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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GUIDANCE NOTES ON

PROPULSION SHAFTING ALIGNMENT

CONTENTS

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 itself[1].

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.

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[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-coupled[2] 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.

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[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 parameters[3].

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.

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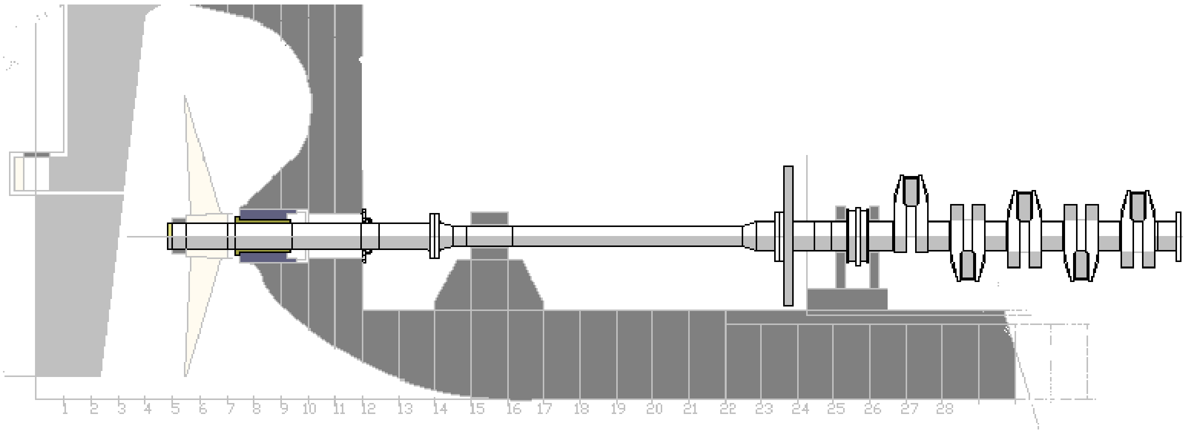
[3] By optimization here, we do not only imply application of a particular optimization tool or software, but also an educated engineering process in combining the design parameter in an acceptable solution which further complies with imposed regulations and requirements.

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 conducing 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.

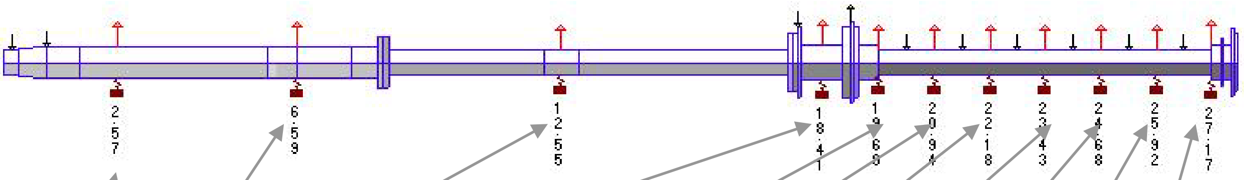
The application of the influence coefficients is very significant in cases like these as it can provide a very fast tool to verify the effects of bearing offset adjustment on not only the bearing to be corrected, but also on the adjacent bearings.

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[0-0ffset]
 Due to 0.1[mm] OFFSET relative to the ZERO bearing Offset
Node      |  <  7>     < 14>     < 27>     < 41>     < 45>     < 46>     < 48>     < 50>     < 52>     < 54>     < 56>     < 58>
     Supp.|    1         2         3         4         5         6         7         8         9         10        11        12
 -------------------------------------------------------------
<  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).

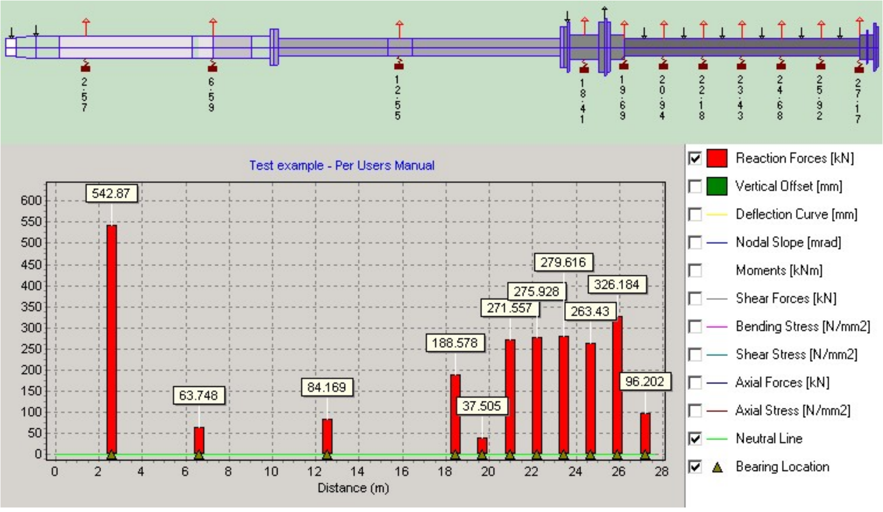
Note: Column 5 and Row 5 of the above influence coefficient matrix (Section 2, Table 1) are all zero because the subject bearing represents the axial (thrust) bearing which reaction is not affected by small changes in vertical offset on any of the bearings in the system.

