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KEY CALCULATION CONSIDERATIONS, MEASUREMENT, AND CORRECTION OF SHIP PROPULSION SHAFT ALIGNMENT

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Abstract. *The propulsion system certainly represents one of the most critical areas of the design, operation, and maintenance of a vessel. In this area, the propulsion shaft alignment can be highlighted as one of the most important subjects. An improperly aligned system can generate many unwanted consequences such as: bearings overheating, bearings failure, excessive vibrations, gears wear down, engine bearing failure, leaks, shaft fatigue failure, environmental pollution, ship and crew safety compromised. The alignment of a propeller shafts involves several variables and issues that influence the system condition, such as: the calculation of alignment, hull flexibility, dynamic effects, different types of propulsion systems, fatigue life calculations, acceptance criteria, thermal compensation, component misalignment (such as gears), measurement methods, alignment verification and correction techniques. This paper presents an overview of the different steps on calculation, measurement, execution, and correction of the propeller shaft alignment systems, considering the main factors that influence it and the care that must be taken to ensure a correct system functioning.*

Keywords: *ship propulsion, shaft alignment.*

1. INTRODUCTION

The Propulsion Shafting is a system that transmits torque and motion from the prime mover to the propeller. The shafting is supported by bearings, whose number and position is 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 (Rudolph, 1959). 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, generally competing with unbalance, and bearing defects (Muszynska, 2005, Braga, 2019). Meanwhile, some studies (Braga, 2019) indicates that machine stoppages in Brazilian industries caused by problems related to inadequate shaft alignment reach more than 50%. In addition, 90% of machines are believed to operate outside of recommended alignment tolerances, which can lead to a great number of machine performances, cost, and component degradation issues. According to a survey conducted by the International Maintenance Conference (IMC-2012) with maintenance and reliability professionals, on the most recurrent machine failures, misalignment stands out first.

An improperly aligned system can generate many unwanted consequences such as: bearings overheating, bearings failure, excessive vibrations, gears wear down, engine bearing failure, leaks, shaft fatigue failure, environmental pollution, ship and crew safety compromised. However, when it comes to alignment of a ship propulsion system, the problem is not as simple as, for example, a case of aligning an electric motor with a centrifugal pump. The alignment of propulsion shafts involves several variables and issues that, directly and indirectly, influence the alignment condition, such as: number of bearings, length between bearings (spans), type of propulsion system (with reduction gear or direct coupling engine), solid or hollow shafts, coupling types, propeller weight, reduction gear weight, thermal displacements, dynamic effects, hull flexibility, sea state and load condition. All these factors must be considered during the shaft alignment calculation to achieve an optimum alignment condition.

Jae-ung Lee (2018), in his recent research, pointed out several studies about current issues for shaft alignment where the trend of ship manufactures to build large cargo vessels with hull structure optimized to reduce deadweight and maximize cargo capacity was highlighted. In other words, while the hull thickness becomes thinner, the trend of designing propeller shaft towards the opposite direction. Unfortunately, the most modern ship design improvements can adversely affect propulsion shafting alignment if this is not correctly addressed. Meanwhile, a key challenge of the conventional shaft alignment methods lies in the fact that most ship designers are generally not able to estimate the range of change in the shaft support bearing reaction force caused by the hull deformation with them.

The propulsion shaft alignment is a process that consists of: alignment calculation and analysis, the alignment procedure and execution, measurement and verification. These steps must be applied to all shaft propulsion systems independently of ship type.

This paper presents an overview of the key alignment calculation considerations, execution, measurement, and correction of propulsion shaft alignment on ships, considering the main factors that influence it and the care that must be taken to ensure a correct system functioning.

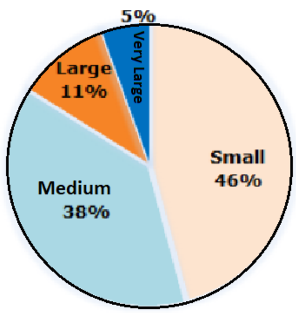
2. TYPES OF VESSELS AND PROPULSION SYSTEM

The world merchant fleet is composed of various vessel types, where the majority (around 84%) of them are related to the small and medium-size vessels. According to the 2019 World Fleet Report Statistics (EQUASIS, 2019).

Table 1. World fleet: total number of ships by type and size
Source: adapted from Equasis, 2019.

