Study Case of Marine Propulsion Shaft Measurements by the Strain Gage Method: before and after a ship hull grounding accident

Marcelo dos Reis Farias[1,2]
orcid.org/ 0000-0001-6994-0218

Luiz A. R. Baptista[1]
orcid.org/0000-0001-5236-4787

Luiz A. Vaz Pinto[1]
orcid.org/0000-0002-3048-5569

Antônio C. Ramos Troyman[1]
orcid.org/ 0000-0001-8915-0379

[1]Department of Ocean Engineering, Federal University of Rio de Janeiro, Rio de Janeiro 21941-909, Brazil.
E-mail: marcelo.farias@oceanica.ufrj.br

[2]Department of Mechanical Engineering, Federal Center of Technological Education Celso Suckow da Fonseca, Rio de Janeiro, 20217-204, Brazil

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RESUMO

O método de extensômetro para verificação do momento fletor do eixo de propulsão está em uso desde a década de 80. Neste trabalho, os autores apresentam o procedimento e os resultados deste método para um navio *Anchor Handling Tug Supply* (AHTS). O método foi aplicado neste navio em duas ocasiões: após a entrega em 2018 e após um acidente de encalhe em 2019. Depois de um período de reparo do casco, as reações dos rolamentos foram verificadas ao mesmo tempo pelos métodos *Jack-up* e *Strain Gage*. Os resultados pela técnica *Strain Gage* são considerados mais precisos e completos que os do *Jack-up* para este caso. Com base nos resultados do *Strain Gage*, concluiu-se que o acidente de encalhe provocou uma alteração no alinhamento das linhas de eixo, principalmente a boreste. A comparação entre os métodos apresentou a mesma forma gráfica, porém as medidas do *Jack-up* diferiram das do *Strain Gage* em alguns pontos devido a alguns fatores apontados e discutidos pelos autores.

PALAVRAS-CHAVE: Propulsão Naval; Extensômetro; Alinhamento de eixo; Reações nos mancais.

ABSTACT

The strain gage method for propulsion shaft bending moment verification has been in use since the 80's. In this work, the authors present their procedure and results of this method to an Anchor Handling Tug Supply (AHTS) ship. The method was applied in this ship in two occasions: after delivery in 2018 and after a grounding accident in 2019. After a period of hull repair, the bearing reactions were verified at the same time by Jack-up and Strain Gage methods. The results by the Strain Gage technique are considered more accurate and complete than those of the Jack-up. Based on the Strain Gage results, it was concluded that the grounding accident caused a change in the alignment of the shaft lines, mainly on starboard side. The comparison between the methods presented the same graphic shape, however the Jack-up measurements differed from the Strain Gage ones at some points due to some factors noted and discussed by the authors.

KEY-WORDS: Marine Propulsion, Strain Gauge, Shaft Alignment, Bearing reactions;

1 INTRODUCTION

The Marine Propulsion Shafting is a system that transmits mechanical power (torque and motion) from the prime mover to the propeller. The shaft is supported by bearings, which quantity and position are determined based on allowable bearing loads and lateral vibration (whirling) requirements. In the late 1950s, the importance of shaft alignment was firstly addressed by the US Navy **[1]**. Since then, a great number of studies were undertaken to establish the practical guidelines for the optimal shaft alignment configuration. Nowadays, the misalignment is considered among the three major sources of rotating machinery faults. According to Ahmed, I., et al **[2]**, the misalignment phenomenon is one of the main causes for economic losses in industry. It occurs since misalignment reduces the machine's life and causes a decrease in motor arrangement efficiency, and misaligned machinery is more prone to failure due to increased load on bearing, seals and couplings **[3, 4, 5]**.

For the marine propulsion shaft alignment, the main practice adopted by the Society of Naval Architects and Marine Engineers (SNAME) and some classification societies, considers that a good alignment configuration must be related to a balanced load distribution on the bearing support reaction **[6,7,8,9]**. Marine propulsion shaft bearing's reaction measurement is performed to guarantee that reactions estimated during the shaft structural analysis must be obtained after the shaft assembling and alignment **[8]**. If the alignment procedure is well executed, the measured reactions will be very close to the estimated values. The most common method for measuring propulsion shaft bearing reactions is the Jack-Up Method, which is simple to be performed but it only allows to measure reactions from accessible bearings. The Strain Gage Method is an alternative to Jack-up Method and it has the advantage of allowing reactions determination of inaccessible bearings **[9]**.

The strain gage is a small electric resistance which is fixed to the surface of a structural member. Two to three strain gages must be mounted to form a Wheatstone bridge **[10]**. This circuit receives an input voltage and, as the structure deforms due to a applied load, the strain gages also deform resulting on an output voltage. The resulting strain of the structure is calculated by a relation between output and input voltages from the active strain gages circuitry and the strain gages nominal factor **[11]**.