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



☑ 🟥 Reaction Forces [kN]
☐ 🟩 Vertical Offset [mm]
☐ Deflection Curve [mm]
☐ Nodal Slope [mrad]
☐ Moments [kNm]
☐ Shear Forces [kN]
☐ Bending Stress [N/mm2]
☐ Shear Stress [N/mm2]
☐ Axial Forces [kN]
☐ Axial Stress [N/mm2]
☑ Neutral Line
☑ ▲ Bearing Location

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.

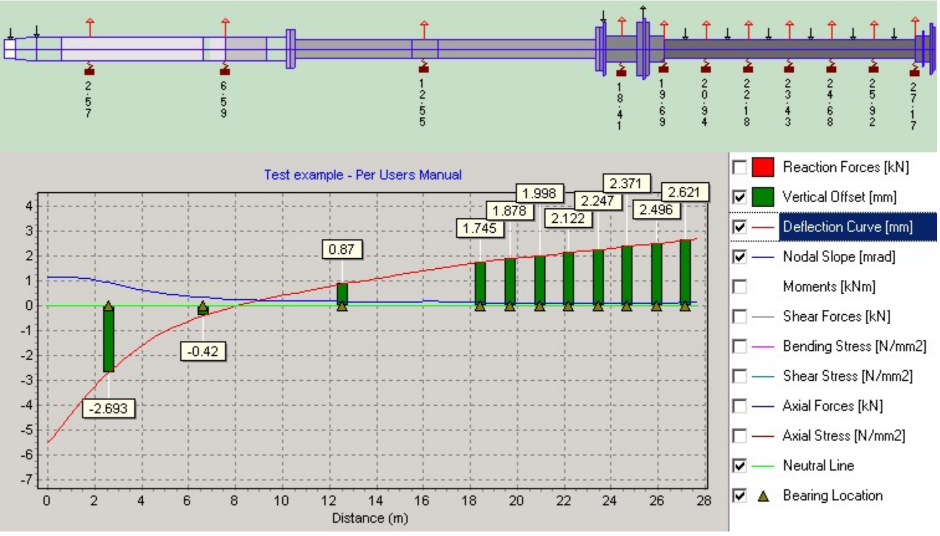
The ABS shaft alignment software provides an interactive routine for tail shaft bearing analysis, which includes slope boring investigation (Section 2, Figure 5).

The industry's rule of thumb for tail shaft bearing slope boring *is* 0.3×10^{-3} *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 0.3×10^{-3} *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.

