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Innovative technologies used for balancing and monitoring the rigging of sailing vessels

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Abstract. The propulsion of sailing vessels is based on the transformation of potential wind energy into traction force, through rigging. The action of the wind can cause considerable loads that can lead to deformations in the elasto-plastic and plastic area of the mast elements, with detrimental consequences on the safety of the vessel's operation. In order to prevent these deformations, it is necessary to permanently balance the masts, which consists in pretensioning the metal cables supporting the mast, in order to have an equivalent distribution of loads depending on the wind speed and its direction.

This article presents a method of balancing the masts, which is based on innovative technologies, the technology of tensometry for the permanent identification of loads in the rigging cables to support the masts, and IT technology for real-time monitoring. This method allows the use of numerical calculation corroborated in real time with the values of the stress in the metal cables. The implementation of this method on board sailing vessel will maintain the rigging of the masts in normal operating parameters, with positive consequences on the traction efficiency of the vessel and on the safety of the vessel, by reducing the possibility of damage to it.

Keywords: sailing vessel, pretensioning, balancing masts, rigging, tensometry.

1. Introduction

Current requirements to reduce air pollution, and in particular greenhouse gas emissions, see the Paris Agreement on Climate Change, have also required maritime scientific research to focus on alternative, clean sources for the propulsion of ships, whereas international maritime transport accounts for about 3% of all global greenhouse gas emissions, according to the United Nations International Maritime Organization [3,5]. Thus, the study of the propulsion of ships based on wind force, such as: propulsion with sails and propulsion with Fletcher rotors, returned to attention. At present, Fletcher rotor propulsion has already been implemented in some merchant ships (see E-ships) [9] as an applied research step. As there are still sailing ship, it is possible to study the propulsion of sails on these ships, thus reducing financial research efforts. The development of smart technologies, as a result of the development of IT technology, makes this study an accurate one. The purpose of the study of sailing propulsion on existing ships is to determine the forces acting on the mast in various loading situations at the limit in order to obtain a mast design that ensures high propulsion efficiency and safe operation of the ship. The operational safety conditions for sailing ship consist of the permanent prestressing of the mast fasteners (fixed maneuvers). Therefore, pre-tensioning is a case of loading of fixed maneuvers (FM) when sailing is done without sails, for which the group of fixed maneuvering pairs (starboard-port) must be chosen accordingly, so that during sailing there is no exceed the permissible values of the stresses in the shaft. This article proposes, with the help of innovative technologies, a detailed, multidisciplinary methodology for determining the optimal tasks for prestressing fixed maneuvers and monitoring them during sailing in order to analyze the behavior of the mast in different loading situations, to determine a maximum safe propulsion efficiency of the ship. From the study of the specialized literature, the proposed methodology represents a novelty in the field, being of a real support in the subsequent researches of behavioral analysis of the mast on the sailships.

2. Method

The stages of implementing the method of balancing and monitoring the mast on board sailships, by using innovative technologies, are presented in Figure 1.

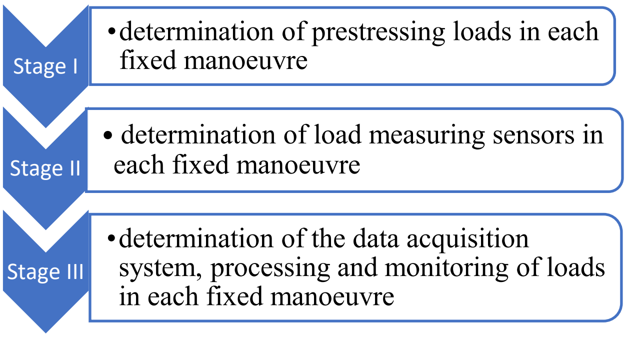


Figure 1. The stages of implementing the method of balancing and rigging monitoring

In order to be able to balance the rigging, four essential conditions are taken into account:

- the efforts of any fixed maneuver must not exceed their permissible values in any scenario of use;
- the forces in any fixed maneuver must have values so that they are permanently tense in any scenario of use;
- the efforts in the fixed maneuvers must have values so that reduced to the shafts not to cause the loss of their elastic balance (not to produce the buckling phenomenon of the shafts). At the same time, these efforts must not cause the hull to deform in areas where the masts are embedded in the hull;
- the forces in the fixed maneuvers symmetrical to the diametrical plane (PD) of the ship must be equal;

2.1. Determination of prestressing loads in each fixed maneuver

In order to be able to perform the operation of balancing the shaft, the prestressing forces must first be determined in the fixed maneuvers in different loading cases, so that the metal ropes from which they are made do not flutter (completely weaken) or are overloaded and also the value of stresses. permissible from the structure of the rigging should not be exceeded.

This requires the following data on the vessel and mast: characteristics of the vessel (overall, hydrostatic and dynamic) and on the structure of the mast (diameters, lengths and shapes of the shafts, material characteristics of which they are made: material type, sheet thickness), characteristics sails (shape and dimensions), characteristic data of the fixed maneuvers of the mast (material, diameters, lengths, breaking forces of the cables, modulus of elasticity).

Since the number of elements of a mast is very large, and in a sailing ship the mast contains at least 2 masts up to 4-5 masts, the analytical calculation for determining the optimal prestressing loads in each FM is laborious. To facilitate the calculations, the finite element analysis method (FEM) is used, through

specialized software (ANSYS, FEMAP, etc.), with which immediate and sufficiently precise results can be obtained, regarding the behavior of the rigging elements in well-specified navigation situations.
In order to perform these calculations, the following conditions must be taken into account, which must be imposed as restrictions in the calculations to be performed:

a) The flow limit of the material from which it is made must not be exceeded in any element of the stand;
b) In all fixed maneuvers there must be an axial stretching effort, respecting the previous condition;
c) The forces appearing in the masts must be such that they do not bring into the elastic-plastic state the structural elements of the ship to which they are connected [4].

The first stage of FEM consists in discretizing the riging. For this, the FM and the masts are considered as bar elements with 12 degrees of freedom, and the sails as triangular plate elements with 4 degrees of freedom per node. Regarding the imposition of the conditions regarding the connections, the masts embedded in the structure of the ship will be considered (all 6 degrees of freedom blocked), and all the fixed maneuvers articulated at one end (mast) and embedded at the other end.
The second step is to identify the efforts in each FM due to the maximum allowable displacements. The loads consist of the introduction on one end of each FM from unit displacements to displacement values at the limit of compliance with conditions a), b), c). This will determine the maximum effort for each FM produced by these limit shifts.
The third stage consists in the analysis of the loads that can appear in each FM for different limit cases at which the mast is required, depending on the wind direction in relation to the position of the ship (stern wind and transverse wind), the positions of the sails tight rods in the rope) - Figure 2, as well as the maximum wind speed which is the one corresponding to level 6 on the Beaufort scale.
Thus, we distinguish four case studies:

- case 1 - Wind from the stern; prestressed sign + FM rods;
- case 2 - Wind from the stern; tight-fitting rods + prestressed FM;
- case 3 - Crosswind; tightened rods + prestressed FM;
- case 4 - Crosswind; tightened rods in prestressed + FM prestressed.

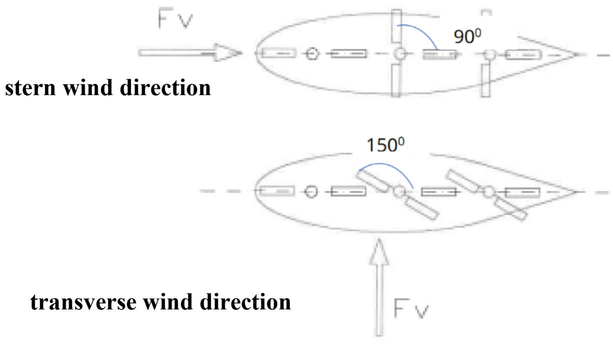


Figure 2. Wind direction and sailing position [6]

For these calculations it is necessary to determine the wind pressure, respectively the resulting approach on the whole sail for the 4 loading cases. Thus, with the help of formula (1), the wind pressure in the sails is calculated:

$$q = \frac{1}{2}\rho_a U_{T,z}^2 \quad (1)$$

in which:
– q [MPa]- wind pressure;
– ρ_a $[kg/m^3]$ - the density of dry air at a temperature of 15^0C in the navigation area; din zona de navigație;

– $U_{T,z}$ [m/s] - average wind speed over time at the height indicated by statistics in [m] above water level. It is adopted according to the Beaufort ladder for the ship's navigation area [1].