The Jack-up method is the primary and widely adopted approach for verifying bearing reactions. It involves utilizing a hydraulic jack to raise the shaft and measure the load near the specific bearing location. The load applied during lifting and lowering of the shaft is indicated by the hydraulic pressure. A dial gauge, fixed to a magnetic stand on the bearing housing, is positioned at the jacking location with its spindle in contact with the shaft. This setup enables the measurement of shaft displacement, and the recorded data is plotted on a graph to calculate the bearing load. However, the Jack-up method requires consistent preparation time for repeated measurements, which can be time-consuming. Accuracy can be affected by misalignment of the hydraulic jack and dial gauge with the shaft center, leading to reduced precision in the lifting and lowering curves and wider hysteresis. Additionally, since the jacked load is measured close to the bearings instead of at the bearing center, correction coefficients must be applied to determine the actual bearing reaction. Different bearing types exhibit distinct jacking curve characteristics, necessitating trained individuals such as builders and surveyors to accurately evaluate and interpret the results. It is important to acknowledge that the Jack-up method's accuracy can be influenced by various factors, including human error and potential uncertainties in the measurement setup. Numerous studies have addressed the limitations and potential sources of error associated with the Jack-up method for measuring bearing reactions in naval applications **[6, 7, 12, 13, 14].**

Therefore the strain gage method is not a direct reading of bearing reaction loads, it is an indirect measurement technique to determine the magnitudes of materials physical properties.

The marine propulsion shaft is an example of a hyperstatic structure, so it is possible to use techniques for obtaining structural support reactions such as "Free-Body Approach" or "Moment Influence Number Approach". Firstly, both techniques require the knowledge of the bending moments from a couple of points on the propulsion shaft. In this case, the bending moments are obtained from the strains measured with the strain gages method. These strains result from the bending due to static loads, spans between bearings and heights of bearings **[9]**.

2 STRAIN GAGE METHOD

The basic steps for applying the Strain Gage Method are covered in the books **[13, 14]** and it was explained by Forrest & Labasky **[15]**, which recommendations were used by the authors. As the bending resulting strain longitudinal to the shaft, the strain gages must be installed axially or parallel to the shaft center line. Although it is possible to use one strain gage in the circuit, the authors prefer to use two or four strain gages of two directions type. The second direction is intended to prevent any influence from axial loads.

The complete installation requires a data acquisition system which is formed by a hardware and a software for signal conditioning, visualization and recording of the data from the strain gage bridge. The authors' data acquisition system uses hardware from National Instruments and a software developed in LabVIEW®.

2.1 *BEARING REACTION CALCULATION*

The linear relations of the structure can be calculated using the matrix expression (1) which relates the structure spans rigidity, supports vertical displacements and an initial condition resulting action to obtain the structure final resulting action condition.

$$[AFi] = [AIi] + [Rij].[Dj] \qquad \mathbf{(1)}$$

where:
$[AFi]$ – vector of resulting action (supports reaction, bending moments, shear forces and inclinations) at the structure's final condition;
$[AIi]$ – vector of resulting action (supports reactions, bending moments, shear forces and inclinations) at the structure's initial condition;
$[Rij]$ – structure spans rigidity matrix;
$[Dj]$ – vector of structure supports displacements.

Rewriting expression (1) for bending moments and bearing reactions, one obtains:

$$[Dj] = \{[MFi] - [MIi]\}\,.\,[IMij]^{-1} \qquad \mathbf{(2)}$$

$$[RFi] = [RIi] + [IRij]\,.\,[Dj] \qquad \mathbf{(3)}$$

where:
$[MFi]$ – final bending moment at measuring point (Nm);
$[MIi]$ – initial bending moment at measuring point (Nm);
$[IMij]$ – bending moment influence coefficients (Nm/mm);
$[RFi]$ – bearing final reactions (N);
$[RIi]$ – bearing initial reactions (N);
$[IRij]$ – reaction influence coefficients (N/mm);
$[Dj]$ – bearing vertical displacements (mm).

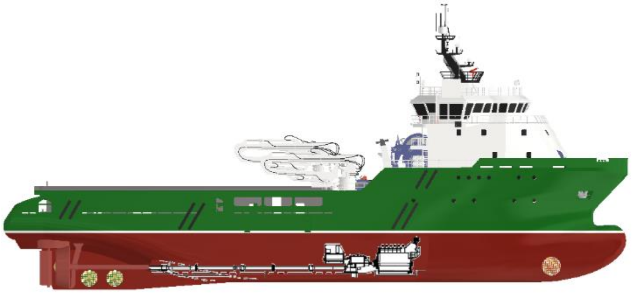
The "bending moment influence coefficients approach" as mentioned by Forrest & Labasky **[15]**, uses expression (2) to obtain the displacement vector $[Dj]$ from the measured bending moment through the strain gage method. The reactions on each support $[RFi]$ are obtained replacing the displacement vector on expression (3).

As one may observe, from expressions (1), (2) and (3) there is a step of structural analysis involved so as to obtain the vectors $[AIi]$ and $[RIj]$.

3 STUDY CASE

The AHTS is a type of ship used to transport, to launch and to retrive offshore floating rigs anchors. It is also used to tow and to perform support operations for offshore floating rigs. The profile of an AHTS ship is seen in Figure 1. The ship under consideration in this paper belongs to a series built in Brazil between 2016 and 2018. Two bearing alignment measurements were performed in this ship, the first in 2018 after the ship was launched, and the second in 2019, after a repair period due to a grounding accident. The bottom of the ship hull was mainly affected under the shaft lines and most of the steel plates had to be replaced as shown in figure 2. Also, some frames were affected and had to be repaired. The shaft lines were not disassembled. After the repair was completed, there was concerns about the condition of the shaft alignments. The ship was put afloat and tied to the shipyard dock in order to verify the shaft alignment by the Strain Gage Method and by the Jack-up Method at the same. The Jack-up Method was performed by the owner team with the propulsion system supplier supervision.