Ship Type	Small[1]		Medium[2]		Large[3]		Very Large[4]		Total	
General Cargo Ships	4,127	7.6%	11,638	25.9%	248	2.0%			16,013	13.6%
Specialized Cargo Ships	7	0.0%	229	0.5%	64	0.5%	6	0.1%	306	0.3%
Container Ships	19	0.0%	2,241	5.0%	1,555	12.5%	1,463	22.5%	5,278	4.5%
Ro-Ro Cargo Ships	33	0.1%	623	1.4%	564	4.5%	249	3.8%	1,469	1.2%
Bulk Carriers	299	0.6%	3,807	8.5%	6,410	51.6%	1,778	27.3%	12,294	10.4%
Oil and Chemical Tankers	1,902	3.5%	7,322	16.3%	2,726	21.9%	2,025	31.1%	13,975	11.9%
Gas Tankers	35	0.1%	1,116	2.5%	389	3.1%	508	7.8%	2,048	1.7%
Other Tankers	401	0.7%	699	1.6%	14	0.1%			1,114	0.9%
Passenger Ships	4,138	7.7%	2,873	6.4%	287	2.3%	194	3.0%	7,492	6.4%
Offshore Vessels	2,715	5.0%	5,211	11.6%	140	1.1%	287	4.4%	8,353	7.1%
Service Ships	2,779	5.1%	2,769	6.2%	26	0.2%	6	0.1%	5,580	4.7%
Tugs	17,949	33.2%	932	2.1%					18,881	16.0%
Fishing Vessels	19,605	36.3%	5,482	12.2%	2	0.0%			25,089	21.3%
Total	**54,009**	**100%**	**44,942**	**100%**	**12,425**	**100%**	**6,516**	**100%**	**117,892**	**100%**

Source: Equasis [1] GT<500 - [2] 500≤GT<25.000 - [3] 25.000≤GT<60.000 - [4] GT≥60.000



Until today only large vessels were considered of relevance in dealing with shaft alignment problems, but the statistics presented on table 1 highlights the importance of considering small vessels because they represent 46% of the global fleet, which, nowadays, has more than 117,000 vessels. This number expresses a high demand of ships owners, operators, and maintenance companies having to deal with propulsion shaft alignment issues.

Regarding the vessel size, one of the most important differences in the propulsion shaft alignment is related to the influence of the sea state on the hull structure. The relation between vessel length (Ls) and wavelength (Lw) is very different from small/medium ships to the large/very large ships, although sometimes the propulsion power is very close. Figure 1 shows an example of this case, based on the Kawasaki Offshore Support Vessel Line (Kawasaki, 2018), represented by a AHTS (Anchor Handling and Tug Supply Vessel) which length is 1/3 of the VLCC (Very Large Crude Carrier) length and their BHP are equivalent (34000 to 37000 BHP).

It is possible to conclude that the sea state will affect more the VLCC's structure than the AHTS's structure. These structural deformations of the cargo area also affect the structure under the propulsion shaft bearings, and this affects the propulsion shaft alignment. However, the effect of the sea state on the small vessels should not be ignored.

However, during an operation of pushing or pulling another vessel, the tugboats use power of the same magnitude as a VLCC and its structure can also suffer deflections to the point of changing the alignment condition. That is an example why small and large ships structures deflections should be considered on the evaluation of alignment change factors.

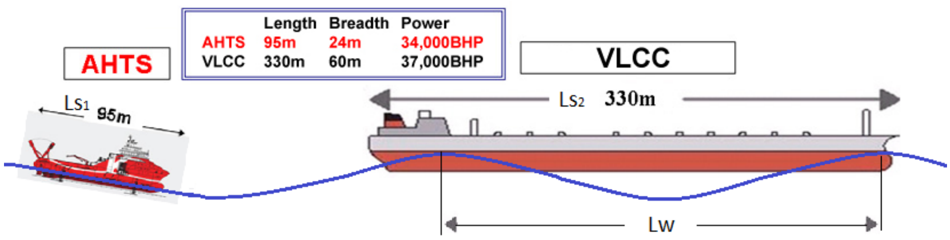


Figure 1. Different ship sizes related to wavelength. Source: Adapted from Kawasaki, 2018.

Another great influence on the alignment considerations should be the type of propulsion system. For general cargo vessels and offshore supply vessels (OSV) it is possible to consider 3 main types of propulsion system, as shown in figure 2: Direct propulsion shaft line; Z-Drive (with horizontal engine/motor, upper gearbox (UGB), lower gearbox (LGB) and propeller shaft); L-Drive system (with vertical electric motor connected to the LGB, and propeller shaft). The last two types are generally applied to offshore supply vessels or drilling and production oil vessels, while the first type is the most common for both small and large ships.

