.

The defined 3D model is then import into ANSYS APDL, which has the capability to import 3D surfaces, solids, and wireframe geometry through its /AUX15 command. The chosen file format from which the 3D geometry will be imported is a vendor-neutral file format known as Initial Graphics Exchange Specification (IGES).

Once imported, a host of APDL commands are defined to accurately find and store the locations of all hard keypoints. This location of the keypoints is imperative, since they are used throughout the FE model to locate nearby nodes, onto which loadings, constraints and couplings are defined.

The proceedings of defining the typical pre-
processor parameters are all automatically updated and revised according to the GUI input. Since MaRSoft is capable of more than one analysis type, each of them can access its own macro template. The solution and post-processing. It is therefore necessary to fully define a FE macro template for each analysis type. This template is updated accordingly from the defined GUI parameters and further control of the macro template is made possible by deactivating the line of code utilising the "I" symbol when not needed. This provides a macro, that is controlled fully from the GUI, utilising the data from the Excel based database which is analysis type specific.

The post processing is kept relatively simple, with the possibility to automatically view nodal contour paths of stress, strain and deformation, as well as plot graphs of Vector Force Sum versus Displacement Sum (FD), and Mast Height versus Displacement in both the transverse and longitudinal directions.

In Figure 8, the FD curve is plotted at the mast head, and at the coupling points of the forestay and spreaders 1,2,3 with the mast.

The Mast Height versus Longitudinal and Transverse Displacements seen in Figures 9, 10 respectively illustrate how the mast tube will react to the loadings and pre-tensions alike. To a mast designer they are extremely useful plots to analyse.

Finally, the full output file generated by ANSYS is available directly from the GUI, whereby a multitude of results and analysis data can be studied.

6. Application of MaRSoft

The primary programme used to store and calculate all the data required by the finite element model is Microsoft® Excel. Excel was chosen as it has an extremely broad range of capabilities, and the typical end user is expected to be familiar with its functionality. Although Excel is the primary programme used in the application of MaRSoft, it is not directly controlled or edited by the user, in fact it is not seen by the user at all. The Excel
spreadsheet is driven utilising a Microsoft Visual Basic Applications (VBA) based Graphics User Interface, from which the user will be able to manage all aspects of the finite element model.

The design tables required by SW to generate the FE Model are updated within Excel. When a new configuration is selected by the GUI, the design table updates accordingly allowing the geometry of the FE Model to be controlled very simply via the GUI. Likewise, the ANSYS macro’s have been written in Excel with the required cells linked and updated to the GUI and updated accordingly. This allows for the running of each analysis directly from the GUI. Since, the post-processing is largely dependant on what the designer is looking to achieve, a very simple results report can be generated through the MaRSoft GUI. This is achieved by predefining the input parameters, with the values being updating within excel. Using VBA macros the report can be generated using open the source word processor \textit{LATEX}, which is saved as a .pdf document for quick review of any changes made.

The GUI is to have the capabilities to suitably update the code for generating the 3D Parametric Model as well as the FEA macro, according to the GUI input. Furthermore, the GUI needs to "call" the required executable applications, and run the necessary functions, with the possibility to analyse multiple mast configurations, through different analysis types without terminating the GUI.

Since \textit{MaRSoft} is an automated design tool for a user with intermediate FEA knowledge, the layout of the GUI has been kept very simple, but functional. The defining of a new MaRS ready for analysis through \textit{MaRSoft} shouldn’t take more than five minutes. This ease of functionality is extremely useful when analysing multiple configurations, and allows the user to interpret the changes made in a short time frame, with full confidence in the results.

Within the GUI there are four main tabs that distinguish the different systems of a typical MaRS, and a right window pane with buttons which carry out the functions of \textit{MaRSoft}.

\textbf{Tab1: Home} The "Home Tab" is where the project information is defined, as well as the working directories required for the installation of \textit{MaRSoft}.

\textbf{Tab2: Mast Definition} The "Mast Definition Tab" is where the mast tube geometry and material specification is defined. Through these few input parameters, the required mast tube geometry constraints and parameters can be fully defined, ready for uploading through design tables into SOLIDWORKS.

\textbf{Tab3: Rigging Definition} All the information relative to the standing rigging is defined in the rigging definition tab. The defining of the spreaders is done in systematic way, and accepted upon completion. The defining of the spreaders can be reset and restarted should the user make a mistake, or want to analyse another
configuration. A library of standard rigging materials is available directly through the GUI, similar to that of the composite material library.

**Tab4: Loading Definition**

![GUI - Loading Definition Tab.](image)

Applying the loads to the MaRS is carried out by inputting the loads from the respective sails found on a sloop. It is a section of MaRSoft that requires further development to obtain a MaRS design tool capable of full explicit analysis.