Figure 1 – AHTS ship profile



Source: The authors.

The ship propulsion shaft's arrangement is seen in Figure 3 and it is formed by three hollow shafts sections connected by flanges, two structural bearings, two intermediary bearings, reduction gear, two diesel engines per shaft line and a four-bladed controllable pitch propeller. The thrust bearing is inside the reduction gear.

Figure 2. Ship hull damage (bottom hull damaged area shown in red, bearings direction shown in blue).
Source: The authors.

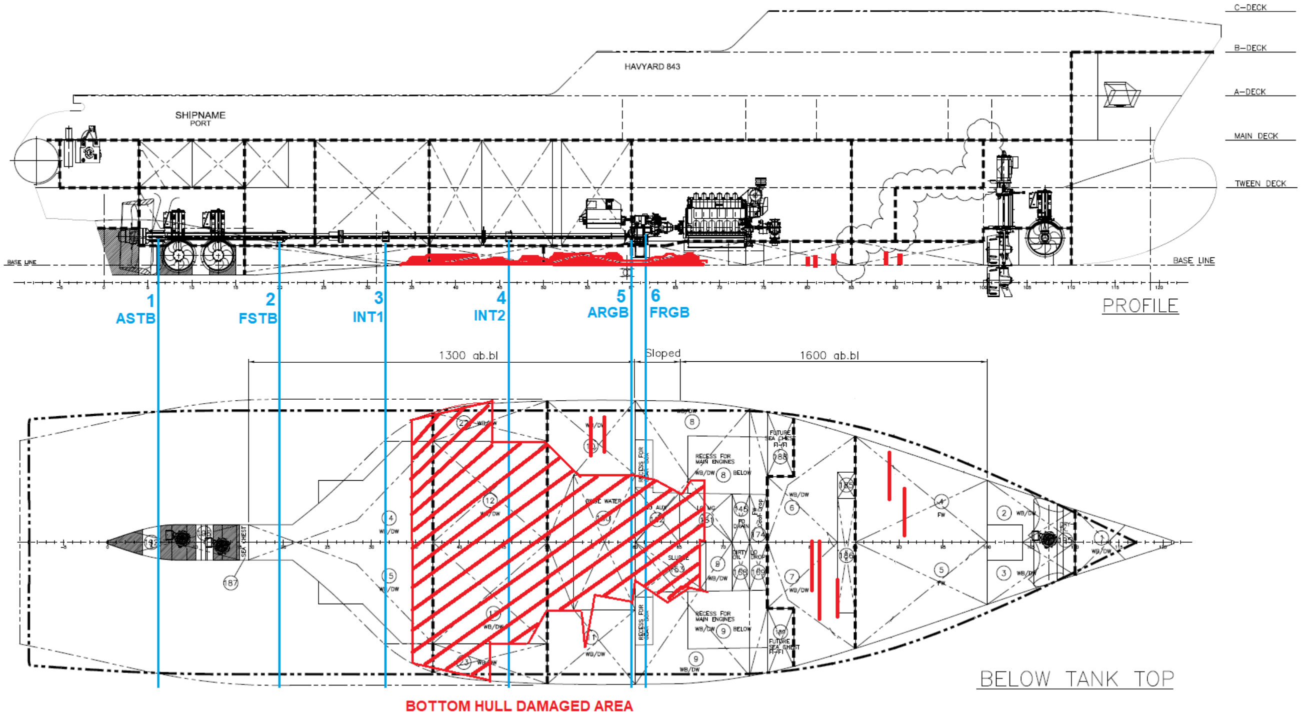
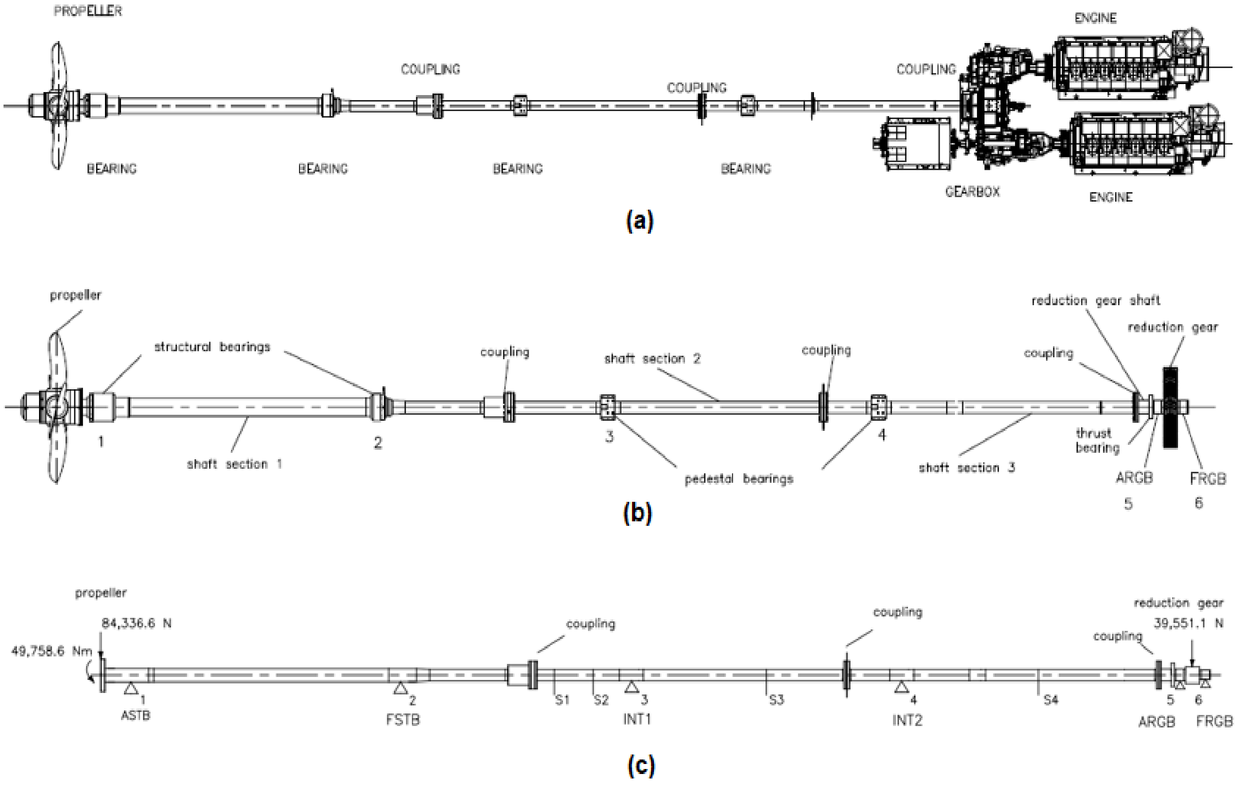