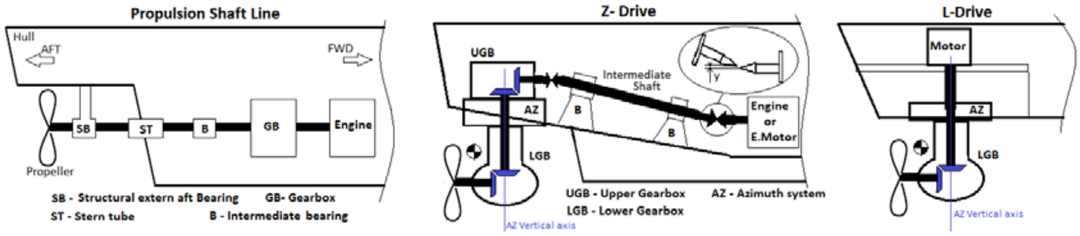


Figure 2. Main types of propulsion system.

The propulsion shafting system must accomplish the following objectives: transmit the power from the main engines or reduction gear to the propeller, transmit the thrust developed by the propeller to the ship's hull, and support the propeller load (SNAME, 2007).

The shaft alignment for the L-Drive system can be considered the easiest one due to the compact configuration not giving place to considerable structure variations. Shaft sections are rigid, but couplings between them generally allow some movement.

For the Z-Drive system, the gear-set alignment should be done in both the upper and lower gearboxes. Between the Engine/Motor and the UGB, the Intermediate Shaft (IS) should be aligned first according to your ends connections (UGB at aft and engine at forward), and after that, have its own smooth curve along its length. When the Intermediate Shaft is long and has more than two bearings, alignment calculation can be done (as will be presented in the section 3) to better load distribution. When the intermediate shaft is tilted towards the Engine and UGB, the system will have cardan shafts to allow movement and torque transmission with an angle between shafts.

The first case in the figure 2 represents the most common configuration of propulsion shaft on ships and may present some variations regarding: length of shaft sections, type of bearings, number of bearings, with and without gearbox, among other peculiarities. Since this is the most comprehensive configuration, this paper will only be addressed to this configuration.

3. SHAFT ALIGNMENT CONSIDERATIONS

3.1. Initial Considerations

Industrial machinery is typically aligned so that the shafts of the driving and driven components are collinear. However, this approach is not always appropriate for marine main propulsion shafting because it does not guarantee that all bearings are sustaining load.

Historically, in the early 60s shafting systems were long and required many bearings. At that time, a straight-line alignment was considered a good solution. This solution, however, tended to place a large amount of the attached line shaft weight on the aft reduction gear bearing in the cold condition. During operation (hot condition) more shafting weight shifted from the forward into the aft reduction bearing. This unequal loading of the gear bearings caused gear skew.

This unequal gear bearing loading was identified when researches were developed to investigate this problem. As a result, the shaft alignment calculation was developed with the main goal of determining bearings reactions and, if necessary, to determine vertical displacements to be applied to some of the bearings resulting in better distribution of load among bearings and avoiding gear problems (SNAME,2007).

3.2. Factors That Can Change Alignment

Resulting from researches over the years it was observed that some factors can affect the alignment: ship's load condition; sea state; thermal growth of ship's structure; thermal growth of mechanical equipment (engines, turbines, reduction gear) connected to the shaft line.

Lehr & Parker in 1961 pointed out some of these factors related to the ship draught, hull deformation, thermal effects, eccentric propeller thrust force and bearing flexibility consideration. The different ballast conditions of the ships generate considerable structural modifications, which can alter the alignment. However, hull deflections that change alignment can also be caused by variations in ship loading, dynamic deflections due to the sea state, vertical and lateral thermal expansion due to temperature difference, accidents in ship maneuvers and welding services. George Korbetis, *et al.* (2018), used Finite element Method (FEM) to evaluate the effects of hull deformation on the static alignment characteristics of VLCC related to different ballast and load conditions. They found variations of bearing offset differences above 10 mm and bearing reactions above 2 times of difference regarding the static condition.

The temperature difference between propulsion system components such as bearings, gearbox, and engine is also a very important subject to be considered. During operation, temperature difference should be taken from these components and thermal grow compensation must be calculated to correctly adjust the components position in a cold condition. The thermal grow effects are often considered just in the vertical direction. However sometimes components, such as gearboxes and bearings, have free side movement just in one direction. Therefore, in these cases vertical and horizontal thermal effects should be considered.

The thrust force generated by the propeller is an axial force that acts on the shaft, which application point does not coincide with the shaft geometric center due to the following factors: sea state and ship loading condition. The consequence is a bending moment that acts on the shaft end and, consequently, affects the propulsion shaft alignment. Both the thrust force and its application point (thrust center) must be estimated and considered on the shaft alignment calculation. Nowadays, it can be estimated by a Computational Fluid Dynamic (CFD) software.