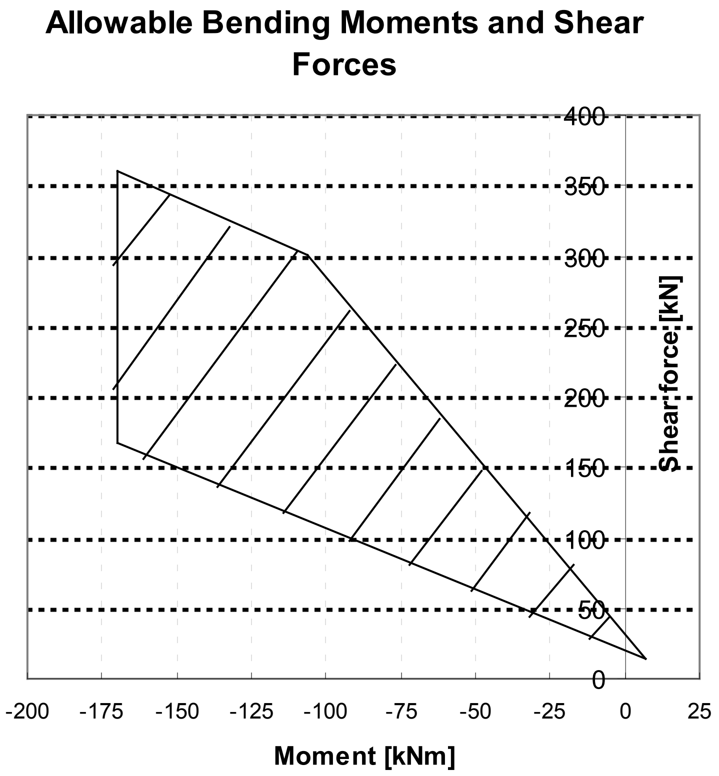
3.4.7 Shear Forces and Bending Moments

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).

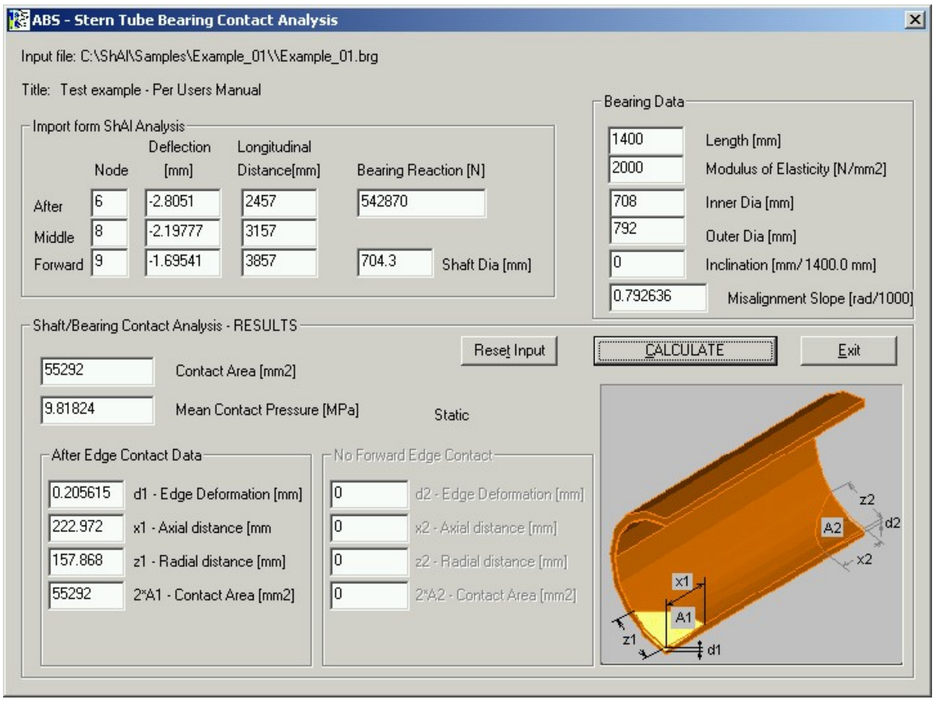
FIGURE 4
Diesel Engine Output Flange Allowable Shear Force and Bending Moment



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:\ShAl\Samples\Example_01\\Example_01.brg

Title: Test example - Per Users Manual

Import form ShAl Analysis

	Node	Deflection [mm]	Longitudinal Distance[mm]	Bearing Reaction [N]
After	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/mm2]
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

After 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 [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]