Figure 3. Propulsion Shaft (a) port side top view (b) mechanical components (c) specified measuring points.
Source: The authors.



The number and location of measuring points on the shaft line were specified according to Grant (1980) **[16]**, considering the number of bearings and its distribution on the shaft line.

The propulsion shaft's main characteristics are shown in table 1, and the specified measuring points (S1, S2, S3, S4) are shown in figure 3 (c).

Figure 2 shows the ship profile and top view below tank top, where the bottom hull area affected by the grounding accident is marked in red.

Table 1 – AHTS Propulsion shaft main characteristics

Feature	Data
Shaft Length (m)	34.550
Number of Blades	4
Average Diameter (m)	0.350
Internal Diameter (m)	0.105
Propeller Power (KW)	6,000
Propeller Weight C1 (N)	84,337
Bend Moment M (N.m)	55,778
Bull Gear Weight C2 (N)	45,910
Shaft Material	Structural Steel

Source: Ship owner.

Note: The six supports considered on Figure 3 (c) are: 1 = after stern tube bearing (ASTB); 2 = forward stern tube bearing (FSTB), 3 = No.1 intermediary bearing (INT1); 4 = No.2 intermediary bearing (INT2); 5 = after reduction gear bearing (ARGB); 6 = forward reduction gear bearing (FRGB).

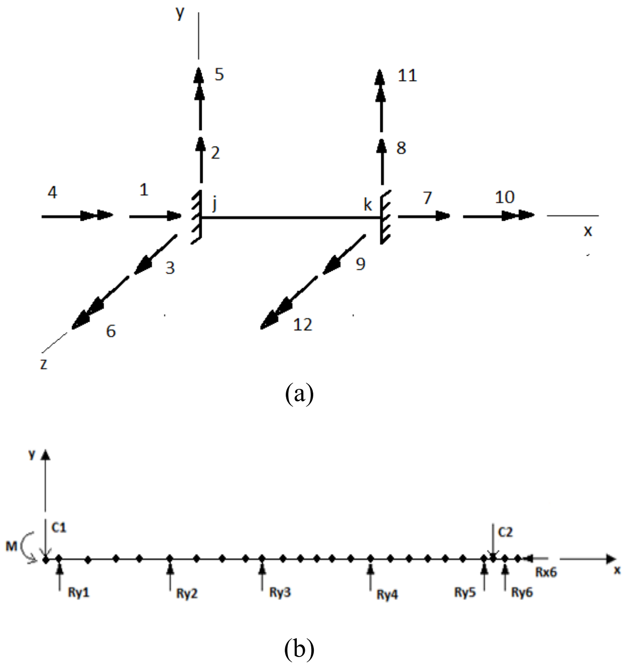
The blue lines represent the propeller shaft bearing support directions. It is possible to see that the affected main area was in the gearboxes direction and intermediate bearings direction.

3.1 SHAFT AS BAR ELEMENTS

Before the onboard measurement, the propulsion shaft must be structurally analyzed to obtain the necessary information (RIi, IRij, MIi and IMij) for solving expressions (1) and (2). The authors developed a framework based on the displacement method **[17]** for structural analysis. The propulsion shaft is idealized as a plane frame discretized with a 2D bar element which is shown in Figures 4 (a) and (b). For each node it is possible to obtain forces, bending moments, displacements and inclinations on the x, y and z directions. As the measurement and the structural analysis conditions must be the same, the structural analysis was done considering the ship afloat and unloaded and propulsion shaft bearings concentrically aligned.

