



GUIDANCE NOTES ON

PROPULSION SHAFTING ALIGNMENT

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Foreword

The mission of the American Bureau of Shipping (ABS) is to serve the public interest, as well as the needs of its clients, by promoting the security of life, property and the natural environment primarily through the development and verification of standards for the design, construction and operational maintenance of marine-related facilities.

The Rules and Guides on which classification is predicated are established from theoretical and empirical principles of naval architecture, marine engineering and other engineering principles that have proven satisfactory by service experience and systematic analysis. The classification Rules are not intended to address every single aspect of the vessel design, but rather to indicate the minimum set of criteria which will ensure safety and functionality of all vital components of the vessel, and at the same time provide sufficient space to the industry to accommodate their practices and technologies with minimum constraints from regulatory bodies.

However, in situations where the complexity of the problem results in conflicting interpretation of regulations and when the consequence of this disparity results in damage to the equipment and affects vessel's safety, additional regulation clarification and guidance may be necessary. The case of shaft alignment is an example of where ABS has noticed the need to provide a more detailed explanation on alignment design and practices, which has resulted in the development of the subject Guidance Notes. These Guidance Notes have been developed primarily to clarify the subject matter for ABS field inspectors and design review engineers to ensure consistency of the survey and plan approval process. Moreover, the subject guidelines may help the industry to improve its approach towards shaft alignment analyses and procedures.

Additionally, ABS has developed state of the art analytical tools primarily for the purpose of engineering analysis and design. The ABS shaft alignment program, combined with alignment optimization software, is capable of analyzing complex propulsion installations and, when used as design tool, may provide an optimal solution to the alignment problem.

We welcome your feedback. Comments or suggestions can be sent electronically to rsd@eagle.org.



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SECTION 1 Introduction

1 Propulsion Shaft Alignment

The propulsion shafting alignment is a process which consists of two parts:

- The design and analysis
- The alignment procedure and measurements

The definition of the shaft alignment process and the practices in performing the alignment are not consistent in the industry. The terminology and requirements for the shaft alignment will vary depending on the machinery application, the propulsion system's size, as well as on the perception of the alignment process itself¹.

In order to avoid misunderstandings in interpretation and definition of the terms in these Guidance Notes, a definition of the propulsion shafting and the propulsion shafting alignment is provided below.

The definitions adopted here and the references made throughout these Guidance Notes, whether mentioned explicitly or not, are considered valid for the alignment of the ship propulsion machinery.

Propulsion shafting is a system of revolving rods that transmit power and motion from the main drive to the propeller. The shafting is supported by an appropriate number of bearings.

Propulsion shaft alignment is a static condition observed at the bearings supporting the propulsion shafts. In order for the propulsion shafting alignment to be properly defined, the following minimum set of parameters (whichever may be applicable) need to be confirmed as acceptable:

- Bearing vertical offset
- Bearing reactions
- Misalignment angles
- Crankshaft's web deflections
- Gear misalignment
- Shaft and bearings' strength
- Coupling bolts' strength

The alignment is considered to be satisfactory when it is possible to control the above parameters, and maintain them within the required limits under all operating conditions of the vessel. By "all operating conditions of the vessel", the intent is that the alignment remains acceptable for:

- Vessel loading variation from ballast to laden
- Temperature variation affecting the propulsion shafting system

The change in loading of the vessel will result in variation of hull girder deflections, thus disturbing offset of the shaft-supporting bearings. Hull deflections will affect all bearings in the system simultaneously. Making the alignment satisfactory for all loading conditions will require several analyses to be conducted to verify alignment acceptability for all different vessel loadings.

¹ The approaches to the alignment presently seen throughout the industry vary from defining the alignment as pure static and a combination of static and dynamic, with a variety of methods in modeling and analyzing the alignment.

The temperature rise or drop will also affect the bearing offset. However, unlike the hull deflections, the effect of temperature change may be local to the particular bearing or to the set of bearings (e.g., main engine, gear-box).

Basic propulsion shafting alignment criteria, requirements and limits are usually defined by Classification Societies, shipbuilders, designers or other regulatory bodies. The ABS criteria and requirements are defined in ABS Rules. For the reader's convenience, appropriate paragraphs of the Rules are replicated, as deemed necessary.

Note: The above definition of the alignment made no reference to the dynamics and vibration. This is because the propulsion shaft alignment is calculated, conducted and verified when the system is at rest. Therefore, throughout these Guidance Notes, the propulsion shaft alignment will be regarded as a static condition.

However, the goal is to ensure that all of the activities on the alignment in the static condition will ensure an acceptable running condition of the shafting. It has been proven that a good static shafting alignment is a prerequisite for trouble-free dynamic operation of the propulsion shafting, as it will lower the probability of excessive whirling and lateral vibration of the shafting, as well as noise transmission

2 Objective

The objective of these Guidance Notes is to provide detailed information on the propulsion shafting alignment design and procedure in order to:

- Ensure safe operation of the propulsion shafting system on ABS-classed vessels.
- Improve the design review process and survey.
- Clarify the [ABS](#) position with regard to the alignment problem in the industry and hope that this clarification may lead to a more unified approach in the alignment design, analysis and application.

The benefit of properly addressed alignment will be:

- Reduction in material damages (in particular) on the stern tube bearings and seals, main engine bearings, gear meshes and shafting coupling bolts
- Environmental pollution reduction

These Guidance Notes will primarily elaborate on the alignment problem in propulsion systems which are deemed alignment-sensitive, such as VLCC, ULCC and large bulk carriers. Accordingly, the following are specifically addressed:

- Directly driven propeller installations
- Low speed diesel installations
- Systems with relatively short and rigid shafting
- Vessels with a relatively flexible hull structure

These Guidance Notes also provide insight into the alignment problems of gear-driven installations (turbine or electric) that fall into the above category of rigid shafts and flexible structures.

Large container vessels will be separately addressed, as these Guidance Notes discuss hull girder deflections in installations with single screw diesel propulsion.

Though the focus is primarily on the vessels which for one reason or another fall into the category of alignment-sensitive installations, it is not intended to disregard possible problems in the other propulsion installations. Accordingly, the discussion concentrates on the propulsion systems which are deemed highly sensitive to small disturbances in bearing offsets. The principles and practices discussed below shall certainly apply (partially or fully) to the other vessels' designs as well.

These Guidance Notes will address the following:

- Shaft alignment design and review
 - General alignment considerations
 - Robust alignment design
 - Tail shaft bearing problems
 - Diesel engine bearing problem
 - Intermediate shaft bearing offset adjustment
 - Crankshaft equivalent model
 - Bearing clearance
 - Gear meshes
 - Acceptance criteria
- Shaft alignment procedure
 - Shipbuilder practices
 - Construction tolerances
 - Construction priorities
 - Sighting through
 - Slope boring or stern tube bearing casting
- Alignment measurement
 - Sag and gap
 - Jack-up
 - Strain gauge
- Hull girder deflections
 - Hull deflection measurement
 - Hull deflection prediction
- Alignment optimization

3 The Alignment Problem

As the vessel's cargo capacity, and consequently, the installed power of the main drive increase, the propulsion shafting alignments are increasingly more sensitive to disturbances affecting vertical offset of the bearings. These disturbances primarily result from hull deflections and temperature change. However, another very significant influence on the quality of the alignment is the accuracy of the shaft alignment analyses and the alignment procedure itself. All of these problems will be specifically addressed in these Guidance Notes.

The shaft alignment problem can be summarized as follows:

- High sensitivity of the shaft alignment to small disturbances in the bearing vertical position
- Disparity between highly flexible hull girder structure and the rigid propulsion shafting
- Difficulties in hull girder deflection evaluation
- Problems in maintaining the desired accuracy of the shaft alignment analysis
- Inconsistency and inaccuracies in conducting the alignment procedure

The shaft alignment allowable tolerances are measured in fractions of millimeters, as opposed to the vessel, which is constructed with tens of millimeters of acceptable error margin. This disparity would eventually not be a problem (required analytical accuracy is practically achievable), if the alignment procedure itself was conducted after a majority of the vessel's structure was in place and welded, i.e., no significant structural changes were made during and after the shaft alignment procedure was completed. However, major structural works are often not finished when the alignment is performed. There are a number of reasons for that, some of which will be addressed below.

Ideally, a shaft alignment analysis should be performed for maximum allowable alignment tolerances, resulting in acceptable bearing reactions and misalignment angles under all operating conditions of the vessel (loaded, ballast, hot and cold). This implies that hull deflections should be accounted for initially.

The hull girder deflections are not easy to predict, calculate or measure. It is therefore difficult for the industry to comply with the requirement that hull deflections be accounted for in alignment calculations.

The alignment process is rather inconsistent among shipbuilders, involving different practices that builders have adopted in vessel construction, which results in a spectrum of different approaches to the alignment. These Guidance Notes will not try to investigate all of the different practices, but will to a certain extent address some of the extreme cases, which if not thoroughly controlled may result in propulsion installation damage and failure.

The alignment sensitivity is measured by bearing reaction response to the bearing offset change. On sensitive installations such as VLCC, ULCC and large bulk-carriers (which are addressed in particular in these Guidance Notes), a fraction of a millimeter disturbance in vertical bearing offset may cause a significant change in bearing reaction.