3.3. Alignment Acceptance Criteria

The only propulsion shaft alignment acceptance criteria is provided by the Society of Naval Architects and Marine Engineers SNAME. The shafting system should be designed and aligned to meet the criteria required for all normal ship operating conditions, including the changes caused by bearing wear down, thermal growth, ship loading and the other factors which affect alignment (SNAME, 2007). The acceptance criteria show the following items:

3.3.1. Reduction gear bearing: The maximum bearing load differential shall not be exceeded. The reduction gear manufacturer will usually provide the allowable differential. However, if this value cannot be obtained, then a general rule is that the static load differential should be less than 25% of the combined total load on the reduction gear bearings in all operating conditions to ensure that the gear tooth meshing contact is not misaligned by a skewed attitude of the gearwheel in its bearings.

3.3.2. Support bearings – minimum allowable loads: Zero or negative loads on the bearings are not acceptable. The bearings shall not be loaded less than its minimum allowable load. A minimum allowable load is required for each bearing to stabilize the shaft in the bearing and prevent shaft vibratory problems. Determining the minimum load is a somewhat arbitrary decision, although one guideline is that the minimum load shall be at least 50% of the bearing's initial design load distribution.

3.3.3. Support bearings – maximum allowable loads: These loads shall not be above its maximum allowable bearing pressure, which is usually specified by the bearing manufactures or based on historical results. The maximum allowable load for a particular bearing is usually determined by using the projected area of the bearing (the product of the effective bearing length and the shaft outer diameter).

3.3.3.1. Shaft Line bearings: Some reference values are given by Modern Marine Engineers Handbook, with pressure limits of 500 kPa for disc lubricated bearings, and 350 kPa for ring lubricated bearings.

3.3.3.2. Waterborne shaft bearings: These bearings may be either oil or water lubricated. The maximum allowable pressure limits are: oil-lubricated synthetic liner (600 kPa); oil-lubricated babbitt liner (800 kPa); water-lubricated synthetic liner (500 kPa); water-lubricated rubber or wood liner (300 kPa).

3.3.4. Shafting stresses – maximum allowable value: The maximum allowable stresses on the shafting are defined by classification societies or good engineering standards and shall not be exceeded. This is a high-priority alignment criterion since the shaft can fail from excessive bending stresses. The alignment directly affects the bending moments and bending stresses on the shaft line and consequently it affects the overall shaft stress and shaft diameter calculations.

3.3.5. Directly connected engines, special couplings, or other equipment**:** The manufacturers of large main engines directly connected to propulsion shafting usually specify shaft alignment limits to prevent excessive crankshaft deflections. These limitations are applied to bending moments and shear at the engine coupling and shall not be exceeded. Obtaining these results during shafting alignment calculation is of major importance.

3.3.6. Slope between the shaft and the aft stern tube bearing: The aft stern tube bearing function is to support the propeller load and shaft weight and counteract the propeller induced hydrodynamic forces. The slope of this bearing is critical, and it must be aligned with the propeller shaft so that the load is distributed over most of the available bearing area. A rule-of-thumb for slope limit on oil-lubricated bearings is 0.003 radians and for water-lubricated structural or stern tube bearing is this may be out of parallel to the shaft by no more than the design minimum bearing clearance. During the shaft alignment calculation, the slope between the shaft and the aft stern tube bearing shall not exceed 0.003 radians. If the calculated slope is above this limit, the aft stern tube bearing bush shall be machined with this slope to guarantee a maximum contact between shaft and bush.

It is important to note that there are many possible alignment configurations that will attend the acceptance criteria. The search for the best alignment configuration of bearing is the goal of optimization studies, which is not the focus of this paper.

3.4. Shaft Alignment Calculations

The typical propulsion shaft line is supported by many bearings which are treated as a hyperstatic beam. A typical shaft with N bearings is statically indeterminate by N-2 degrees, since there are only two independent static equilibrium equations useful for determining the vertical bearing reactions. The two static equilibrium equations are: (1) the sum of forces in the vertical direction is zero and (2) the sum of moments about any point is zero. Therefore, to calculate bearing reactions on this type of static problem, structural analytical methods are applied. The most common methods are Integration, Stiffness and Finite Element Method (FEM) have been commonly used in these applications. Stefan Tenv (2020) used commercial software of FEM to model, analyze and optimize a propulsion shaft alignment, obtaining bearings vertical offset for smooth distribution of bearing reactions.