Figure 4- (a) Prismatic constrained bar element and its unknown node displacements; (b) Propulsion shaft idealized as a plane frame and discretized with elements and nodes (supports reactions and loads are also indicated).

Source: The Authors.



3.2 STRAIN GAGE MEASUREMENTS

The strain gage method is advantageous for alignment measurements, allowing for using even while the system is in operation and providing results into all bearing reactions, including those that are inaccessible from inside ship stern tube. The number of measurement points is determined by static equilibrium equations, with a minimum of N-2 points needed for an N-bearing shaft (in this way it was used 4 measurement points). For up to two inaccessible bearings, the free body method suffices, while the moment theorem is necessary for cases with three inaccessible bearings. Strain gages are installed at sensitive bend moment locations between bearings, employing configurations like half-bridge (minimizes temperature effects) or full-bridge Wheatstone setups (used in this case and it minimizes the effect of torsional loads). Longitudinally affixed strain gages measure bending deformation and transverse strain gages measure torsion effects. The full bridge configuration used requires 2 sets of Longitudinal and transverse sensors for each measure point and careful positioning and adhesive

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application are crucial, spaced 180° apart. After calibration under this condition, the measurement is conducted by rotating the shaft 360° (static measurement) using a motor ratchet or a strap wrapped around the shaft pulled by a hoist. The results are obtained by measuring the deformation caused by shaft bending through resistance measurements in the Wheatstone bridge with the strain gauges **[18]**. Once the maximum bending moments for each measurement point are obtained, the bearing reactions can be determined through reverse engineering, as the moment equals the force (reaction) multiplied by the distance. To achieve this, a system of linear equations can be established to determine the relationship between the bearing reactions and the bending moments at each measurement point **[9]**. The acquisition time used was 180 seconds per complete measurement, with a sample rate of 2048Hz, since it was done a static measurement, just one or two complete shaft rotations is required, with all sensors being measured simultaneously.

The bending moment measurement is done using strain gages applied to the shaft, which is capable of measuring the axial shaft strain. This strain (ε) is proportional to the normal stress (σ) which is directly proportional to the acting bending moment (M). Both shaft lines were instrumented with strain gages at the selected measuring points. Differing from the previous measurements (before accident), at this time it has been used a National Instruments Data Acquisition (DAQ), which permitted to measure the four points of the shaft at the same time. The signals were acquired and stored through a customized LabVIEW® software installed in a notebook. The following figures 5 and 6 show the instrumentation installed during the measurement.

During the measurement, the ship was tied to the shipyard dockside at shattered waters and unloaded. Each shaft line was turned with one engine ratchet. The directions of rotation where: port side – clockwise and starboard side – counterclockwise (looking forward). Figure 7 shows the recorded signals from the second turn of both shaft lines.

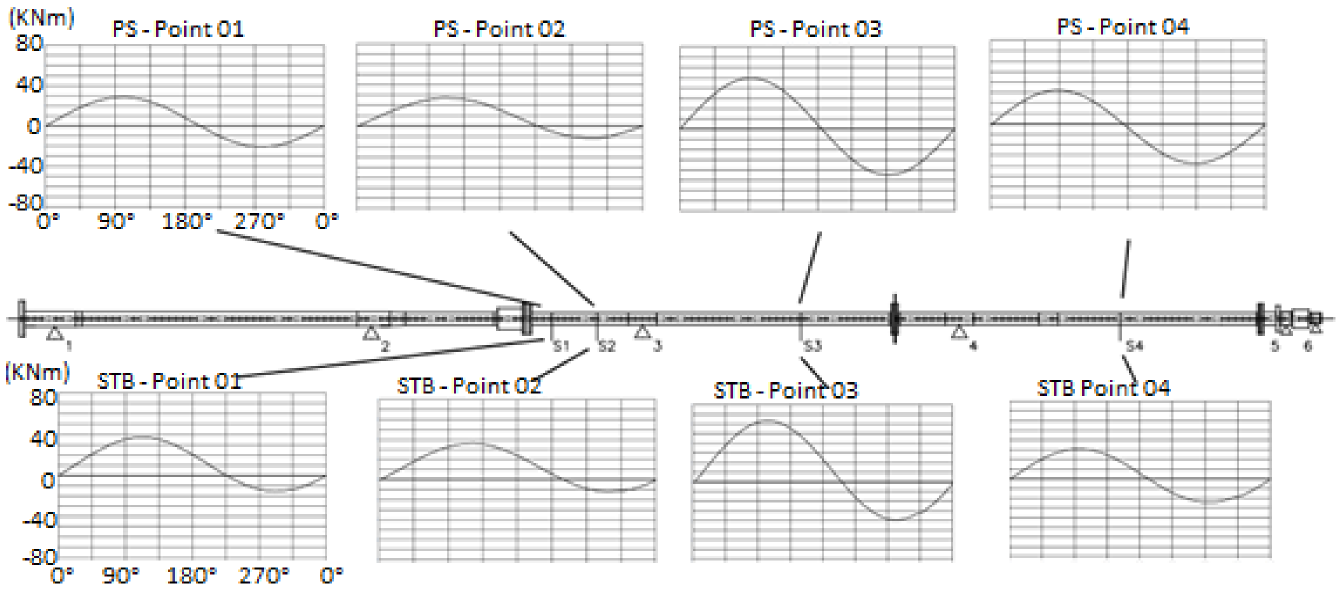
All graphs have the same scale range on the ordinate axis (kNm) and the same scale range on the abscissa axis (degrees) to allow a comparison between measuring points and shaft lines.