3.1 Solution to Alignment Problem

The preferable condition for performing the propulsion shafting alignment procedure would be in the dry dock, just before the vessel is launched. At that stage, the vessel's structural work is nearly complete. Thus, a minimum disturbance on the alignment resulting from the construction work after the launching may be expected.

However, to comfortably rely on dry dock alignment, the hull deflections need to be predicted with relatively high confidence. Prediction of hull deflections would enable the design of a dry dock alignment robust enough to prevent other than hull deflection disturbances from adversely affecting the alignment. ABS achieved this goal by conducting comprehensive hull deflection measurements on a series of different vessels (various types and sizes), which now constitutes a database of expected hull deflections for certain categories of vessels. ABS now has the ability to relatively accurately estimate the hull deflections (for more details, consult Section 6) and to conduct optimization of the alignment, utilizing optimization software (Section 7).

3.2 Analytical Support

There are a number of computer programs in the industry which can address the alignment problem accurately and comprehensively.

The ABS shaft alignment software, however, has several features that distinguish it from most of the other similar computer programs. Namely, in addition to the common analysis which provides bearing reactions, misalignment angles, sag and gap data, influence coefficient matrix, the ABS alignment software is further capable of:

- Estimating hull deflections for the given ship type and the basic ship parameters
- Evaluating the stern tube bearing contact and misalignment condition, and
- Optimizing the alignment within given constraints (hull deflections, thermal growth, etc.).

More details on shaft alignment optimization are given in Section 7.

Basic ABS shaft alignment analysis software is available for distribution to third parties. The software package includes sample shaft alignment models, user's manual and theoretical backgrounds. On specific demand, software application training can be provided as well.

4 Modern Vessel Design

The propulsion system of a modern merchant vessel commonly consists of a diesel engine driving a propeller through directly-coupled² shafting. As mentioned, such a design results in an increased disparity in flexibilities between the hull girder structure and the shafting. Namely:

- As the demand for power rises with the increase in the vessel's size and with scantling optimization, the vessel's hull becomes more flexible.
- The shafting diameters become larger and the shafts stiffer.

Consequently, the alignment of the propulsion system becomes increasingly sensitive to small deviations in bearing offsets resulting in difficulties in analyzing the alignment and conducting the alignment procedure.

The alignment-related damages are attributed to a number of factors which are addressed in detail in these Guidance Notes. However, in order to prevent and reduce alignment-related problems, it is important to ensure that:

- The shaft alignment analysis provides the necessary (accurate and applicable) data to support each stage of the actual alignment process.
- The alignment procedure is conducted with the required accuracy in accordance with Class regulations and good marine practices.

5 Rule Requirements

The propulsion shaft alignment is a static process where acting loads are static forces and moments. Dynamic factors are not normally considered, as the primary purpose of the analysis is to support the static shafting alignment procedure. Accordingly, these Guidance Notes apply to the static design of the propulsion shafting alignment, as well as shafts, couplings, clutches and other power transmitting components for propulsion purposes.

It has been recognized that accurate alignment at the stern tube bearing is crucial in order to avoid the occurrence of bearing failure problems. Slope boring (or bearing inclination) has been used in the marine industry to achieve the required level of alignment.

It is normally required that the shaft alignment be carried out in the presence of a Surveyor. It is desired that sighting-through and, when applicable, Sag and Gap measurements be verified after the superstructure is put in place and all major welding works are completed. Final alignment should be verified in the afloat condition. When alignment calculations are required to be submitted in accordance with 4-3-2/7.3 of the *Rules for Building and Classing Steel Vessels*, the calculated alignment data are to be verified and recorded by appropriate measurement procedures in the presence and to the satisfaction of a Surveyor.

Shafts and associated components used for transmission of power essential for the propulsion of the vessel are to be designed and constructed so as to withstand the maximum working stresses to which they may be subjected in all service conditions.

In addition to the design requirements addressed in the *ABS Rules for Building and Classing Steel Vessels*, consideration is to be given to additional stresses in the shafting system given rise to by shaft alignment.

In general, shaft alignment calculations and a shaft alignment procedure are to be submitted for reference. Specifically, they are to be submitted for review for the following alignment-sensitive type of installations:

- i) Propulsion shafting of diameter larger than 400 mm (15.75 in.)
- ii) Propulsion shafting with reduction gears (refer to 4-3-1/1.5 of the *ABS Rules for Building and Classing Steel Vessels*) where the bull gear is driven by two or more ahead pinions.
- iii) Propulsion shafting with power take-off or with booster power arrangements.
- iv) Propulsion shafting for which the tail shaft bearings are to be bored sloped.

² "Directly coupled installation" means a diesel engine connected to propeller through propulsion shafting only (no elastic couplings or reduction gears are used in the system).

The alignment calculations are to include bearing reactions, shear forces and bending moments along the shafting, slope boring details (if applicable) and detailed description of the alignment procedure.

The alignment calculations are to be performed for theoretically aligned cold and hot conditions of the shaft with specified alignment tolerances.

Calculations are to be performed for the maximum allowable alignment tolerances and are to show that:

- Bearing loads under all operating conditions are within the acceptable limits specified by the bearing manufacturer.
- Bearing reactions are always positive (i.e., supporting the shaft).
- Shear forces and bending moments on the shaft are within acceptable limits in association with other stresses in the shaft.
- Forces and moments on propulsion equipment are within the limits specified by the machinery manufacturers.

In general, if calculated relative misalignment slope between the shaft and the tail shaft bearing is greater than 0.3×10^{-3} rad, then consideration is to be given to reducing the relative misalignment slope by means of slope boring or bearing inclination.

SECTION 2 Shaft Alignment Design and Review

1 General

A shaft alignment designer has to ensure, and the reviewer has to verify, that the strength of the designed parts (bearings, shafts, coupling bolts, couplings) is sufficient to prevent the stress exerted by the acting loads to damage the same.

In particular, the alignment design should satisfy the following:

- Bearing condition:
 - Acceptable reaction load
 - Even load distribution throughout the bearing
- Shaft strength
- Satisfactory crankshaft deflections
- Acceptable gear contact condition
- Satisfactory coupling bolts strength
- Acceptable clutches and flexible coupling misalignment tolerances

2 Review vs. Design

Analytical models do not always represent the propulsion systems accurately and may not always provide sufficient information to ensure an “error free” alignment procedure. This Section is intended to address the incompatibility problem between the analyses and the alignment procedures, discuss possible solutions and provide advice, where possible. First, differences between the review and the design process will be defined.

The review process serves to verify soundness of an existing design, and it has to thoroughly follow the alignment criteria and guidelines, as defined in the Class Rules. These criteria are mostly strength of material related to specific concerns for safety of life, equipment and environment.

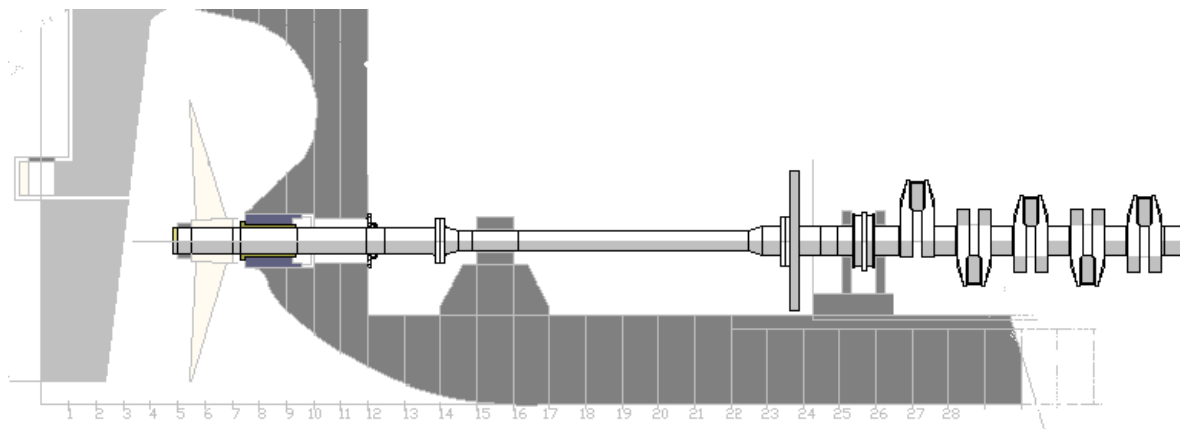
The design process is more complex than the review itself. It requires experienced personnel and is a time-consuming effort with a goal of defining a satisfactory set of parameters to comply with all alignment criteria. The parameters that primarily need to be defined are bearing offset (vertical position) and bearing location (horizontal position). Moreover, it is to be verified that alignment complies with shaft geometry, material properties, installation constraints and other requirements related to the propulsion shafting interaction with surrounding systems.

The design process, if conducted properly, should essentially optimize propulsion shafting for the given parameters³.

The design and review requirements are detailed primarily for the installations involving direct driven propulsion systems (Section 2, Figure 1). Other designs may have slightly different requirements but, in general, a similar approach will apply.

³ By optimization here, we do not only imply application of a particular optimization tool or software, but also an educated engineering process in combining the design parameter in an acceptable solution which further complies with imposed regulations and requirements.