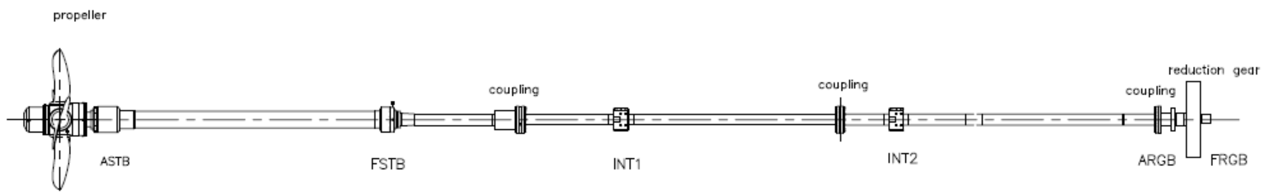
The Stiffness Method, also known as the Displacement Method, is widely used in the calculation and analysis of structural systems. Due to its characteristics, the method is extremely suitable for computational implementation as it incorporates the use of matrix algebra in a very intuitive and efficient way. In this method the structure is idealized by 2-dimensions bar or beam elements that contain the geometric and material data of the system. Each element has two nodes, one at each end. Each node contains six degrees of freedom (DOF) that may represent loads and displacements of the structure (restricted or not). The system solution provides reactions on supports, linear and angular displacements, shear forces, bending moments, axial forces and torsional moments on all nodes of the structure.

3.4.1- Case study:

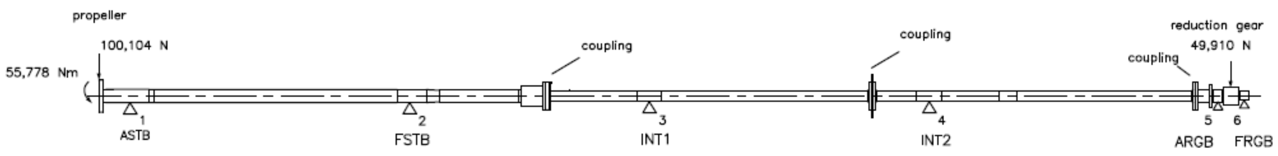
An AHTS shaft line was selected as a case study to exemplify the shaft alignment calculation. The shaft line is shown in figure 3, where ASTB and FSTB are the aft and forward stern tube bearings, INT1 and INT2 are the intermediate shaft bearings, and ARGB and FRGB are the aft and forward gearbox bearings. Shaft line characteristics are shown on the following table 2 and the figure 4 is shown the propulsion Shaft line idealized as a beam and discretized with elements and nodes as the input in the structure calculation software used, where “Ry” are the bearing vertical reactions, “C1” and “C2” are the vertical loads from propeller and Gearbox, and “M” is the bend moment related to the propeller center mass and his distance to the shaft.

Table 2 – AHTS shaft line characteristics

Characteristics	Data
Length (m)	34,55
Maximum outside diameter (m)	0,405
Minimum outside diameter (m)	0,335
Internal diameter (m)	0,105
Number of sections	12
Propeller weight C1 (N)	100.104
Bending moment M (N.m)	55.778
Reduction gear weight C2 (N)	45.910
Shaft material	Structural steel



(a)



(b)

Figure 3 – (a) AHTS propulsion Shaft line arrangement (b) The shaft line as a structure with loads and supports

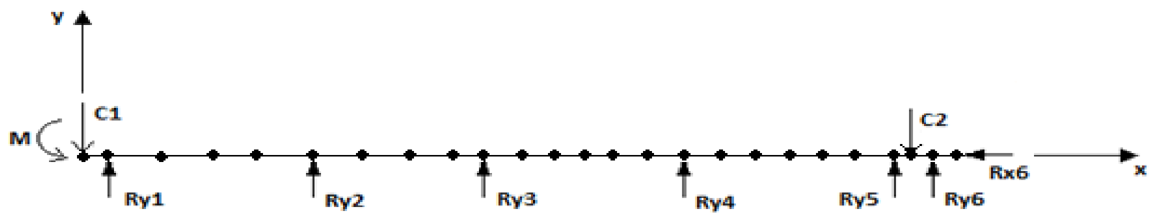


Figure 4. AHTS propulsion Shaft line idealized as a beam and discretized with elements and nodes.

Computational software developed by one of the authors uses the Stiffness Method to analyze reticular structures such as beams, gantries 2D e 3D, grills, etc. It was used to model and analyze the above propulsion shaft line. The analyzes involved two basic conditions: 1) Docked ship with all the bearings concentric aligned and 2) Docked ship with some of the bearings vertically displaced to attend the mentioned criteria.

The results from the first condition are presented on table 3 and show that the bearing number 6 is unloaded and, according to the first criteria, it is not allowed.

This is the exact condition mentioned in section 3.1, where the gears suffer damages due to imbalanced loads on bull gear bearings (SNAME, 2007). To correct this situation, a new alignment condition was proposed and calculated in which new displacements were determined to bearings 3,4,5 and 6 (1 and 2 are structural bearings). In introducing these displacements in the Stiffness Method Software, the new bearings' reactions were obtained. This new alignment condition results are shown on table 3, and it is observed that reactions 5 and 6 are very close and satisfy the first criteria and the gears' teeth will be preserved. Figure 5 shows the deformed configuration of the shaft line, shear force and bend moment diagrams of both conditions.