From the graphs of figure 7, it is possible to observe that the signals are continuous without steps or irregularities, meaning that the shafts do not have irregular contacts with bearings. However, all signals do not cross the axis at 180 degrees. This fact leads to the conclusion that both shafts may have some sideward misalignment. On both shafts the sideward misalignment is bigger on S1 and S2 points, but the starboard side shaft S3 also presents a significant sideward misalignment. On both shafts the sideward misalignment is bigger on S1 and S2 points, but the starboard side shaft S3 also presents a significant sideward misalignment. The nearest adjustable bearing to S1 and S2 points is the number 3 bearing. On the starboard side shaft, as S3 point is almost at the same distance from number 4 as it is from number 3 bearing, it is possible to conclude that the number 4 has some sideward misalignment.

Figures 5 – Computer and DAQ system.
Source: The Authors.

Figure 6 – Strain gage installed.
Source: The Authors.

Figure 7- Recorded bending moment signals at each measuring point (port side above, starboard side below).
Source: The Authors measurements.



Although the authors use the term "sideward misalignment", this could also be caused by unleveled bearing due to unleveled shocks under the bearings. This problem was observed by the authors in some other ships of the same manufacturing series.

The resulting bending moment at a measuring point is given by expression (4), as follows:

$$Mf = \frac{(Mfmax - Mfmín)}{2} \qquad \textbf{(4)}$$

where *Mfmax* is the maximum bending and *Mfmin* is the minimum bending moment at the measuring point.

Table 2 – Vertical and horizontal measured bending moments at points S1, S2, S3 and S4
Source: The Author – by strain gage.

MEASURED BENDING MOMENTS (Nm)				
POINT	PS		STB	
	VERT	HORIZ	VERT	HORIZ
S1	24,029.0	5,088.0	24,390.0	9,654.0
S2	17,762.0	8,164.0	20,604.0	12,542.0
S3	47,224.0	1,484.0	50,150.0	10,893.0
S4	35,018.0	2,068.0	27,410.0	2,491.0

The authors applied the Gauss Method to expression (2) to solve this set of linear equations. As a result, the vertical displacement at each bearing is obtained, as shown in table 3.

Table 3 – Measured bending moments vertical displacement and reactions.
Source: The Authors.

DISPLACEMENTS (mm)			
BEARING		PS	STB
1	ASTB	0.00	0.00
2	FSTB	0.00	0.00
3	INT1	−8.59	−10.09
4	INT2	−7.87	−9.88
5	ARGB	4.51	0.80
6	FRGB	6.41	2.20
REACTIONS (N)			
BEARING		PS	STB
1	ASTB	126,948	125,781
2	FSTB	93,155	96,401
3	INT1	40,221	37,704
4	INT2	67,914	65,461
5	ARGB	49,070	82,239
6	FRGB	29,308	−969

Doing the same to expression (3), the vertical bearing reactions are obtained, as shown in table 4. The final bearing reactions between measurements performed in 2018 and 2019 compared with the estimated results are expressed in table 5.

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Table 4 – Vertical bearing displacements comparison – measured after delivery in 2018 and after a grounding accident in 2019.
Source: The Authors.

PORT SIDE (mm)			
BEARING		2018	2019
1	ASTB	0.00	0.00
2	FSTB	0.00	0.00
3	INT1	−8.89	−8.59
4	INT2	−10.75	−7.87
5	ARGB	4.96	4.51
6	FRGB	7.25	6.41
STARBOARD SIDE (mm)			
1	ASTB	0.00	0.00
2	FSTB	0.00	0.00
3	INT1	−9.68	−10.09
4	INT2	−8.78	−9.88
5	ARGB	7.41	0.80
6	FRGB	9.84	2.20

Although the results shown in table 3 are sufficient to get conclusions about the shafts alignment condition, a more complete analysis will be presented. The following table 5 present comparisons between the required shaft alignment calculation issued by the propulsion system supplier and by strain gage measurements made by the authors in 2018 soon after this ship entered in operation and the above results from 2019.

Table 5 – Vertical bearing reactions comparison between estimation report and measurements: after delivery in 2018 and after a grounding accident in 2019.
Source: The Authors.

PORT SIDE (N)				
BEARING		CALC.	2018	2019
1	ASTB	125,23	127,185	126,948
2	FSTB	80,699	90,85	93,155
3	INT1	45,804	46,299	40,221
4	INT2	62,178	60,775	67,914
5	ARGB	46,845	60,251	49,070
6	FRGB	40,072	21,257	29,308
STARBOARD SIDE (N)				
BEARING		CALC.	2018	2019
1	ASTB	124,484	126,097	125,781
2	FSTB	84,405	95,542	96,401
3	INT1	40,437	39,012	37,704
4	INT2	65,341	67,742	65,461
5	ARGB	41,390	38,554	82,239
6	FRGB	44,409	39,670	−969

Both measurements were made at the same ship conditions and with the same measuring points and procedure.