FIGURE 1
Directly Coupled Propulsion Shafting – Example



3 Review

Overall, the plan review during and after construction is conducted by **ABS** to verify to itself and its committees that a vessel, structure, item of material, equipment or machinery is in compliance with the Rules, Guides, standards or other applicable criteria.

Engineers need to confirm that all information required for review is received:

- Shaft alignment model
- Scope of submitted calculation
- Results of analysis
- Shaft alignment procedure

After the review is completed, the reviewer needs to document the result of this review.

The review of the submitted shaft alignment analysis and procedure is to be conducted by inspecting the results of the alignment analysis and by conducting check analysis using the ABS shaft alignment software.

3.1 Plans and Particulars Required

Plans and particulars to be submitted for review most commonly include the following:

3.1.1 For Propulsion Shafting

Shafting arrangement

Rated power of main engine and shaft rpm

Thrust, line, tube and tail shafts, as applicable

Couplings – integral, demountable, keyed, or shrink-fit, coupling bolts and keys

Shaft bearings

Stern tube bearings detailed drawings

Allowable bearing load

Shaft seals

Power take-off to shaft generators, propulsion boosters, or similar equipment, rated 100 kW (135 hp) and over, as applicable

Material properties of the shafts and the bearings (modulus of elasticity and density)

Propeller mass and material

3.1.2 For Cardan Shafts

Dimensions of all torque-transmitting components and their materials

Rated power of main engine and shaft rpm

Engineering analyses

3.1.3 Calculations and Procedures

Propulsion shaft alignment calculations and detailed shaft alignment procedure where propulsion shaft is sensitive to alignment (see *ABS Rules for Building and Classing Steel Vessels* 4-3-2/7.3).

3.1.4 Diesel Engine

Crankshaft equivalent model

Location and mass of the following equipment, when applicable: flywheel, chain drive tightening load, cam-drive gear, torsional vibration damper

Detailed drawings, material properties and location of the main engine bearings

Allowable bearing load

3.1.5 Reduction Gear

Detailed drawings of the gear shafts and main gears

Mass and location of the gears

Material properties

Location and material of the gear shaft bearings

Allowable bearing load

3.1.6 Shaft Alignment Procedure

Detailed description of the shaft alignment procedure

3.2 Shaft Alignment Model

By exercising sound judgment, the engineer should verify that the submitted discrete model represents the actual propulsion system with sufficient accuracy:

The engineer should verify that the line shaft model and reduction gear model (where applicable) correspond to the respective design drawings. The diesel engine equivalent model shall be evaluated by confirming that the engine equivalent model complies with engine design particulars (engine type, diameters, location of the timing gear, etc.). Bearing offsets shall be verified to include hot and cold conditions.

3.3 Scope of Calculation

A goal of the shafting alignment calculation is to provide data to the ship production personnel in order to ensure satisfactory alignment under all operating conditions of the vessel (from ballast to full-load). Accordingly, the submitted calculations shall be conducted and verified for:

- Dry dock condition
- Waterborne vessel, hot and cold engine or gear box.

As the alignment procedure starts in the dry dock (positioning of the bearings, slope boring, etc.), the calculation needs to provide sufficient information to the production personnel for the dry dock procedures. It may be beneficial to conduct most of the alignment procedures (sag and gap, and bearing reaction load verification) in the dry dock just before launching of the vessel, as one can take advantage of the fact that the alignment analysis can be quite accurately confirmed for the dry-dock condition, as the alignment is not influenced by hull deflections which are difficult to predict.

Once the vessel is launched, it is also important to evaluate the alignment's sensitivity to hull deflections. In cases where hull deflections are not available (neither analysis of hull deflection nor the measurements from sister vessels are available), the assessment of alignment sensitivity to hull deflections may be attempted by inspecting the influence coefficient matrix (see 2/3.4.1). Since the influence coefficient matrix inspection alone is not sufficient to confirm shafting interaction with the hull structure, some knowledge of the vessel's basic structural data is also needed.

Explanation: At least one analysis shall be provided, considering vessel afloat and hot engine condition. This condition would imply a fully or partially submerged propeller, and must confirm that all bearing reactions are positive and all measured reactions are within reasonable tolerances from their calculated counterparts (see 2/4.7).

Separate analyses are normally provided for the Sag and Gap procedure. Sag and Gap measurements alone shall not be accepted as adequate for alignment acceptance. Sag and Gap analytical data is normally given for dry dock condition. Bearing reactions are often measured after the Sag and Gap procedure is finished and shafting assembled. However, if reactions are measured in the dry dock, at least one additional reaction measurement shall be conducted with the vessel afloat.

Note: The shaft alignment procedure is a part of a static process, thus the analysis shall provide adequate information to support the procedure. Dynamic loading may not be appropriate to apply if the verification is to be conducted under the static condition.

3.4 Results Verification

The verification shall include, but not be limited to the following:

- Influence coefficient matrix
- Bearing reactions
- Deflection curvature
- Stern tube bearing slope boring requirements
- Angular inclination at the main gear wheel
- Shear forces and bending moments
- Allowable loads on all bearings

3.4.1 Influence Coefficient Matrix

The influence coefficient matrix tabulates a relationship among relative reactions in bearings and the unit offset change at each particular bearing (Section 2, Table 1). Accordingly, the influence coefficient matrix can be used to evaluate shafting sensitivity to possible disturbances in the bearing offset and assess changes in the bearing reactions. The disturbances of concern are:

- i) Hull deflections
- ii) Thermal deviations
- iii) Bearing offset adjustment

On the main diagonal of Section 2, Table 1, the influence coefficient matrix also provides information on the gradient of the bearing jack-up curvature. For detailed elaboration on jack-up measurements, see 5/2.1.

3.4.1(a) Hull Deflections. ABS established a method (Section 6 and Section 7) to account for a hull deflection effect on the shafting alignment for several categories of ships (tankers, bulk carriers and container vessels) which will allow designers to estimate hull deflection of those vessels with relatively high confidence. On the vessels where no hull deflection data base is available, the following approach is suggested:

The influence coefficient matrix can be used to assess hull deflection influence on the propulsion shafting. The problem is that the influence coefficient matrix provides information on sensitivity of the shafting, but it gives no indication of the supporting hull structure behavior. Without knowing the deflections of the structure below the shaft line, the propulsion system's behavior cannot really be evaluated. In other words, some relative value or ratio between the stiffness of the shafting and the structural stiffness of the hull structure is needed, as the interaction of the two will define propulsion system behavior; i.e.:

i) *Scenario 1 – Compliant System:* Proportionally rigid shafting and hull:

- If the stiffness of the shafting is proportional to the stiffness of the hull structure, theoretically, it is expected for the shafting to follow the flexing of the hull without changing the alignment condition on the bearings.
- Rigid shafting will have large influence coefficients and will be sensitive to very small deviations in the bearing offsets. However, at the same time, the proportionally rigid hull structure will not disturb bearing offset as the deflections of the stern part of the vessel are also expected to be in the negligible range.

This scenario may be a typical case for a smaller vessel.

ii) *Scenario 2 – Noncompliant Shafting:* Rigid shafting and elastic structure:

This condition is not desired.

- Stiff shafting and a relatively elastic structure will most probably have as a consequence a propulsion system that is highly sensitive to hull deflections.
- Stiff shafting (accompanied with large influence coefficients) will not be able to accommodate relatively large hull deflections and will change reactions significantly as the relatively elastic hull flexes. As the hull bends, the shaft stays relatively undeformed, thus detaching itself from the bearings.

This condition may represent large vessels with very short shafting of a very high power. Arrangements like this, although not desired from the point of view of alignment, are very energy efficient and are most common in VLCC, ULCC and large bulk carrier design.

iii) *Scenario 3 – Compliant Shafting:* Elastic shafting and rigid structure:

This is the desired condition.

- Elastic shafting and a relatively rigid structure will result in a very submissive shafting, which no matter how the hull flexes, remains in contact with the bearings.

If no hull deflection analysis or measurements are available, an engineer can assess structural flexibility through:

- Experience from similar installations
- Basic vessel data (type, length, breath, block coefficient, double/single hull, etc.)

Explanation: Past experience has shown that common propulsion shafting design on VLCCs as well as ULCCs, and similar size bulk carriers of 100,000 dwt and larger, with directly coupled diesel engine propulsion and single propeller have alignments that are very sensitive to hull deflections.

For Scenarios 1 and 3, it is also important to note that even though the shaft remained in contact, the bearing may become damaged if the relative misalignment angle between the shaft and the bearing increases so as to result in edge bearing contact. The edge bearing contact implies a high contact pressure being exerted by the shaft, and a possible dynamic problem as the oil film development may happen at much higher revolutions or not at all in extreme cases.

Moreover, the diesel engine sensitivity to the alignment problem will not change much with vessel design.

A sample influence coefficient matrix, which corresponds to sensitive alignment of a large bulk carrier (per Shaft Alignment Program's Users Manual), is shown in Section 2, Table 1 below.

3.4.1(b) Thermal Deviations. The effect of thermal deviations is typically local. Temperature change affects a particular bearing offset as the structure that the bearing is attached to is exposed to heating or cooling. The influence coefficient matrix can be directly applied as an investigative tool to assess how this local change affects the bearing reactions.