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

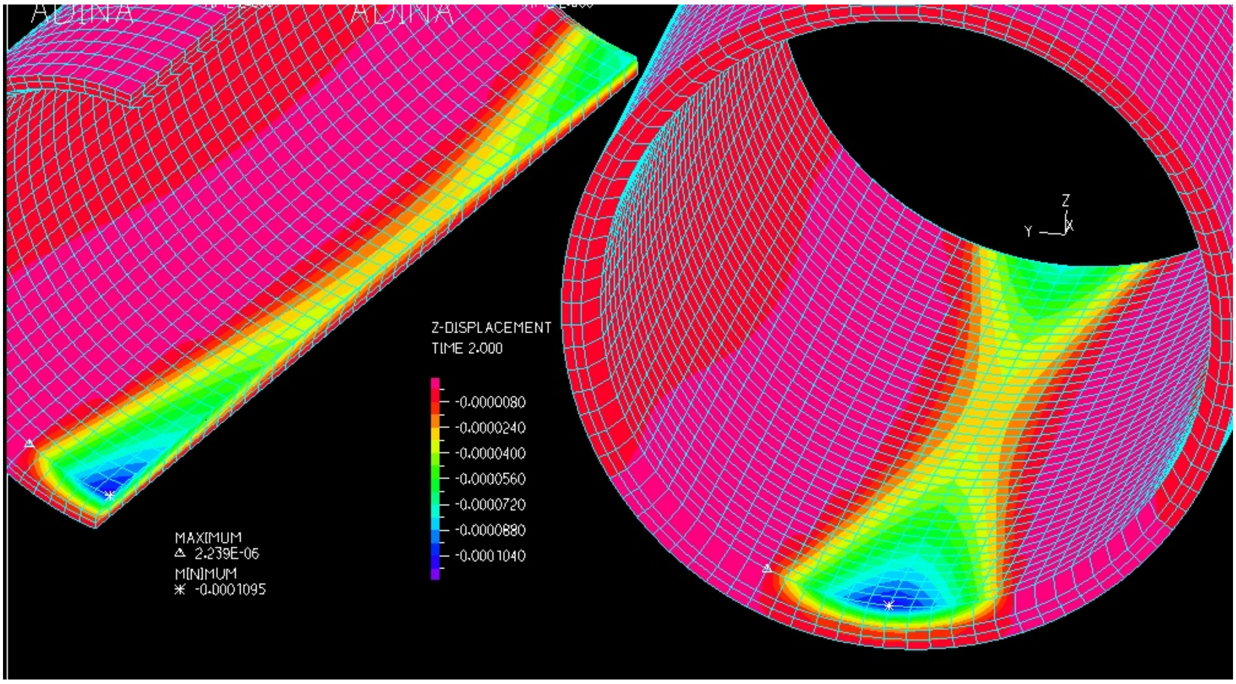
The strut bearing, if installed, or the aft S/T bearing contact pressure in the static condition shall not exceed the stress limit (contact pressure) permitted by the bearing manufacturer. This condition will be best ensured by a low misalignment angle between the shaft and the S/T bearing. The ideal 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 applies 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:

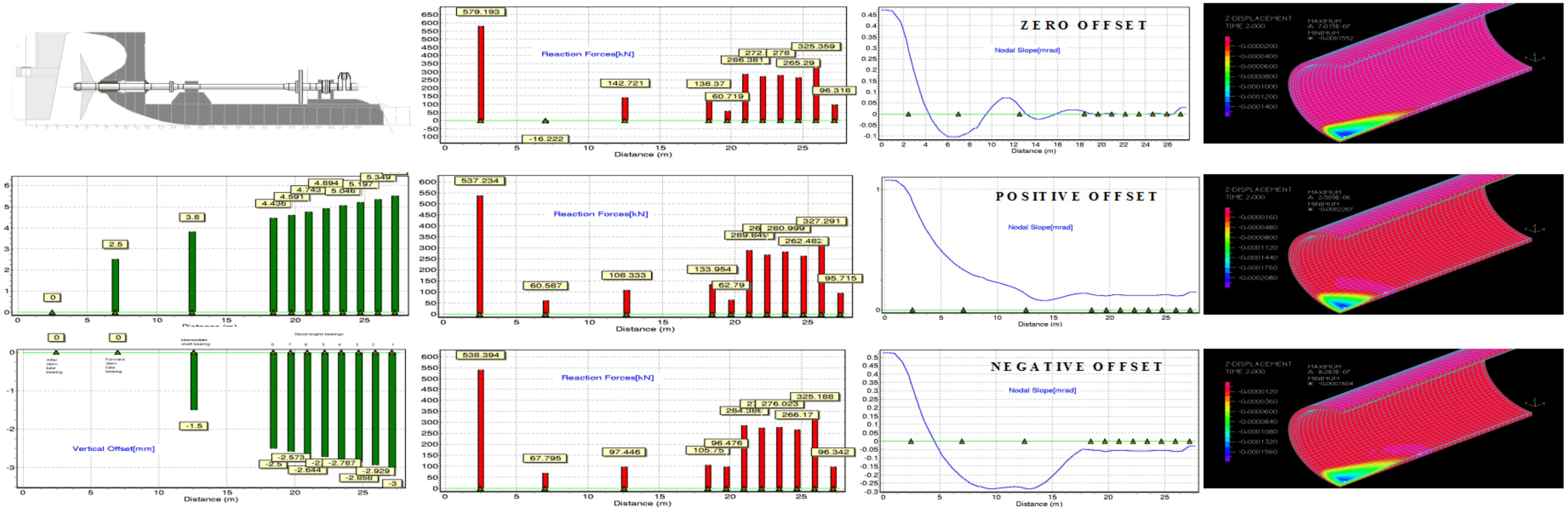
- Zero offset alignment
- Positive offset alignment
- Negative offset alignment