When determining the loads, the shading factor must be taken into account, ie the active surface of the sail under the action of the wind for each case of loading. Thus, the wind force on shaded sails is determined using formula (2):

$$F_{V,umb} = F_V \cdot \eta \qquad (2)$$

in which:

– $F_{V,umb}$- the force of the wind on the shaded sails;

– F_V – wind force on each sail surface resulting from the formula (1);

– η - the shading factor of the sails from the central shaft to the adjacent shaft, which is determined according to the solidification factor Φ which is calculated as the ratio between the projected area of the sails and the area between their contour [1].

The values obtained as a result of the FM stress under the above conditions determine the loads or discharges of their stress depending on the position of the sails, the direction and the intensity of the wind. From the analysis of these values, the absolute stress will be identified in the most unfavorable conditions for each FM.

In the last stage of the FEM analysis, the value of the prestressing stress in each FM will be determined. The absolute stress for each FM is composed of the value of the stress under the action of the wind in the most unfavorable conditions summed with the optimal value of pretensioning. Thus, the actual prestressing displacements for each FM are obtained by successive iterations taking into account the maximum allowable displacements of the clamping ends of the ship FM. The final state of prestressing ensures the extension of all FM in the combined cases of wind load and prestressing and will not lead to equivalent stress levels in the structure of the shaft higher than the allowable.

2.2. Method of choosing load measuring sensors in FM

Rigging prestressing is an essential requirement for shaft balancing and this involves a series of specialized equipment for measuring and transforming the values obtained into information that can provide the stress state in the shaft elements.

The measurement of the loads in the FM is the way to check the prestressing values or the compound stress during the operation of the sailing ship. The determination of the stress in each FM, taking into account the material characteristics, can be done by permanently mounting sensors that permanently measure the linear displacements.

The following conditions must be considered when choosing the type of sensors for measuring linear displacements:

- to fall within the range of values of the maximum displacements identified by the FEM;
- high measurement accuracy, ie very good resolution and reproducibility;
- to withstand the climatic conditions of the marine environment, ie humidity, salty environment, large temperature variations.
- to operate for a long time, ie to be robust and maintenance-free.
- to be able to operate even in vibration conditions;
- to have a small size;
- to be able to be mounted on FM tensioners;
- allow real-time analysis and visualization of measured values.

There are 3 types of sensors for measuring small linear displacements, namely: resistive transducers, inductive transducers and capacitive transducers.

Resistive displacement transducers - linear displacement is transformed into a variation of the resistance of a rheostat or a potentiometer.

The advantages of the resistive transducer are:

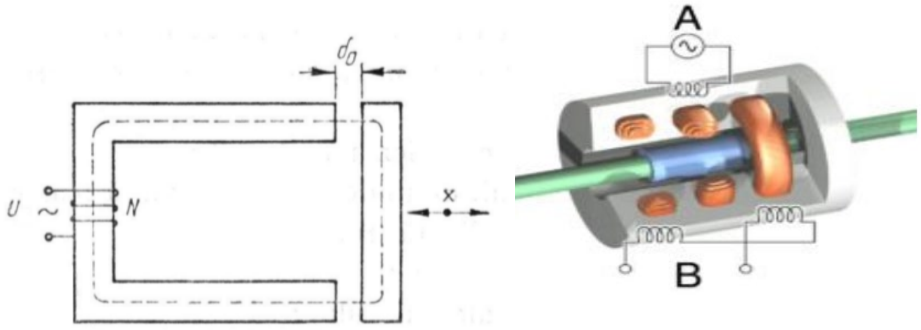
- can be powered by both AC and DC;

- provides the quick answer;
- is available in various sizes and has a wide range of strengths.
- have low costs;

The disadvantages of the resistive transducer are:

- high power is required to move the sliding contacts.
- Sliding contacts wear out over time, can become uneven, and can make noise [7,10].