Example: An oil tank, if located beneath the bearing, may cause a local structural deflection which may change the bearing's offset. As the offset changes, the bearing reactions may be adversely affected. This is particularly true in systems where influence coefficients are high.

Temperature changes in the diesel engine and the reduction gear foundation will result in simultaneous offset changes in all of the engine and gearbox bearings. It is often assumed that the thermal condition change will affect all bearings with equal intensity. This is, however, not completely true, as for example, the midsection of the diesel engine will expand more with temperature increase than the forward and after engine structure. One way to compensate for this thermal discrepancy is that a prescribed sagging of the diesel engine bedplate may be applied (see also Subsection 3/5).

3.4.1(c) Bearing Offset Adjustment. Correction of the alignment condition may be necessary when:

- The bearing reaction measurement shows a large deviation from the calculated values, or
- The diesel engine crankshaft deflections do not comply with the engine designer's requirements, or
- Gear tooth contact is smaller than required by the Rules.

The bearing offset is often adjusted at the intermediate shaft bearing(s). This adjustment has a local effect similar to the thermal changes explained above.

The application of the influence coefficients is very significant in cases like these as it can provide a very fast tool to verify the effects of bearing offset adjustment on not only the bearing to be corrected, but also on the adjacent bearings.

3.4.2 How to Read Influence Coefficients

As mentioned before, the influence coefficient matrix tabulates the relationship among relative bearing reactions due to the unit offset change at each particular bearing/support. A sample influence coefficient matrix (per Shaft Alignment Program's Users Manual; Sample Example_01.sha) is shown below:

A sample propulsion shafting system has 12 bearings, one of which (bearing #5) is the thrust (axial) bearing, which is not of particular interest for alignment purposes.

TABLE 1
Influence Coefficient Matrix

RELATIVE BEARING REACTIONS [kN] -> R[0.1-offset]-R[0-Offset]
Due to 0.1[mm] OFFSET relative to the ZERO bearing Offset

Node	Supp.	< 7>	< 14>	< 27>	< 41>	< 45>	< 46>	< 48>	< 50>	< 52>	< 54>	< 56>	< 58>
< 7>	1	4.289	-7.896	4.768	-3.222	0.000	2.120	-0.069	0.014	-0.003	0.001	-0.000	0.000
< 14>	2	-7.896	15.425	-11.112	9.951	0.000	-6.546	0.215	-0.044	0.009	-0.002	0.000	-0.000
< 27>	3	4.768	-11.112	13.421	-25.421	0.000	18.858	-0.618	0.125	-0.025	0.005	-0.001	0.000
< 41>	4	-3.222	9.951	-25.421	166.594	0.000	-250.824	123.820	-25.141	5.104	-1.035	0.202	-0.028
< 45>	5	0.000	0.000	0.000	-0.000	0.000	0.000	0.000	-0.000	-0.000	-0.000	-0.000	-0.000
< 46>	6	2.120	-6.546	18.858	-250.824	0.000	511.825	-379.402	125.081	-25.395	5.148	-1.004	0.141
< 48>	7	-0.069	0.215	-0.618	123.820	0.000	-379.402	461.940	-295.733	108.086	-21.910	4.273	-0.599
< 50>	8	0.014	-0.044	0.125	-25.141	0.000	125.081	-295.733	389.320	-280.955	104.921	-20.460	2.870
< 52>	9	-0.003	0.009	-0.025	5.104	0.000	-25.395	108.086	-280.955	386.156	-279.504	100.648	-14.120
< 54>	10	0.001	-0.002	0.005	-1.035	0.000	5.148	-21.910	104.921	-279.504	381.883	-259.045	69.538
< 56>	11	-0.000	0.000	-0.001	0.202	0.000	-1.004	4.273	-20.460	100.648	-259.045	281.235	-105.848
< 58>	12	0.000	-0.000	0.000	-0.028	0.000	0.141	-0.599	2.870	-14.120	69.538	-105.848	48.046

Each column provides bearing reactions change corresponding to the relating bearing rise of 0.1[mm] at respective bearing (e.g. column #2 are bearing reactions to 0.1[mm] offset at bearing #2)

Support designation for this particular model:

#1 Aft stern tube brg; #2 Fwd. Stern tube brg; #3 Intermediate shaft brg; #4 to #12 main engine bearing;
Brg #5 is axial brg having all coefficients zero.

The larger the influence coefficient number, the more sensitive a particular bearing will be to the offset change at the respective bearing/support.

The relationship between the offset and the reaction load is linearly proportional, therefore, to obtain the same matrix for 1 mm offset change (instead of 0.1 mm as in the case above) all matrix coefficients shall be multiplies by factor 10.

Experience has shown that the shafting model, as shown in this example, represents a propulsion shafting system which is relatively sensitive to the offset variation (hull deflection changes, thermal influence, etc.). Sensitivity of the alignment shall be judged relative to the stiffness of the structure that is holding the bearings. Namely, flexibility of the double bottom structure may be expected to be higher below the intermediate shaft bearings than below the main engine bearings.

The particularly sensitive area to be evaluated is the interface between the shafting and the main engine. The reason for this sensitivity is the sudden change in the stiffness of the supporting structure between the two.

Influence coefficients determined for the engine bearings are very high, which leads to the conclusion that the engine is much more sensitive to bearing offset variations than the shafting. This is a correct statement. However, the structure supporting the crankshaft (engine block) is also of a relatively large degree of stiffness compared to the structure of the double bottom below the shafting. Thus, the engine bearings will not change offset significantly as the structure below them is relatively rigid.

Therefore, even though the influence coefficient factors for the engine bearings are high, the deflections within the engine will be smaller for the shafting. Accordingly, the sensitivity to hull deflections may be lower than for shafting. Similarly, for the shafting where influence coefficients are small, the bearing offset change is expected to be high due to a more flexible double bottom, thus, it may result in higher sensitivity to hull deflections.

Why is the engine still very sensitive to hull deflections? Most of the time, it is not because of the engine itself, but rather because of the discrepancy in stiffness between the engine structure and the double bottom structure below the shafting. This may consequently result in the two aftmost main engine bearings (Section 2, Table 1: #4 and #6) being very sensitive to change in intermediate shaft bearing (Section 2, Table 1: #3) offset deviation (e.g., in Section 2, Table 1, the offset raise of 1 mm at the intermediate shaft bearing would unload M/E bearing #4 for 254 kN, and add an additional 166 kN at bearing #6).

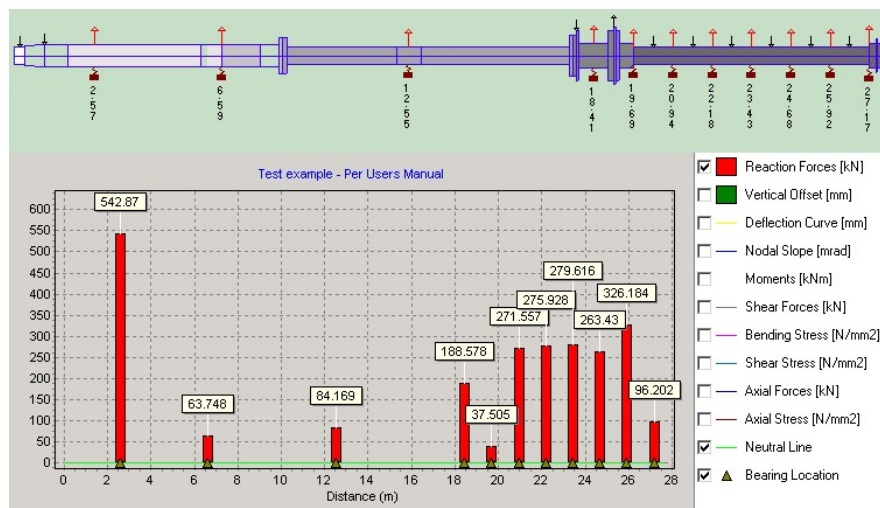
Note: Column 5 and Row 5 of the above influence coefficient matrix (Section 2, Table 1) are all zero because the subject bearing represents the axial (thrust) bearing which reaction is not affected by small changes in vertical offset on any of the bearings in the system.

3.4.3 Bearing Reactions

Satisfactory bearing reactions are one of the primary criteria for alignment acceptance. It is difficult to establish an acceptability margin as the factors influencing reaction load are very difficult to predict accurately. Essentially, alignment is acceptable as long as the bearing reactions are always positive (under all operating/loading conditions) and no bearing is unloaded. Any positive static load is therefore acceptable. However, for practical reasons, at least 10% of the allowable load would be desired on the bearing in order to prevent unloading due to unaccounted-for disturbances.

Reaction loads are not the only criteria that are important for alignment acceptance. Relative misalignment between the shaft and the bearings has at least the same importance.

FIGURE 2
Bearing Reactions



3.4.4 Deflection Curve

Relative misalignment between the bearing and the shaft may be evaluated from information defined by deflection curvature. Deflection curvature defines the angle of the shaft inclination at each node of the system. The angle is measured from the theoretical zero alignment line.

In a case when hull deflections are considered in the analysis, the actual misalignment between the shaft and the bearing should consider:

- Absolute slope on the shaft
- Angular change in the bearing central line due to the hull deflections

For cases where the misalignment angle is found excessive, slope boring or inclination of the bearing may be required.