The pre-tensioning of the standing rigging, or "Dock Tuning" can be carried out by predefining tensions on each of the rigging lines. Depending on the rigging material, the diameter of the rigging line, and the length of the rigging line, an initial strain is calculated and transferred on to the FE model. This is a powerful section of MaRSoft as in practice it is very difficult to accurately measure the pre-tensioning and pre-bend of a rig. For future work, the validating of this section of MaRSoft on an actual rig would be a great exercise.

The four main analysis types that MaRSoft is capable of simulating are Linear Structural, Linear Buckling (Eigenvalue), Modal (Vibration), Nonlinear Structural Analyses. Each of these analyses types have their own purpose within MaRSoft, and are necessary to analyse the structural characteristics of a MaRS. Due to the complexity of setting up the solution to a FEA, the input available to the user has been kept to a minimum to reduce the risk of creating a analysis that will not converge. Off course, in practice certain analysis will not converge, and will require some manipulation of the solution coding. This can be done directly to the macro itself, which is automatically generated by MaRSoft.

**Right Window pane** The right pane houses the buttons required to carry out the analysis (see Flowchart Figure 15 for MaRSoft sequence). Once the defining of all the tabs discussed above, the "Accept Input" button is selected. By doing this, all the selected input is directed to the database within Excel. It is the first and most important step of carrying out an analysis with MaRSoft.

The next step is to "Create Mast Model" which is the process of generating the required .iges file for input into ANSYS. This is a fully automated procedure, whereby SOLIDWORKS is executed and through SOLIDWORKS API Script. A 2D General Arrangement (GA) drawing is also produced during this step (See Appendix), which allows the user to check the input before running an analysis. This GA drawing also puts the scale of the heights and spans of the mast tube, spreaders and other associated geometry into perspective, and should the user want to make any adjustments, these can be performed directly through the GUI, and re-updated by simply selecting the "Create Mast Model".

Now with the .iges file has been generated, the FEA can commence. First the finite element macro is generated. A .mac file is created and depending on the selected analysis type, loaded into the correct file directory. With the ANSYS macro created, the option to launch ANSYS APDL can be done through the GUI. If ANSYS is already open, this step can be skipped, and then by selecting the "Run Analysis" button the macro will be uploaded into ANSYS APDL, and commence with the analysis. During the time of running the analysis, the GUI can used, and the user can start on a new configuration if desired.

Finally the results can be viewed via the output file, directly available from the GUI buy selection "Review Output File" or via a basic report which documents the input parameters, and presents nodal contour plots of the displacement vector sum, Von Mises Stress, and Equivalent Strain. The report file has not been developed in detail, as the post-processing options in numerical analysis are extremely vast and dependant on what the designer is trying to achieve.

Once complete with the analysis, the user has the option to directly modify existing parameters they deem necessary in order to optimise the MaRS, or the user can reset and restart the analysis, which erasers the previous database created by the user. Should the user want to exit MaRSoft, selecting the "Close" button will terminate all associated executables, and third party software.

The typical design methodology and implemen-
ration of can be seen in flow chart Figure 15.

Figure 15: MaRSoft Design Methodology

7. CONCLUSIONS AND FUTURE WORK

Yacht mast and rigging system design tools do exist, but typically lack the functionality to geometrically design and structurally optimise the rig. This is largely due to the fact that simplified models based on empiricism are used in simplified 1D Linear FE models. The necessity for a design tool capable of a more detailed, explicit approach to MaRS design is apparent, and is achievable. This paper details and reports the development of MaRsoft, which is such a design tool, along with a basic introduction to the engineering principles on which MaRsoft is built.

The objective of this paper is to develop a MaRS design tool that is capable of parametric complex numerical analyses for preliminary detail design, made possible through a simplified GUI. The fundamental requirements to achieve this objective are to develop a robust FE geometry modeller, FE macro generator, and a GUI to manipulate data which have been achieved.

The reliance of loading input from third party software is a hindrance to the accuracy and ability to truly simulate the structural performance of the designed rig. The finite element method is only as accurate as the input defined, and the accuracy of loading input is critical to achieve reliable results.

For future work, the incorporation of numerical methods such as computational fluid dynamics and explicit dynamics to generate detailed, specific loading results would be a great advance in MaRSoft’s capabilities. Furthermore, the rigging capabilities have been greatly simplified, specifically in the longitudinal standing and running rigging. The development of this rigging is however, not difficult and can easily be implemented into the current coding of MaRSoft. The material database is limited, and a revised detailed material database would allow for a more involved analysis, and therefore the potential to greater optimise the MaRS.

REFERENCES

[8] A. Zamarin, T. Matulja, M. Hadjina Methodology for Optimal Mast and Standing Rigging Selection of a Racing Yacht Using AHP and FEM
A. Appendix