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



PRESCRIBED DISPLACEMENTS BEARING REACTIONS NODAL SLOPES T/S BEARING CONTACT CONDITION

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 then 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 then *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

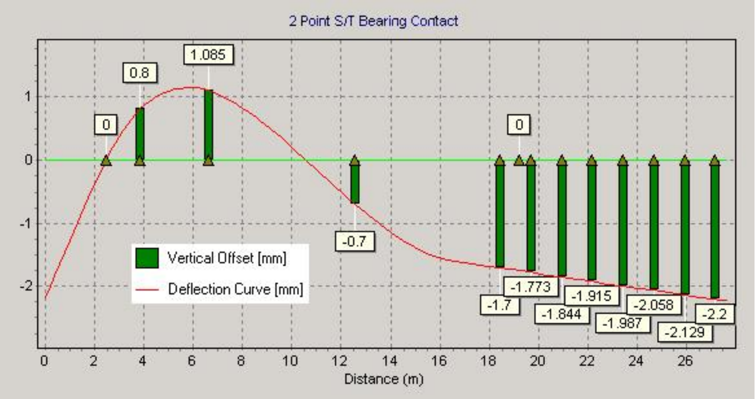
Below, both solutions with single and two point contact approaches have been analyzed and the following procedure is suggested:

1) *Two Point Contact*

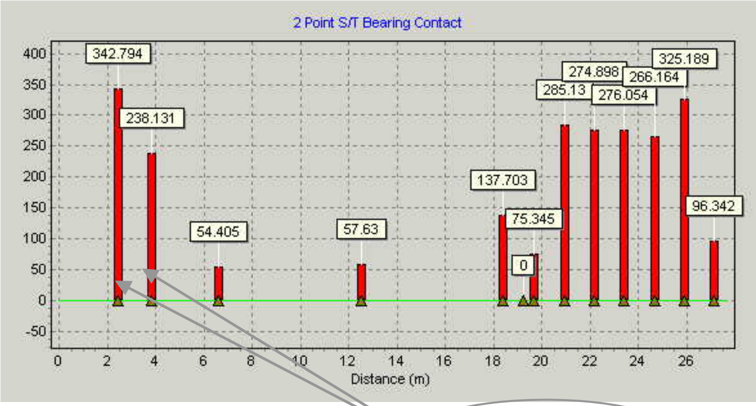
If the two point contact approach is undertaken, it is strongly suggested that it be considered as only a transient case, and the single-point contact is verified to be satisfactory as well.

a) Bearing offset is selected to satisfy bearing reactions.

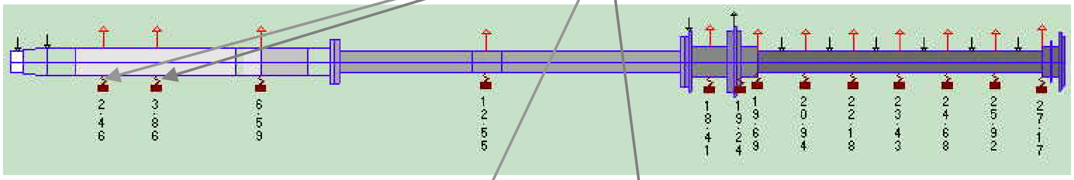
First, it is to be confirmed that selected offset at the bearings complies with the requirements for all positive bearing reactions (in two point contact analysis, misalignment slope is zero).

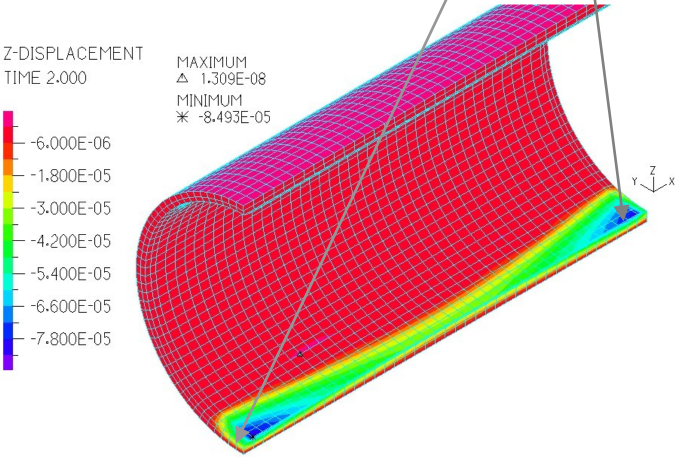


b) Reactions are verified to be satisfactory.