3.4.5 Slope Boring/Bearing Inclination

Slope boring or bearing inclination is adopted as a marine industry practice to prevent excessive edge loading of the tail shaft bearing.

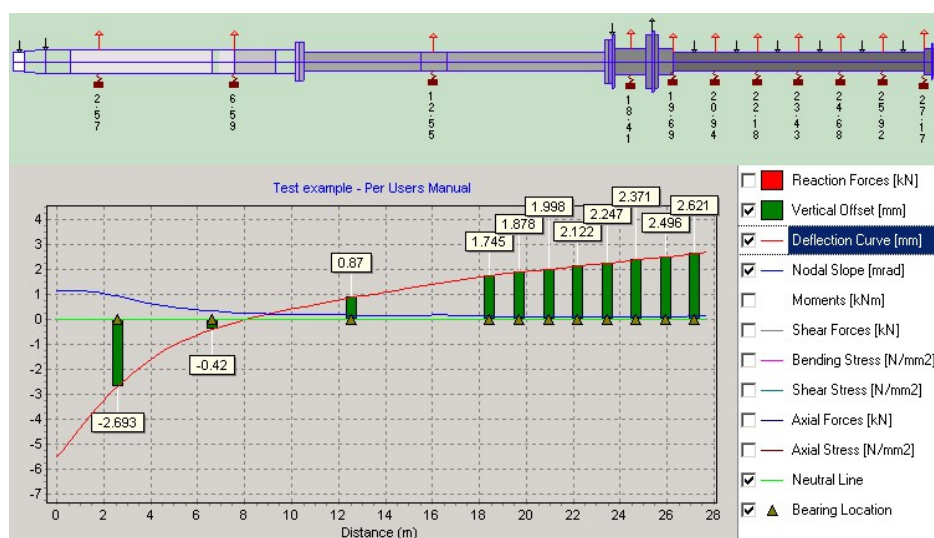
The ABS shaft alignment software provides an interactive routine for tail shaft bearing analysis, which includes slope boring investigation (Section 2, Figure 5).

The industry's rule of thumb for tail shaft bearing slope boring is $0.3 \times 10^{-3} \text{ rad}$. When the misalignment angle exceeds this value, slope boring is normally conducted.

The engineer shall advise the client of a possible excessive misalignment angle and suggest the slope boring if:

- The submitted analysis did not investigate misalignment, or
- Predicted a misalignment slope greater than $0.3 \times 10^{-3} \text{ rad}$.

FIGURE 3
Nodal Slope and Deflection Curve



3.4.6 Angular Inclination at the Main Gear Wheel

In installations with reduction gear, an investigation into the bending curvature and contact condition between the main gear wheel and the pinion is an important part of shaft alignment analysis. More details on reduction gear alignment are provided in 2/4.10.

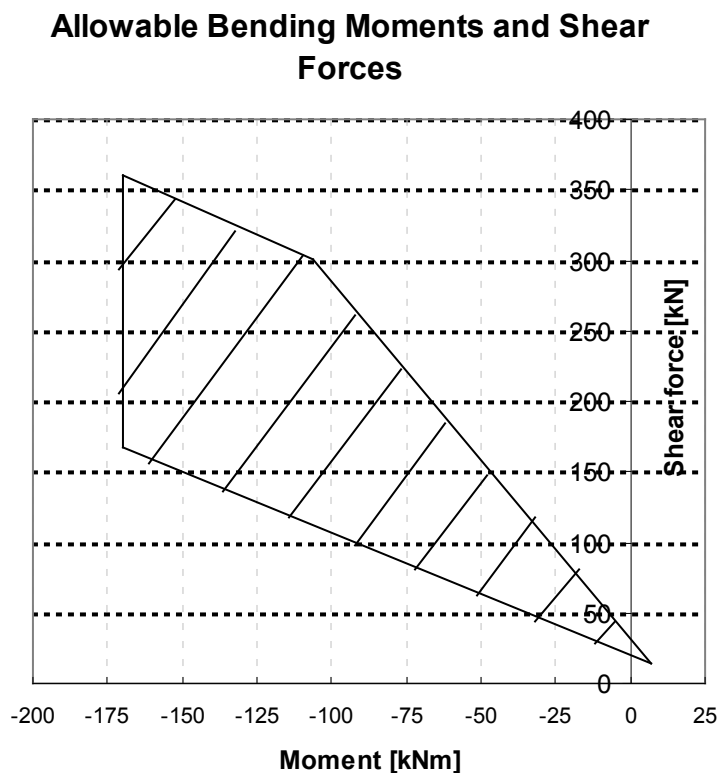
3.4.7 Shear Forces and Bending Moments

Shear forces and bending moments on the shaft should be within acceptable limits, in association with other stresses in the shaft.

Forces and moments on propulsion machinery are to be within the limits specified by the equipment manufacturers.

In addition, some diesel engine manufacturers require bending moments and shear forces at the main engine after flange to be within the required boundaries in order to protect the engine from eventual harmful misalignments (Section 2, Figure 4).

FIGURE 4
Diesel Engine Output Flange Allowable Shear Force and Bending Moment



3.4.8 Allowable Bearing Load

Allowable bearing load is related to the acceptable compressive stress levels within the bearing material. The current ABS Rules provide the stern tube bearing acceptability criteria of 0.8 N/mm^2 for metallic and 0.6 N/mm^2 for oil-lubricated synthetic bearing materials. The acceptability criteria consider compressive pressure estimated from the bearing load over the projected area of the bearing. These criteria may not be sufficient if misalignment between the bearing and the shaft is not kept very low (preventing edge loading). The ABS Shaft Alignment Program provides an interface to analyze the tail shaft bearing static loading condition from the actual contact between the shaft and the bearing.

FIGURE 5
Tail Shaft Bearing Evaluation Program

ABS - Stern Tube Bearing Contact Analysis

Input file: C:\ShA\N\Samples\Example_01\Example_01.brg
Title: Test example - Per Users Manual

Import from ShA Analysis

	Node	Deflection [mm]	Longitudinal Distance[mm]	Bearing Reaction [N]
Alter	6	-2.8051	2457	542870
Middle	8	-2.19777	3157	
Forward	9	-1.69541	3857	704.3

Shaft Dia [mm]

Bearing Data

1400	Length [mm]
2000	Modulus of Elasticity [N/mm ²]
708	Inner Dia [mm]
792	Outer Dia [mm]
0	Inclination [mm/ 1400.0 mm]
0.792636	Misalignment Slope [rad/1000]

Shaft/Bearing Contact Analysis - RESULTS

55292 Contact Area [mm²]
9.81824 Mean Contact Pressure [MPa] Static

Alter Edge Contact Data

0.205615	d1 - Edge Deformation [mm]
222.972	x1 - Axial distance [mm]
157.868	z1 - Radial distance [mm]
55292	2*A1 - Contact Area [mm ²]

No Forward Edge Contact

0	d2 - Edge Deformation [mm]
0	x2 - Axial distance [mm]
0	z2 - Radial distance [mm]
0	2*A2 - Contact Area [mm ²]

3D Model

The 3D model shows a cross-section of the bearing and shaft. Dimensions x1, x2, z1, z2, d1, and d2 are indicated. Contact areas A1 and A2 are highlighted.

3.5 Documenting the Review

The engineer conducting the review of the submitted shaft alignment calculations shall document the results of the alignment review in a format which shall include, but not be limited to, the following contents:

- Descriptions of the propulsion system, including details of:
 - The shafting, reduction gear, equivalent crankshaft model, propeller
 - Masses of all attached equipment (flywheel, turning-wheel, shaft generator, gears, etc...)
 - Location of the permanent bearings, temporary bearings and location of the jacking points for reaction measurements
 - Bearing offset data (hot and cold conditions)
 - External static loads

(Data sources should be provided).

- The review engineer shall verify submitted analyses for:
 - Hot and cold and at least one afloat condition
 - Sag and Gap analysis
- Where deemed necessary, the engineer may apply the optimization routine to investigate the system's sensitivity to introduced disturbance and accordingly evaluate the submitted calculations and prescribed displacements.

The engineer is to comment on eventual differences between the submittal and the check analyses. Comments on significant differences which may affect propulsion installation and ship safety shall be stated in the review letter.

4 Design

4.1 General

When designing the shaft alignment, particular attention shall be paid to the following:

- Stern tube bearing condition
- Crankshaft modeling
- Intermediate-shaft bearing offset adjustment
- Main engine bedplate sag application
- Slope boring concerns
- Sag and gap procedure
- Bearing initial clearance
- Bearing elasticity
- Bearing material
- Gear meshes misalignment

Conditions to be satisfied are primarily:

- Bearing reactions
- Bearing load distribution
- Crankshaft deflections
- Gear meshes misalignment angle

4.2 Stern Tube Bearing

4.2.1 Design

S/T bearing design is significantly different from other bearings in propulsion shafting. The length of the bearing is considerably larger than the journal bearings supporting the intermediate shaft or M/E bearings.