Inductive linear displacement transducers - transform a linear displacement into a variation of the inductance of a magnetic circuit. The magnetic field must change with a certain frequency (alternating signal), and the displacement of the conductor appears as amplitude modulation, ie the amplitude of the alternating stress changes with distance or displacement. There are 2 constructive types of inductive transducers, namely with variable air gap and movable core (Figure 3) [7].



a. b.

Figure 3. Principle of operation of an inductive displacement transducer [7,10].
a. inductive transducer with a variable air gap; b. differential inductive transducer with a movable core

The advantages of core inductive transducers are:

- very long service life and high reliability, due to the lack of friction when moving the core;
- very good resolution and reproducibility;
- insensitivity to radial displacements of the core;
- operation in corrosive environments, or environments with high pressures or temperatures, due to the possibility of coil protection;
- ensuring galvanic separation.
- measuring range of tens of microns;
- reduced size;

The disadvantages of inductive transducers are:

- the main source of errors is the changes in the magnetic characteristics of the core due to aging;
- higher costs than resistive transducer.

Capacitive linear displacement transducers - transform a linear displacement into a variation of the electrical capacity of a capacitor [7].

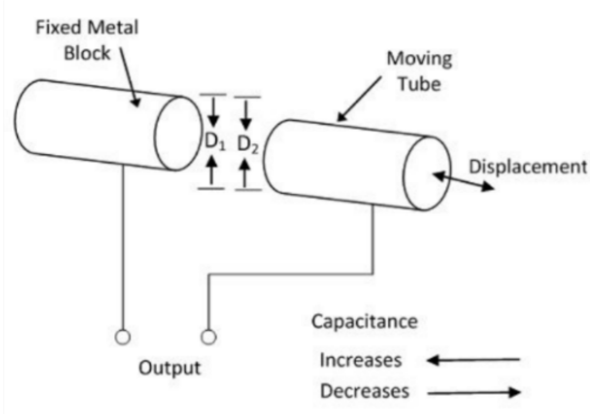


Figure 4. Operating diagram of a capacitive transducer [9].

The major advantages of capacitive transducers are:
- requires external power to operate and is therefore very useful for small systems.
- is very sensitive.
- provides a good frequency response, due to which it is used for dynamic study.
- has a high input impedance, therefore it has a small charging effect.
- requires low output power for operation.

The main disadvantages of the capacitive transducer are the following:
- metal components of transducers require insulation.
- the capacitor frame requires grounding to reduce the effect of the external magnetic field.
- is non-linear behavior due to the edge effect which is controlled by the use of the protective ring.
- the transducer cable causes a measurement error [9].

From the analysis of the working characteristics of the 3 types of linear transducers presented, based on the conditions mentioned above, inductive transducers are the most recommended to be used to measure the linear displacements of the FM on board sailing ships.
After choosing the transducers, the tensioners will be chosen according to the maximum loads they have to bear. A tensioner model used for FM pretensioning is shown in Figure 5 [6].

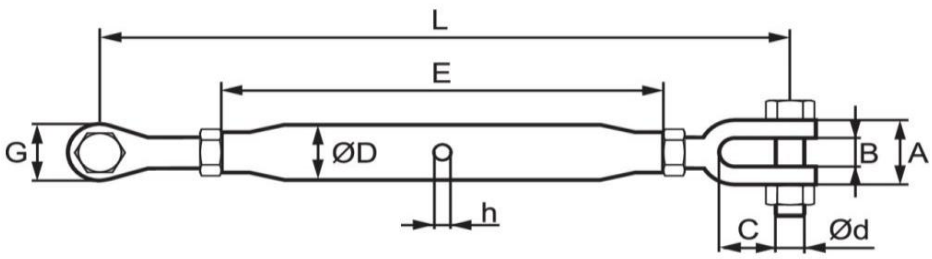


Figure 5. Type of tensioner used for FM prestressing [6].