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).



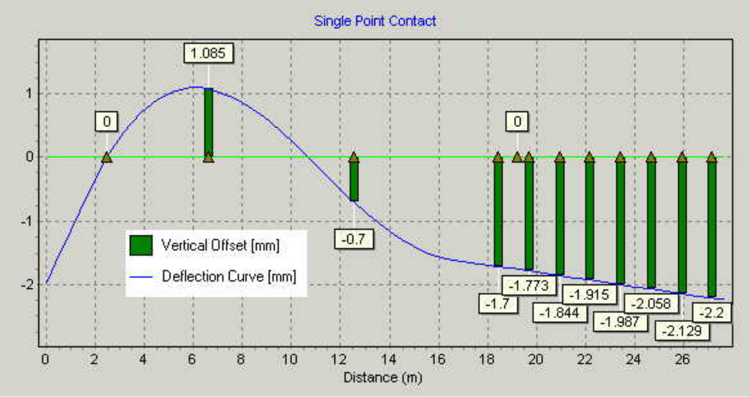


d) Alignment analysis is repeated, considering single contact points.

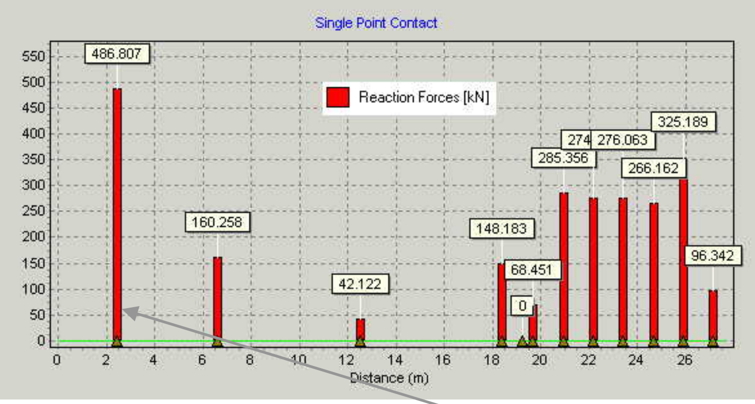
Providing that the above resulted in acceptable solutions, the final step is to remove the front-edge contact point and investigate the single point contact only. If the single contact is not satisfactory, the analysis should not be accepted as valid.

2) *Single Point Contact*

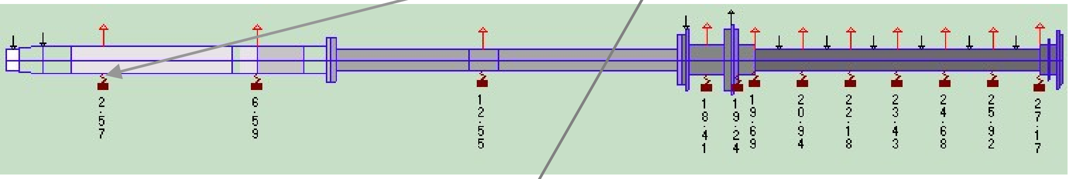
a) Bearing offset is selected to satisfy bearing reactions.

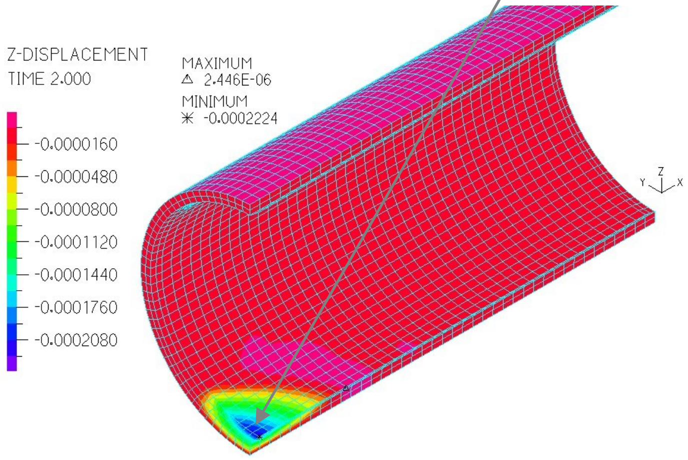


b) Reactions are verified to be satisfactory.