4.2.2 What is Desired

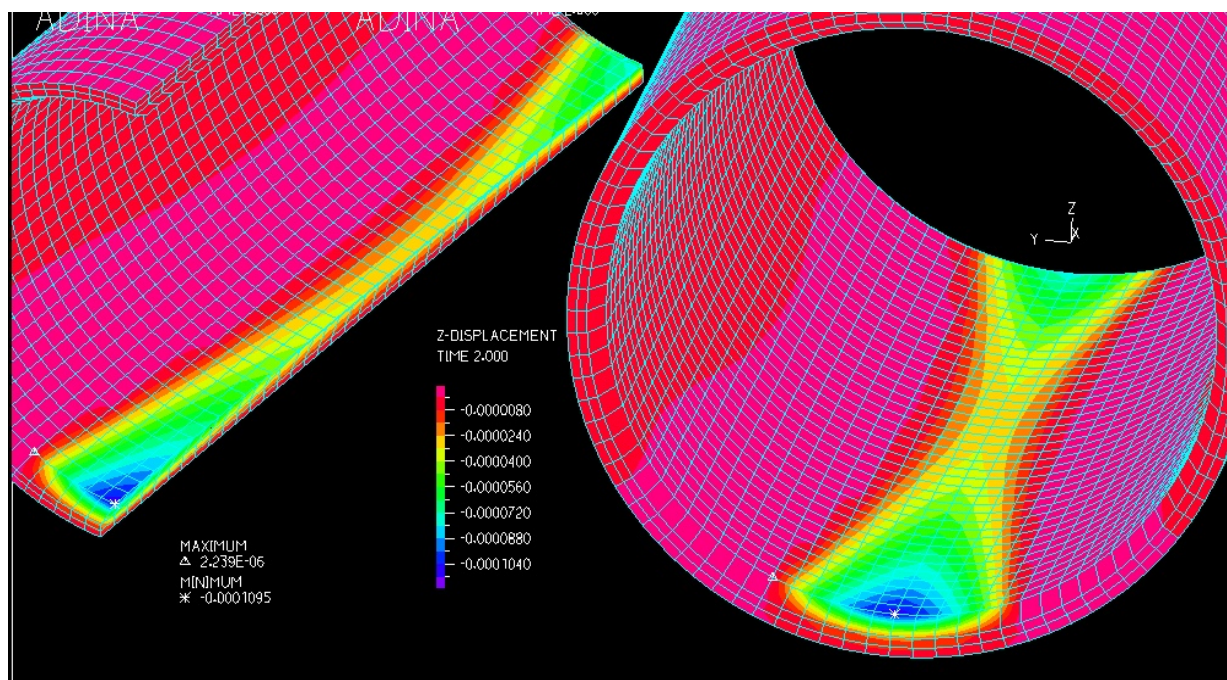
The strut bearing, if installed, or the aft S/T bearing contact pressure in the static condition shall not exceed the stress limit (contact pressure) permitted by the bearing manufacturer. This condition will be best ensured by a low misalignment angle between the shaft and the S/T bearing. The ideal condition is zero misalignment when the shaft is maintaining maximum contact area and minimum contact pressure with the bearing shell (Section 2, Figure 6). Under ideal circumstances, the contact area is symmetrically distributed between the forward and after edge of the bearing. Low angle of misalignment will ensure a larger area of static contact between the shaft and the bearing, smaller contact stress exerted on the bearing from the shaft and faster oil film development, resulting in an extended bearing life.

4.2.3 Class Requirements

The maximum acceptable misalignment between the shaft and the bearing is adopted to be 0.3×10^{-3} rad, which is applied widely as a marine industry practice. If this value is exceeded, the reduction of the misalignment angle is to be considered by slope boring or bearing inclination. The level of safety of this tolerance is not fully explained yet, and this criteria should not be applied blindly. The issue is complex, as the misalignment angle directly influences bearing hydrodynamics, and dynamic analysis with fluid-structure interaction is required (ABS is currently involved in research addressing the bearing dynamics).

The Rule requirement on bearing length is minimum 1.5 times shaft diameter (ABS *Rules for Building and Classing Steel Vessels* 4-3-2/5.15).

FIGURE 6
Ideal Contact Area on the Bearing Exerted by Shaft (Misalignment Angle Zero)



4.2.4 Modeling

The shaft alignment modeling process consists of:

- Finding an adequate bearing offset to suit all operating conditions
- Defining the location of S/T bearing contact point (see 2/4.3)
- Defining the bearing contact area and load
- Accounting for disturbances from hull girder deflection and the thermal expansion of the structure

The contact area between the shaft and the bearing is in direct correlation with the approach taken in the shafting alignment design. As indicated below, three alignment solutions (bearing offsets selection) are analyzed to investigate their impact on the load distribution throughout the S/T bearing. Three different approaches to alignment designs are compared on a diesel engine-driven VLCC installation:

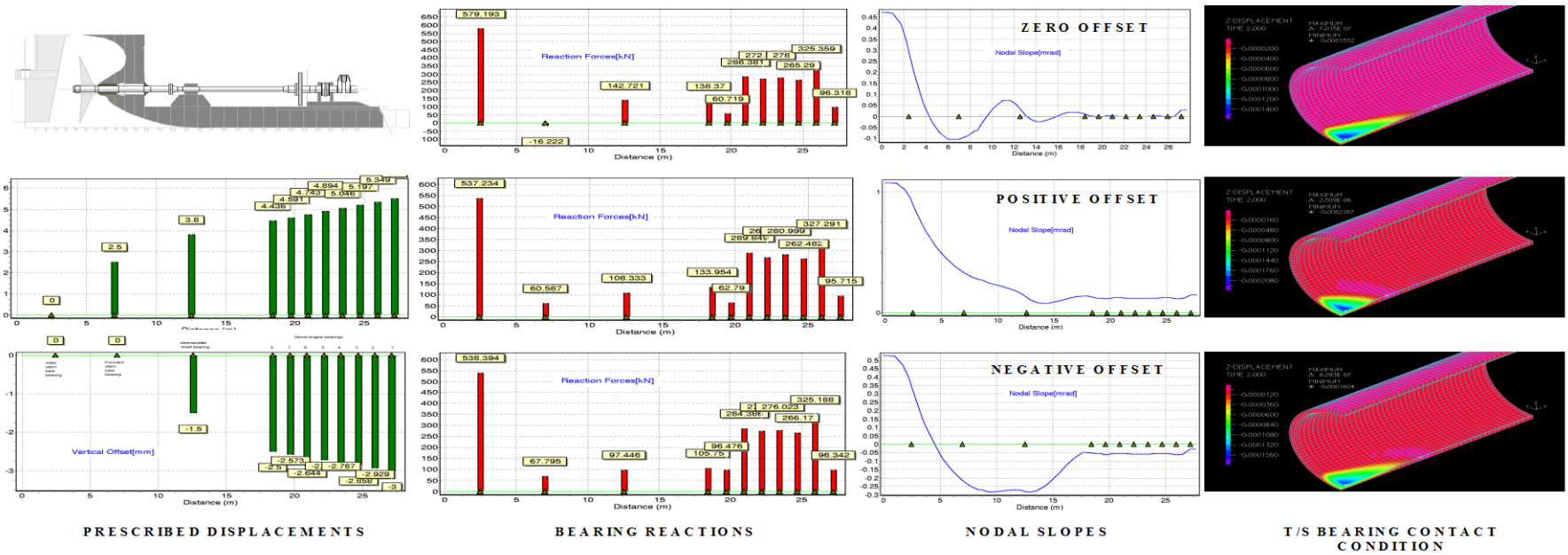
- Zero offset alignment
- Positive offset alignment
- Negative offset alignment

Zero Offset Alignment: Zero offset refers to the position of the bearings which corresponds to ideally straight shafting which centerline is horizontal and undeformed. The results of the alignment analysis conducted with zero offset bearings are often not satisfactory. In the example shown below (Section 2, Figure 7 – row 1), the forward stern tube bearing gets fully unloaded for zero offset. However, the load distribution along the aft stern tube bearing is very good, with a relatively large area of contact between the shaft and the bearing.

Positive Offset Alignment: is characterized by the shafting design where most of the bearings in the system are located above the after stern tube bearing position. The bearing offset should be selected so as to satisfy the alignment criteria. In this example (Section 2, Figure 7 – row 2), the bearing reactions are all acceptable. However, the contact area between the bearing and the shaft is not so good. Relative misalignment slope between the shaft and the bearing is estimated to be 0.855 mrad.

Negative Offset Alignment: is characterized by the shafting design where most of the bearings in the system are located below the after stern tube bearing position. The bearing offset should be selected so to satisfy the alignment criteria. In this example (Section 2, Figure 7 – row 3), the bearing reactions are all acceptable and the contact area is relatively large (approximately twice as large as in the *Positive Offset* approach). Relative misalignment slope between the shaft and the bearing is estimated to be 0.213 mrad.

FIGURE 7
Tail Shaft Bearing Contact as a Function of Alignment Design



4.3 Stern Tube Bearing Contact Modeling

Related topics:

- Bearing elasticity (2/4.8)
- Bearing wear down (2/4.9)
- Bearing wear down survey and inspection (4/2.4)
- Intermediate shaft bearing offset adjustment (Subsection 3/10).

The particular issue which is addressed in this paragraph is modeling of the contact between the shaft and the stern tube bearing. The procedures proposed below are considered to be most appropriate in addressing the problem.