3.2 MEASUREMENTS ANALYSIS

According to SNAME [9], the criteria for an acceptable mechanical and structural conditions of a marine propulsion shaft system are presented in the following items:

1. The maximum allowable bull gear bearing load differential shall not be exceeded. The maximum allowable value is:

$$(R5-R6)\leq 25\%(R5+R6) \qquad \textbf{(5)}$$

where: R5 = ARGB reaction (N); R6 = FRGB reaction (N)

2. No support bearing in the system shall be loaded above its maximum allowable pressure;
3. No support bearing in the system shall be loaded under its minimum allowable load;
4. The maximum allowable stresses in the shafting shall not be exceeded;
5. The design alignment criteria for directly connected engines, special couplings or other equipment shall not be exceeded.

The table 6 displays item 1 of the alignment acceptance criteria applied to the strain gauge measurements in 2019, while table 7 presents the maximum and minimum loads on the bearings corresponding to items 2 and 3.

Table 6 – Maximum allowable bull gear load differential criteria.
Source: The Authors, based in **[6,9].**

CRITERIA	**PS (N)**	**STB (N)**
R5 + R6	78,378	81,269
25% (R5 + R6)	19,595	20,317
R5 – R6	19,762	83,208

Applying the SNAME **[9]** criteria, the conclusions for 2019 strain gage measurement results after the accident and hull repairs are:

Starboard side shaft line: the shaft condition is not acceptable. Observing table 6 it is possible to conclude that items 1 and 3 of criteria were not satisfied for maximum bull gear (R5 – R6) load differential and minimum allowable load (R6).

Portside shaft line: the shaft condition is not acceptable. Observing table 6 it possible to conclude that item 1 of criteria was not satisfied for maximum bull gear (R5 – R6) load differential. It's expected to be less or equal to 25% of R5 + R6. However, 19,762 / 78,378 is 25,21%. The difference is very close to the limit, but it does not meet the alignment acceptance criteria.

Table 7 – Maximum and minimum allowable bearing loads.
Source: The Authors.

BEARING		AREA (mm^2)	Max. Press (N/mm^2)	Max. Load (N)	Min. Load (N) (4)
1	ASTB	516,573	0.8 (1)	413,259	20,663
2	FSTB	191,135	0.8 (1)	152,908	7,645
3	INT1	97,467	0.8 (2)	77,973	3,899
4	INT2	97,467	0.8 (2)	77,973	3,899
5	ARGB	139,487	2.9	403,700 (3)	20,185
6	FRGB	121,737	3.0	365,400 (3)	18,270

[1]SNAME **[9]**; [2]bearing supplier; [3]gear box supplier; [4]considered 5% of maximum load

4 HYDRAULIC JACK-UP AND STRAIN GAGE RESULTS COMPARE

Complementing the previous analysis, a comparison between the results of jack-up and strain gages methods is shown in the following figures.

Table 8 compares results from jack-up and strain gage measurements for port side and starboard side shafts respectively.

Port side shaft methods results are closer except for number 2 (FSTB) bearing which shows a 39.4% difference between measurement methods, being the jack-up result lower than the strain gage result. As the other bearings reactions have a small difference between methods, the jack-up measured value for number 2 (FSTB) is considered to be inaccurated. In this type of ship design, the available space between the shaft and the hull structure is very tight and it is difficult to reach near the stern tube. Another possible source for the discrepancies is that the jack-up was supported directly on the hull bottom plate without reinforcement as observed by the authors during measurement.

The results from the Strain Gage method for the starboard side shaft are higher than those from the Jack-up method, except for bearing number 4 (INT2), which shows a -1.22% difference between the methods, with the strain gage result being lower than the hydraulic jack at this point. Due to the significant disparity in bearing reactions between the methods, the authors do not rely on the values obtained using the hydraulic jack method for the same reasons stated for the port side shaft.

Table 8 – Bearing reactions – jack-up and strain gage measurements comparison.
Source: The Authors.

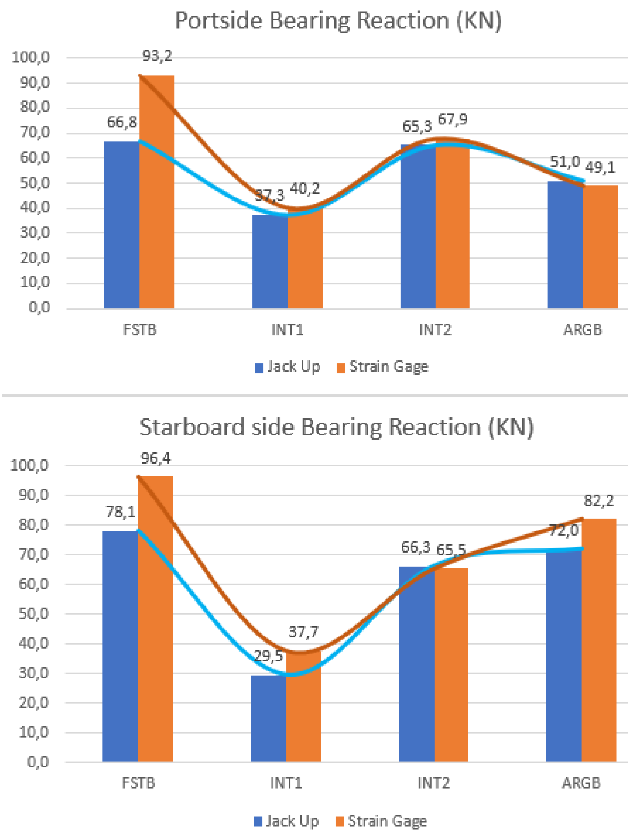
PORT SIDE (N)				
BEARING		JACK UP	STRAIN	Δ%
1	ASTB	NM	126,948	NA
2	FSTB	66,836	93,155	39.38
3	INT1	37,312	40,221	7.80
4	INT2	65,260	67,914	4.07
5	ARGB	51,008	49,070	−3.80
6	FRGB	NM	29,308	NA
STARBOARD SIDE (N)				
BEARING		JACK UP	STRAIN	Δ%
1	ASTB	NM	125,781	NA
2	FSTB	78,051	96,401	23.51
3	INT1	29,457	37,704	28.00
4	INT2	66,266	65,461	−1.22
5	ARGB	72,011	82,239	14.20
6	FRGB	NM	-969	NA