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).

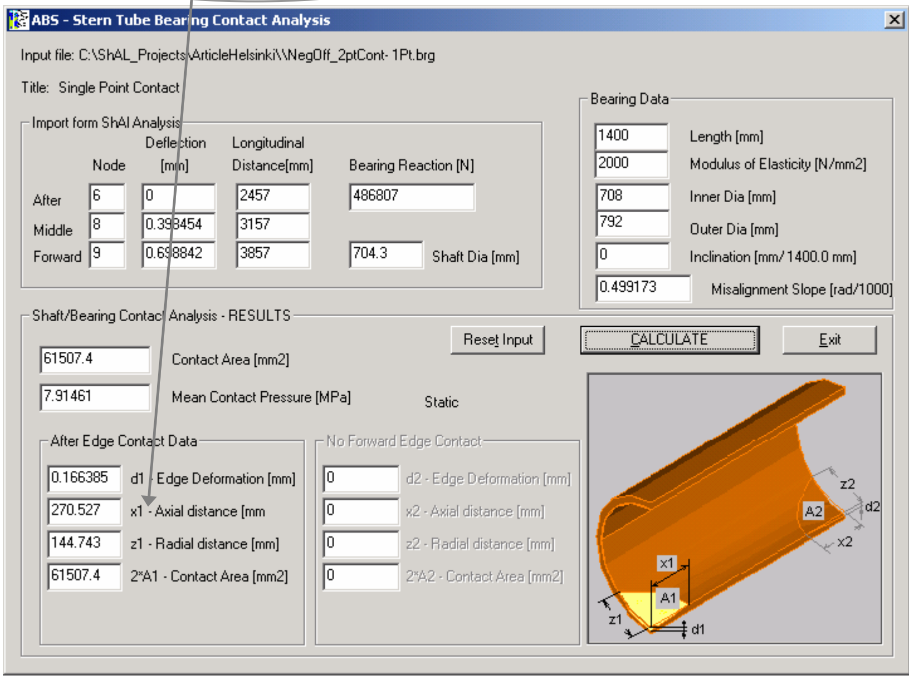




d) Bearing misalignment angle and contact position is recorded and analyzed.

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]).



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

Title: Single Point Contact

Import form 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

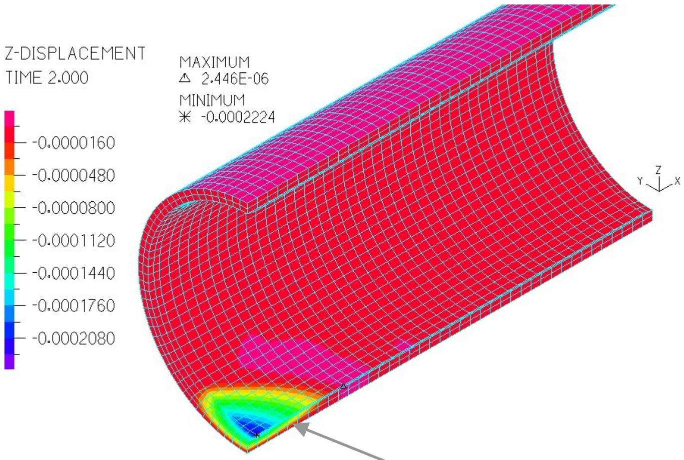
0.166385	d1 - Edge Deformation [mm]
270.527	x1 - Axial distance [mm
144.743	z1 - Radial distance [mm]
61507.4	2*A1 - Contact Area [mm2]