Table 3– AHTS Alignment calculation for concentric bearings and the proposed alignment position.

Condition		Bearings					
		1	2	3	4	5	6
Concentric	Offset (mm)	0	0	0	0	0	0
	Reaction Force (N)	164993	61396	70214	61643	133784	-37050
Proposed Alignment	Offset (mm)	0	0	-1	-2,5	-2	-1,15
	Reaction Force (N)	164258	63419	67289	71509	45906	42597

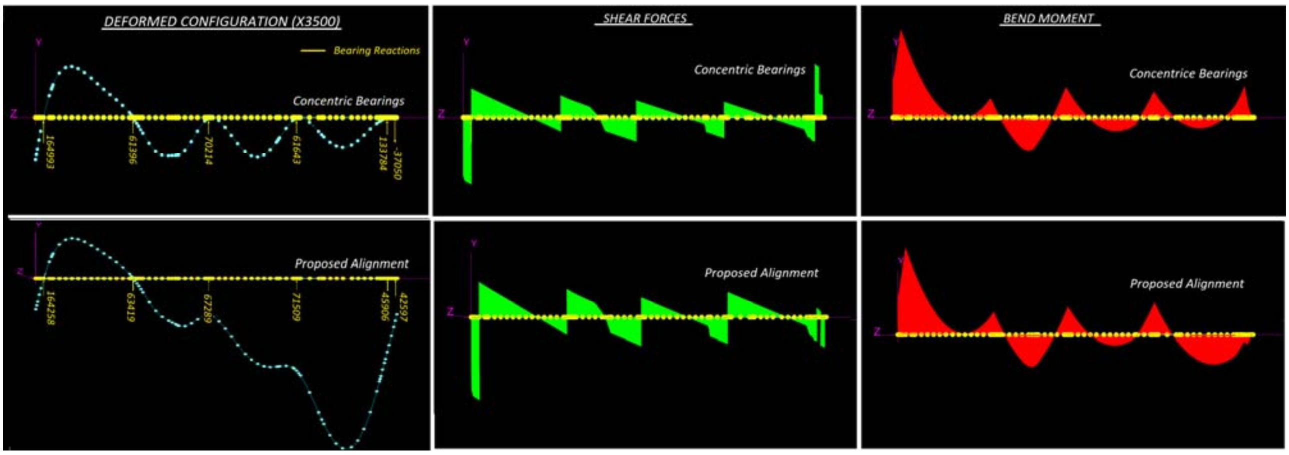


Figure 5. AHTS propulsion Shaft line drawing.

From table 3 it is possible to observe that all bearings are positively loaded, and the reaction difference between bearings 5 and 6 (reduction gear) also attends the acceptance criteria.

4. ALIGNMENT EXECUTION

The alignment execution involves the following steps: as initial reference, the components of the shaft line (bearings, gearbox, engines, generator, etc.) must be concentrically aligned; the calculated vertical bearing displacements are applied to each bearing; shaft sections are assembled and connected. The initial reference is obtained by a process called “Sighting-through” or “Bore-Sighting”. This process is performed before the propulsion shaft assembling and establishes a reference line through the center of the bearings bore. The purpose of the bore sighting is to set the propulsion shafting bearings, the engine or the gearbox, to the initial concentrically aligned position, as well as to define and verify the stern tube bearing slope boring angles. Basically, two methods are used to perform the sighting-through or bore-sighting: The Piano Wire and The Laser or Optical methods.

The Piano Wire method uses steel wire (~0,5mm diameter) to represent the reference line. The wire extends from outboard of the stern tube’s aft end through the full length of the stern tube, continue to the aft end of the main engine flywheel or to a temporary support that represents the main engine’s future location if the main engine has not been installed yet. The wire is threaded through centering spiders positioned at the stern tube casting aft and forward ends and is pre-tensioned with a known force using push-pull scales or a certified weight. Vertical and side measurements are taken between the piano wire and the bore of the bearings with a micrometer. The measurements are used to establish the bearing and main engine positions relative to the reference line. The piano wire measurements must be adjusted to compensate for the natural wire sag. The main advantage of this method are the low cost and the relative precision of results (0,01mm) if used digital micrometer gauges. In other hand, the main disadvantages are that tasting surface irregularities, cleanliness, and wire vibrations may influence measurement accuracy; used just in drydock condition; used just without shaft assembled, great influence of human error (SNAME, 2007).