2.3. Determining the system of data acquisition, processing, and monitoring of rigging
The data acquisition, processing, and monitoring system of the rigging must meet the following requirements:
- the equipment that is used will not be affected by the marine environment (humidity, corrosive environment);
- the information processed by the transducers will be displayed in real-time;

- communication between transducers and the data processing and display unit shall not interfere with or interfere with the ship's on-board navigation equipment.

The components of a data acquisition, processing, and monitoring system of the rigging, depending on the number of entries desired (number of FM) include:

- inductive transducers mounted on each tensioner;
- tensiometric bridges that sum up the input quantities from the transducers of each mast;
- connection cables between transducers and bridges and between bridges and the data processing unit;
- recording and data processing unit.
- specialized software for processing and interpreting the data received from each FM;

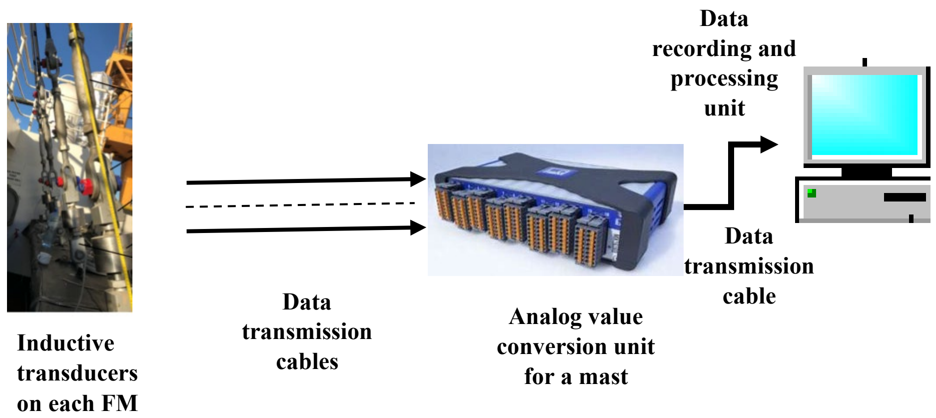


Figure 6. Components of a data acquisition, processing and monitoring system

3. Results:

This method was successfully implemented on board the Mircea School Ship. a 3-masted sailing ship.

3.1. Determination of prestressing loads in each fixed maneuver

The FEMAP specialized software was used to determine the prestressing stress in each FM. In the first stage, the mast was discretized and then, based on the finite element analysis, the maximum efforts in each FM were determined, by studying the 4 load cases of the mast. In the last stage of the FEM analysis, the value of the prestressing stress in each FM will be determined.

In Figure 7 presents the model for discretizing the mast and determining the loads in each FM on a 3-masted sailing ship, using the FEMAP software.

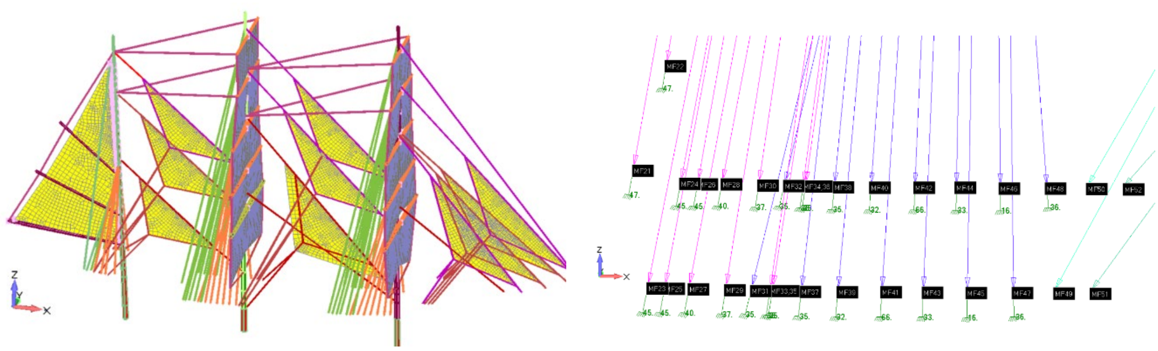


Figure 7. Modeling the mast and determining the movements of 3-masted sailing ships, using FEMAP software - Finite Element Modeling and Postprocessing [4].