4.3.1 Suggested Procedure

When the ABS Shaft Alignment program is applied, it is suggested that the following approach be undertaken when stern tube bearing contact is modeled:

- i) Model the aft S/T bearing as two point contact with contact points placed at each edge of the bearing.
- ii) Define bearing offsets which satisfy the alignment criteria.
- iii) Conduct new analysis with single point contact by removing the forward contact point.
- iv) The same bearing offsets are applied as for the two point analysis.
- v) Bearing contact condition is evaluated with bearing evaluation interface.
- vi) The after contact point is amended with regard to results of the bearing contact evaluation program.
- vii) Slope boring shall now be defined for this corrected alignment.

4.3.2 Single Point Contact vs. Two Point Contact

In the shaft alignment analysis, the contact between the shaft and the bearing is normally modeled as a single point contact. The contact point represents the position of the assumed bearing reaction. Location of the contact point will define reaction intensity and, even more importantly, the misalignment slope between the shaft and the bearing.

Single point contact modeling is not the only approach, however. The two-point contact is equally valid, but only if the single point contact is verified first and if the slope boring is defined for the single point solution.

When defining an “actual contact point” between the shaft and the bearing, the engineer shall take advantage of the ABS Stern Tube Bearing Evaluation program. The ABS alignment software has the ability to evaluate the contact area and provide relatively accurate prediction of the bearing condition when the shaft does not rotate or rotates at very low speeds (before the oil film develops). With contact information on hand, the designer is able to correct the initially predicted contact point by comparing its location with the “actual” position of the contact point.

With regard to the number of contact points, generally speaking, neither the single nor the two point contact is the correct approach as the bearing-shaft contact is actually established over the area of penetration of the shaft into the bearing. ABS has established a practice to initially assume either the combined approach or the single point contact only. If the ABS software is used, it is suggested that the engineers consider combining the two-point and the single-point approach, where one can take advantage of the S/T bearing evaluation interface. Otherwise, it is recommended that the single point contact approach be undertaken, as well as to consider the contact point at $D/3$ (one third of shaft diameter) distance from the after bearing edge.

On the other hand, if one is applying the ABS shaft alignment software (which also allows bearing contact analysis to be conducted), it is suggested that the designer:

- Take the initial bearing contact at the after edge of the bearing, or $D/3$ from the after edge.
- Evaluate the contact area.
- If necessary, correct the initially estimated bearing location.

The correction of the initial prediction of the bearing contact is recommended if the area of contact is larger than one-third of the shaft diameter. If the analysis indicates contact at both edges of the bearing, the initially applied point of contact should be changed in accordance with the findings. Several iterations may be needed in order to stabilize the results. (Area of contact can be provided when the ABS Stern Tube Bearing Evaluation program is invoked).

Basically, it is desirable to design the alignment and define the slope boring angle for some real condition under which the ship will operate most of its life. Accordingly, when the system is analyzed, two point contact is not desired, as the two point contact will exist only in special cases which will rarely happen in the ship's life. However, the analysis may start from the premise of an ideal alignment, define the bearing offset for it and then verify if this satisfies a more realistic case of shaft-bearing contact (i.e., single point contact). Doing so will also ensure a more realistic slope boring condition and a more preferable load distribution along the bearing length.

Note: Amending the bearing contact position to more accurately represent the actual contact area is particularly important when bearings are of composite material, rubber or wood and where the area of contact is relatively large. The white metal bearings usually have a relatively small static contact area, therefore, if the contact point is set closer to the bearing edge (no more than $D/3$ from the edge), neglecting the correction will result in less influence on the overall results.

The single point contact modeling only (without two point contact verification) is considered an acceptable alternative to the above proposed combined procedure. However, the two point contact modeling without verification of the single point condition is not endorsed.

4.3.3 Example

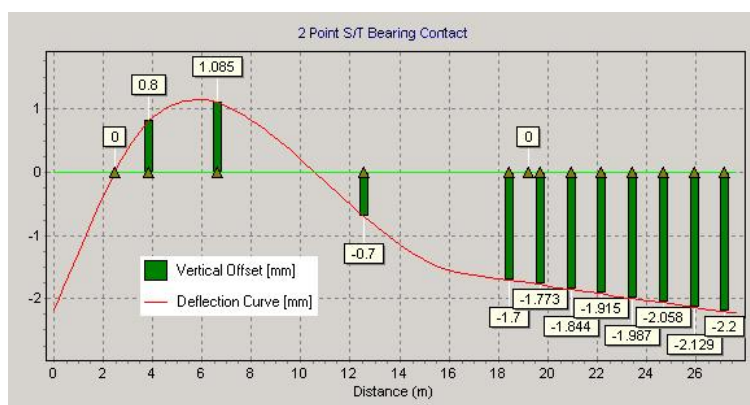
Below, both solutions with single and two point contact approaches have been analyzed and the following procedure is suggested:

1) Two Point Contact

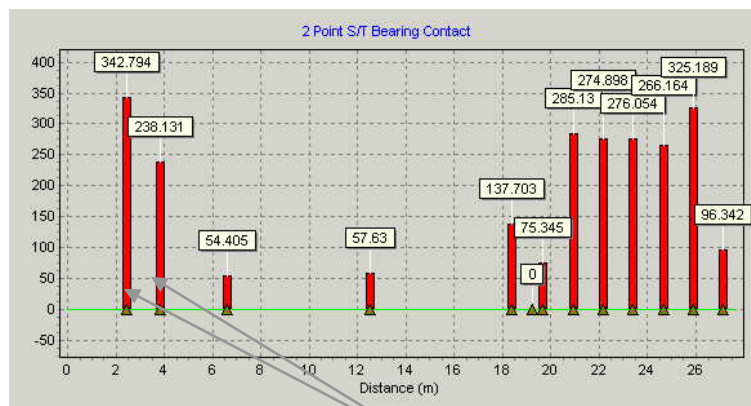
If the two point contact approach is undertaken, it is strongly suggested that it be considered as only a transient case, and the single-point contact is verified to be satisfactory as well.

a) Bearing offset is selected to satisfy bearing reactions.

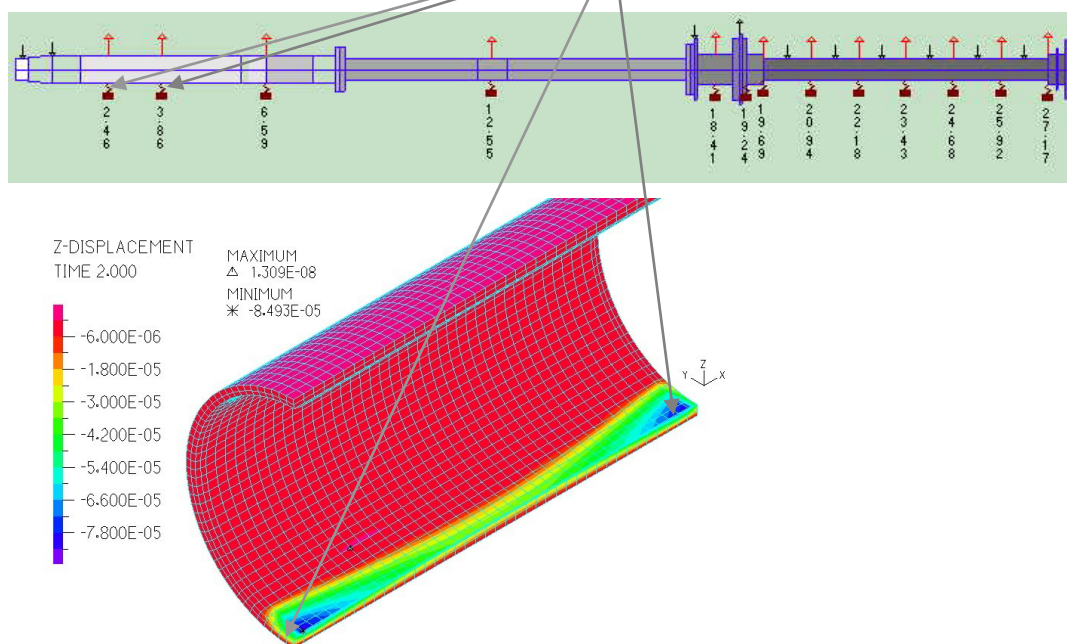
First, it is to be confirmed that selected offset at the bearings complies with the requirements for all positive bearing reactions (in two point contact analysis, misalignment slope is zero).



b) Reactions are verified to be satisfactory.



c) The contact points are selected at the aft and forward edges of the S/T bearing (in this approach, it is not suggested to start with $D/3$ from the edges).

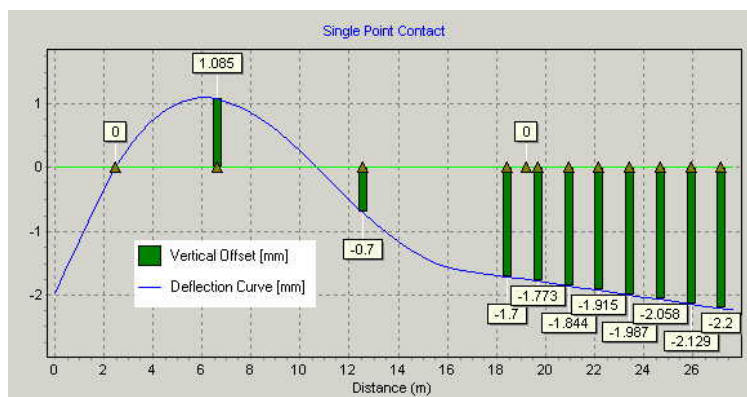


d) Alignment analysis is repeated, considering single contact points.