The following figure 8 shows a graph related to the table 8, where it plots only those bearings that were measured by both techniques: jack-up and strain gage. It means that only the FSTB, INT1, INT2, and ARGB bearings were plotted. From Figure 8 it is possible to see, by the trend lines, that the load distribution shape is the same for both applied measurement techniques.

It is possible to notice that the results at the aft ends of the graphs are where the reaction values differ the most. According to the reasons mentioned before, this fact probably occurs because the jack-up technique does not have access to the subsequent bearings at the ends (ASTB and FRGB), and a structural reinforcement was not used for the jack-up as recommended by the general adopted guidance **[19]**.

Because of this, the measurement result can be significantly affected due to bottom plate deflection resulting in lower load on the hydraulic jack-up, obtaining a lower reaction value. In the strain gage technique, the obtained results are based on measurements and extrapolated for all the shaft line based on the analytical model related to its geometric and materials characteristics, decreasing the likelihood of inaccurate measurements.

Figure 8 - Jack-Up and Strain Gage measurement comparison.
Source: The Authors.



Seo, Chul-Oh, et al **[20]** in their research trying to confirm the reliability of the analysis between the estimated and Jack-up values of bearing reactions. They also found a difference about 25% in some bearings. Large deviations were observed in the bearings that the Reaction Influence Number (RIN) are higher than others. The relative deviation between the measured reactions and the numerically estimated values in the bearings was presumed to be due to the influence of the crankshaft web bending stiffness, the estimation accuracy and the measurement limitations of the RIN.

Therefore, it can be observed that there was also a difference between the estimated method and the measured method by Jack-up in the mentioned work [16], similar to the difference found between the Strain Gage and Jack-up methods in this article. Despite the fact that in this article, the results from both techniques exhibit the same curve shape, magnitude, and trend, the reasons for the differences in results were pointed out, and together with the case highlighted by [16], it leads us to believe that the measurement accuracy of Jack-up (due to the significant influence of human error and all other reasons presented) is lower than that of the Strain Gage method and calculated methods for this particular case of load measurement in naval propulsion shaft bearings.

5 CONCLUSION

Marine propulsion shafts bearing reaction verification by strain gages method exists for, at least, four decades. The requirements and care of the method are well disseminated and, when properly performed, the measurement results are reliable. Through the analysis carried out and comparison made, the authors consider the strain gage method more reliable than the jack-up method, since it is not subject to measurement limitations from the Jack-up Method such as from access difficulties, unreinforced bottom or double bottom plates used to support the jack-up, which might yield as the bearing load is transferred to the jack-up.

From strain gage measurement results it is possible to conclude that both shaft lines were affected by the accident and damaged hull. The starboard side shaft line was the most affected. The SNAME **[9]** criteria were used to evaluate the bearing reactions obtained from the strain gage measurements and it was concluded that, for a reliable operation and enhanced component life, both shaft lines should be realigned due to uneven bull gear bearing reactions.

The hydraulic jack-up verification was performed at the same day and conditions of the strain gage method by the shipyard staff under supervision of a propulsion system representative. This method can be reliably used in the condition that the hydraulic jack-up is supported by a rigid base like the bearing pedestal and when only accessible bearings need to be measured. What was not the case, as mentioned in this article.

The authors recommended to the shipyard to realign the shaft lines to achieve the estimation report reaction values or, at least, to change the heights of intermediary bearings to balance the reactions from the bull gear bearings. Without even reactions on the bull gear bearings, the gears teeth are affected increase de risk of wear or premature break. Through this paper and case study, some general conclusions can be highlighted, such as:

- The Strain Gage technique can be used successfully for the alignment of marine propeller shafts.
- It is important to evaluate changes in the alignment of the vessels shaft lines when structural damage occurs to the hull.
- Changes in the marine shaft alignment can be observed by the changes in the bending moment, and it can be measured by strain gage.
- The Strain Gage Method is well applied for measuring the alignment of a marine propeller shaft because it does not require access to external bearings in the engine room and only with measurements from internal bearings is it possible to obtain very accurate results in relation to the estimated numerical values.

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