The other two sighting-through processes most used are the Laser and Optical measurements. Laser instrument is very versatile being possible to use with and without the shaft assembled on the system. Without the shaft in place, it uses a laser source set in the center of one reference diameter, such as the recess at the aft side of the stern tube. Two reference targets are defined. The receiver target is positioned inside the bearing at a location specified in the shaft alignment calculation and a reference reading is taken. The receiver is then moved to selected measuring positions along the reference line and additional readings are taken. The results are digitally recorded. The bearing offsets are automatically calculated in relation to the reference line and may be presented in the form of a graph or table. The advantages of this method are the high accuracy of ±0.005 mm, fast measurement process, possible continuous data acquisition, less human reading error. The only disadvantage is the high cost of the equipment.

Optical instrument sighting employs a precision telescope to project an optical reference line. The instrument is positioned on a base or tripod and is leveled in the horizontal plane before sighting begins. A reference target, which is utilized to establish a reference line, is fixed at one end and not touched throughout the measurement process. Transparent targets are set in the physical center of the casting bore at several positions. The deviation of each target center is recorded relative to the reference line. Typically, four to six target locations are selected for the stern tube sighting. The advantages are related to the easy set up and operation and easy results reading, with accuracy of ±0.01 mm. While the disadvantages are that sighting accuracy greatly depends on the target’s setting, centering precision, and telescope leveling along the reference line, and this method is just used for measurements when the shaft is out (in drydock).#

5. METHODS FOR MEASURING THE ALIGNMENT

The goal of the alignment measurement is to obtain the reaction value in each bearing after alignment execution. There are several proven methods to measure the alignment of propulsion shafting. Each method has its own particularity regarding the measurement process, accuracy, and restrictions. The alignment verification compares the measurement and the calculation results to conclude if the executed alignment is the required one by calculation.

There are some methods to obtain the bearing reactions directly or indirectly. Jack-up measurement is a direct reaction measurement, while strain gauge and sag and gap procedure are indirect methods to measure the deflections and strain in the shaft and correlate those measurements to the bearing reactions.

The jack-up test method is a direct reaction measurement procedure in which the reaction of a bearing is measured in correlation with the jack load that is set as close to the bearing as possible. The bearing reaction is estimated from the relationship between the jack load and the jack displacement. The required tools are: Hydraulic Jack with well-known pressure area which will be used in the final load measurement equation. The jack should not be large, as the accuracy of the pressure gauge is better in the higher-pressure range; Hydraulic Pump with an accurate pressure gauge (Bar), good quality needle valve and pressure adjustment device; Dial Gauge with 0.01 mm resolution and adjustable mounting on magnetic foot; Load Cell: Non-essential tool, however, it improves measurement accuracy significantly. The Jack-up disadvantages are that the entire process is time-consuming and labor intensive, high rate of human errors, it is not possible or very difficult to measure reactions for outside aft bearings and gearbox bearings (Workshop Insider, 2020).

The other two mostly used procedures that indirectly provide the bearing loads are the Strain Gauge method and Gap and Sag procedures. The strain gage method is the only available technique for measuring the alignment of the entire connected propulsion shaft line with the vessel afloat and even during operation. It provides a more complete assessment of the shaft's alignment condition than the hydraulic jack method and is generally more accurate. The strain gage method provides shaft alignment information through the fundamental theory of flexural beam analysis. These principles can be used to derive mathematical equations for calculating the bending moments along the shaft from the measured strains, which can then be used to calculate the bearing reactions for the shafting system (Jae-ung Lee, 2018)

The sag and gap procedure is commonly performed prior to the shafting assembly and is simultaneously applied on all open flanges of the system. The procedure sets up the shafting system to bring the measured sag and gap values close to the calculated values. It can be considered as a secondary alignment check procedure in which the conditions and sequence of adjusting the sag and gap values between coupling flanges is to be specified in the approved shaft alignment procedure. Sag and gap can only be used as a cursory verification method and should not be considered as a final alignment confirmation.

6. SIGNALS AND SYMPTOMS OF MISALIGNED PROPULSION SYSTEM

As mentioned before, some factors may affect the shaft alignment. When those factors are not accounted for into the alignment calculation or due to another reason, the optimum alignment is missed, and it is said that it is misaligned. There are some signals or symptoms that indicate this condition: vibration and excessive bearing temperature. If any of those signals arise, the alignment must be checked, the cause identified and corrected.

7. PROPULSION SHAFT ALIGNMENT CORRECTION

The propulsion shaft alignment correction basically consists of repositioning the bearings to the required alignment specified in the original calculation. Therefore, the alignment correction possibilities are related to the different forms to repositioning the shaft bearings supports. These forms are:

- Intermediate / line shaft bearings – the internal vessel accessible bearings may be vertically moved by jack-bolts or lifted by chain block or hydraulic jack and laterally with jack-bolts. Shims can be used to chock the bearing base. These shims can be made of machined steel, resin or adjustable bolted chocks as vibracon (SKF, 2020).
- Stern tube bushings or outside bearings – Worn bushes must be substituted. If required by the shaft alignment calculation, the aft stern tube bush must be machine bored to accommodate the shaft.
- Gearbox and Engine can be repositioned according to the shaft alignment calculation.