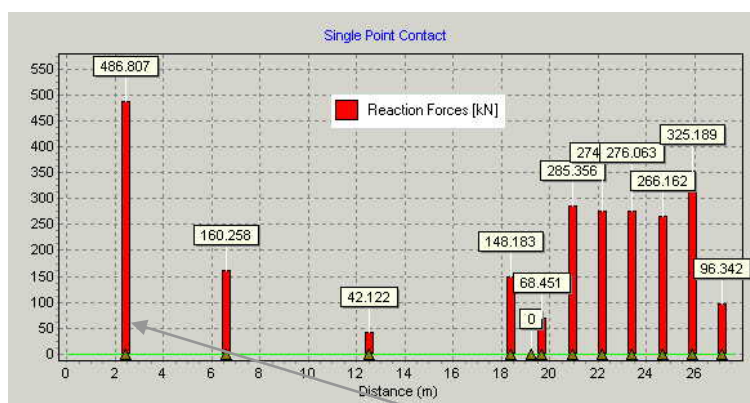
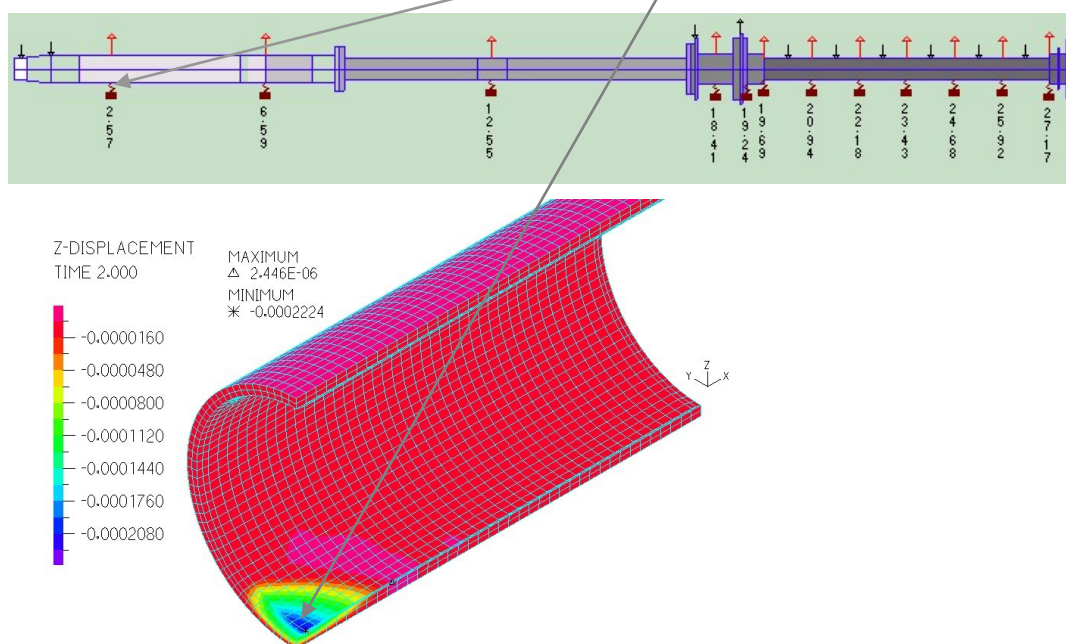
Providing that the above resulted in acceptable solutions, the final step is to remove the front-edge contact point and investigate the single point contact only. If the single contact is not satisfactory, the analysis should not be accepted as valid.

2) Single Point Contact

a) Bearing offset is selected to satisfy bearing reactions.



b) Reactions are verified to be satisfactory.


c) Initially, the contact point is selected at the aft edge of the S/T bearing (or, if desired, at $D/3$ from after edge).


- d) Bearing misalignment angle and contact position is recorded and analyzed.

In the above shaft alignment analysis, the contact between the bearing and the shaft is arbitrarily placed at the aft edge of the bearing.

However, it can be seen from the bearing contact evaluation routine (figure below) that the contact area is established up to 270 mm from the bearing's aft edge (x1-Axial distance [mm]).

ABS - Stern Tube Bearing Contact Analysis

Input file: C:\ShAL_Projects\ArticleHelsinki\NegOff_2ptCont-1Pt.brg

Title: Single Point Contact

Import from ShAl Analysis

	Node	Deflection [mm]	Longitudinal Distance[mm]	Bearing Reaction [N]
After	6	0	2457	486807
Middle	8	0.398454	3157	
Forward	9	0.698842	3857	704.3

Shaft Dia [mm]

Bearing Data

1400	Length [mm]
2000	Modulus of Elasticity [N/mm²]
708	Inner Dia [mm]
792	Outer Dia [mm]
0	Inclination [mm/1400.0 mm]
0.499173	Misalignment Slope [rad/1000]

Shaft/Bearing Contact Analysis - RESULTS

61507.4 Contact Area [mm²]

7.91461 Mean Contact Pressure [MPa]

Static

After Edge Contact Data

0.166385	d1 - Edge Deformation [mm]
270.527	x1 - Axial distance [mm]
144.743	z1 - Radial distance [mm]
61507.4	2*A1 - Contact Area [mm²]

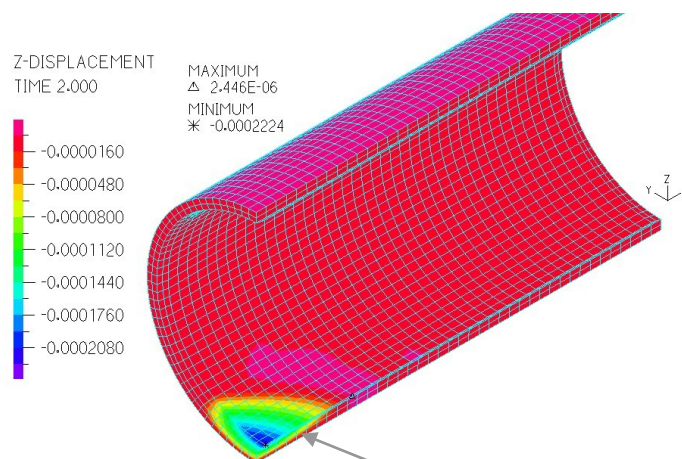
No Forward Edge Contact

0	d2 - Edge Deformation [mm]
0	x2 - Axial distance [mm]
0	z2 - Radial distance [mm]
0	2*A2 - Contact Area [mm²]

3D diagram of bearing and shaft contact showing contact area A1 and A2, and distances x1, x2, z1, z2, d1, d2.

Therefore, it is suggested that the initially assumed contact point be corrected and moved forward.

- e) Alignment analysis is repeated with amended bearing contact point.



The shaft alignment analysis is now conducted with a corrected bearing contact point location, which is now moved 110 mm forward (arbitrarily selected distance approximately half the distance of the contact area). The shaft alignment model needs to be amended, and node is generated as selected.

ABS - Stern Tube Bearing Contact Analysis

Input file: C:\ShAL_Projects\ArticleHelsinki\1Pt_Rec.brg
 Title: Single Point Contact - Rectified in accordance with Bearing evaluation

Import from ShAL Analysis

	Node	Deflection [mm]	Longitudinal Distance [mm]	Bearing Reaction [N]
After	6	-0.0824795	2457	500485
Middle	8	0.349363	3157	
Forward	9	0.671537	3857	704.3

Shaft Dia [mm]

Bearing Data

1400	Length [mm]
2000	Modulus of Elasticity [N/mm ²]
708	Inner Dia [mm]
792	Outer Dia [mm]
0	Inclination [mm/1400.0 mm]
0.538583	Misalignment Slope [rad/1000]

Shaft/Bearing Contact Analysis - RESULTS

60266.8 Contact Area [mm²]
 8.30448 Mean Contact Pressure [MPa]
 Static

After Edge Contact Data

0.174077	d1 - Edge Deformation [mm]
260.168	x1 - Axial distance [mm]
147.47	z1 - Radial distance [mm]
60266.8	2*A1 - Contact Area [mm ²]

No Forward Edge Contact

0	d2 - Edge Deformation [mm]
0	x2 - Axial distance [mm]
0	z2 - Radial distance [mm]
0	2*A2 - Contact Area [mm ²]

Reset Input CALCULATE Exit

Results are as expected: the misalignment angle increased from 0.499 mrad (per analysis with contact point placed at after bearing edge) to 0.538 mrad, thus reducing contact length to 250 mm from the bearing's aft edge (x1 Axial distance [mm]).

It can be concluded from the above analyses that the contact point between the shaft and the S/T bearing plays a significant role in defining the misalignment angle and proposing the slope boring condition. It is suggested that the contact area be investigated for several vessel conditions to ensure the "optimal" slope boring angle is obtained.

4.4 Crankshaft Modeling

Related topics:

- Sag and Gap procedure (Subsection 3/6)
- Applying a partial equivalent model (2/4.5)
- Engine bearing misalignment (2/4.6)
- Alignment measurement, Jack-up method (5/2.1)

FIGURE 8
Crankshaft Outline