3.2. The choosing load measuring sensors in FM

The choice of load transducers was made according to the calculated maximum loads that can appear in the metal cables, calculations made by the finite element method. At the same time, the maximum useful load of the load transducer must be at least 10% higher than the maximum permissible load (PLd) of the respective cable.

The value of the pretensioning load is chosen so that under the action of the wind, the cables are not relaxed. Pretensioning was established by deviating from predetermined displacements. The set pretension values take values between 10-20% of the calculated maximum value. Table no.1.

Table no.1 Example of setting the prestressing load and choosing the load transducer [4]

Rings				**Calculated maximum load**		**Pretension**	**Transducer**
Name	**L (m)**	**S (mm)**	**PLd (tf)**	**(N)**	**(tf)**	**(N)**	**(tf)**
No 1	11.950	26	16	101.417	10.142	10.142	20

Load transducers were selected of 5 tf, 10tf and 20 tf according to the maximum permissible load of each cable in the installation (PLd). Also, another selection criterion was their use in corrosive environments, choosing transducers with protection factor IP 65 (Figure 8).

Figure 8. Load transducer 5 tf and 10 tf [4]

3.3. Choosing the system of data acquisition, processing, and monitoring of rigging

Catman software was chosen for data processing, plant parameter monitoring, and data logging. The hardware and software components have been fitted into the navigation control so that the decision-maker can monitor their changes in real time and make decisions about the navigation surface exposed to the wind or the direction from which it is coming. (Figure 9).

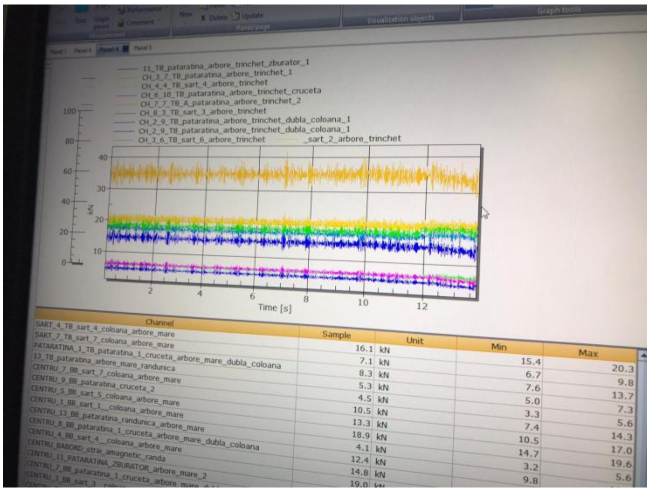


Figure 9. Monitoring rig parameters using Catman software [12].

Conclusions:

Balancing the rigging on sailing ships is an essential procedure to prevent accidents or damage on board sailing ships.

The proposed method of balancing and permanent monitoring of the shaft uses innovative technologies as follows: finite element method for determining the prestressing loads needed to balance the shaft, sensors such as low displacement transducers for real-time measurement of FM displacement from the pretension position, such as IT technologies for data acquisition (computer) and for their permanent monitoring during the operation of the ship (monitoring and analysis software).

By knowing in real time the stress state in the elements of the mast we can permanently maintain the state of the ship's mast in equilibrium, by correcting the stress in the FM to pretension values.

Even if this method requires substantial investments for implementation on board, the benefits during operation are multiple: the use of the mast at an optimal propulsion efficiency; reducing the premature wear of the elements of the rigging, which will allow their use for a long period; ensuring operational safety by eliminating accidents that may occur as a result of wear of the shaft elements (breaking of the shaft anchor elements and due to premature wear and stress on the loads).

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