8. CONCLUSION

A general ship propulsion shaft alignment overview was presented based on the current studies and technical guides since there are no international standard rules for this specific subject. The following flowchart (figure 6) is showing a resume of the propulsion shafting alignment process.

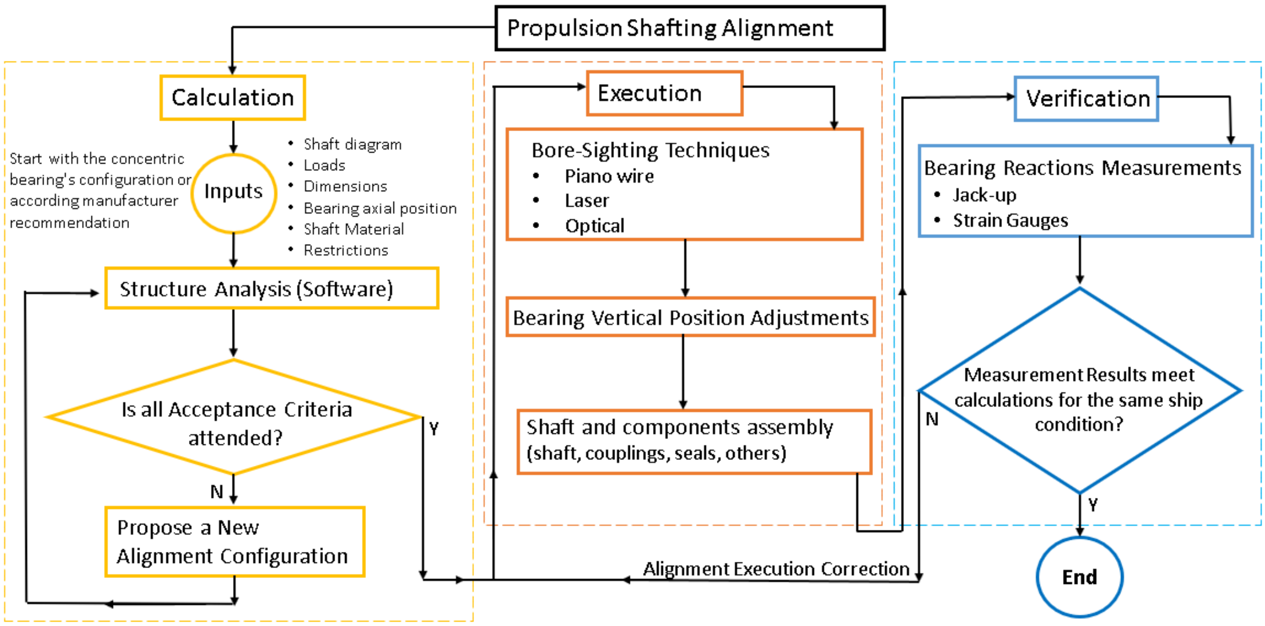


Figure 6 – Flowchart of Propulsion shafting alignment process.

Through this flowchart diagram, readers can quickly understand and know the process for propulsion shaft line alignment. It can be used as a start guidance process for shipyard, owners, and maintenance companies that often must deal with shaft alignment since this proposed flow chart is based on current research and documents on this subject.

This paper presented the main practices and considerations about calculation, execution, measurement, verification, and correction of alignment on ship propulsion systems.

An AHTS ship propulsion shaft alignment calculation example was done. The structure analysis Stiffness Method was applied through a software calculation toll developed based on this method. The results from the example show that concentric bearing alignment is not appropriated because one bearing was not sustaining load. A new ideal alignment condition was proposed and calculated, obtaining some vertical displacements to be applied to the movable bearings, achieving good load distribution for all bearings and meeting the acceptance criteria requirements.

This paper highlights the importance of propulsion shaft alignment to small and medium-sized ships, as they are most of the world fleet, while until today the concern is focused on large-sized ships. Against the common sense, even for small and medium-size vessels, the concentric bearing alignment is not always the correct solution to the propulsion shaft alignment. It was proved for a medium-size AHTS vessel on the alignment calculation example on this paper. This fact reinforces the necessity of care about all steps of the alignment procedure presented on this paper. A well-aligned propulsion shaft system better uses and enjoys his components lifetime, while a misaligned system generates inappropriate bearing load distributions and unappropriated operational condition causing an increase probability of premature failures on propulsion components.

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10. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.