No Forward Edge Contact

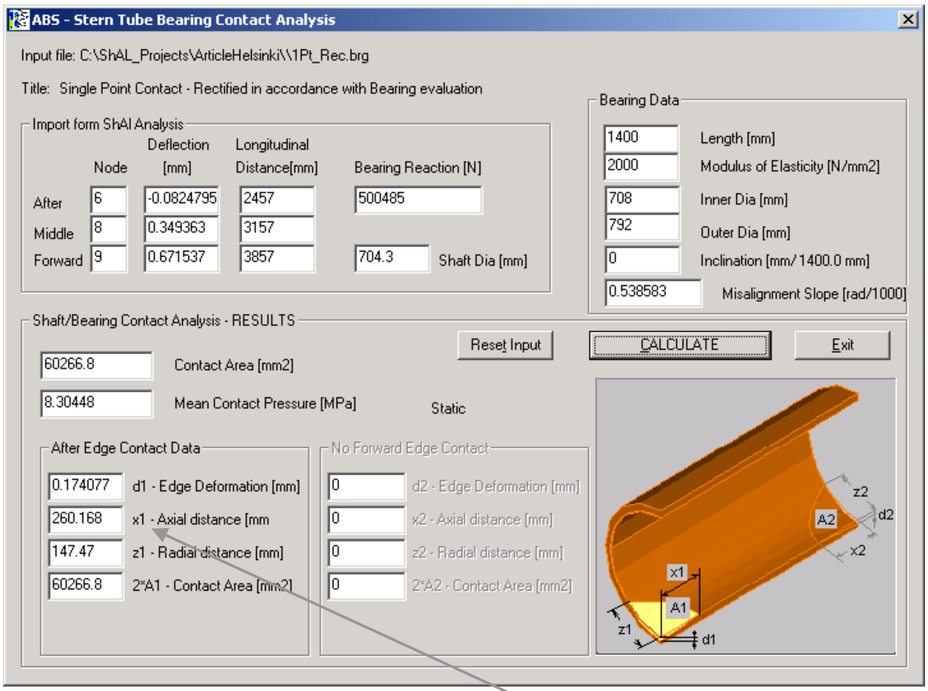
0	d2 - Edge Deformation [mm]
0	x2 - Axial distance [mm]
0	z2 - Radial distance [mm]
0	2*A2 - Contact Area [mm2]

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 form 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/mm2]
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 [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]

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]).

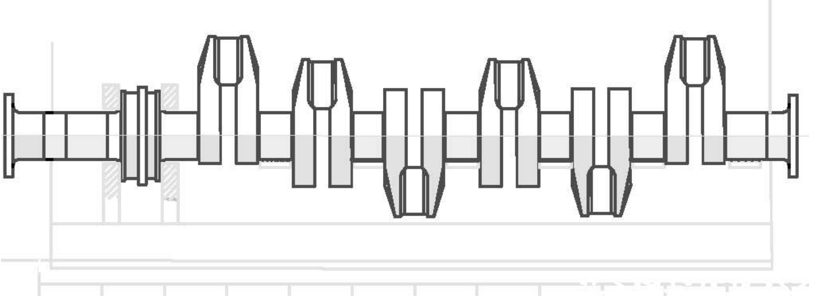
It can be concluded from the above analyses that the contact point between the shaft and the S/T bearing plays a significant role in defining the misalignment angle and proposing the slope boring condition. It is suggested that the contact area be investigated for several vessel conditions to ensure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



The crankshaft modeling is a particularly sensitive and sometimes controversial issue, as explained below.

Bearings of the large two-stroke cross-head diesel engines are sensitive to alignment condition, and the occurrences of alignment-related diesel engine bearing damages and failures are becoming more common, primarily as the result of the following:

- The engine bearings' proximity
- Relatively flexible engine structure itself
- The complexity of the crankshaft design (Section 2, Figure 8)

Particular attention should be paid to the crankshaft model when alignment is designed, and the first step to ensure quality alignment is to derive the accurate equivalent crankshaft model. However, defining an accurate crankshaft model is not without difficulties.

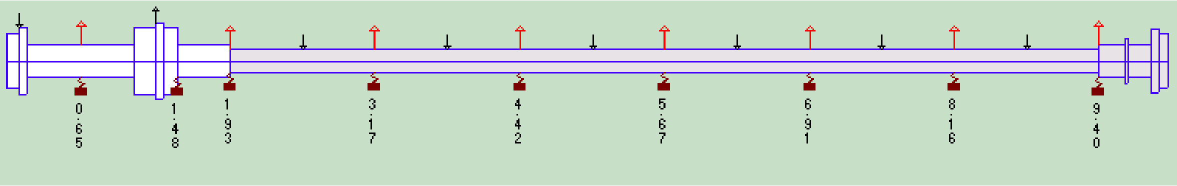
The problem in modeling of the engine crankshaft for shaft alignment purposes is in defining an accurate equivalent system for crankshaft cranks. The cranks are of complex shape, and in big engines, the cranks have significant flexibility which cannot be neglected.

The appropriate modeling would be a full-scale 3-D finite element (FE) model which, however, is not suitable for commercial shaft alignment analysis.

A possible solution to the modeling problem is to define an equivalent system consisting of an appropriate number of straight shaft segments, which will behave identically to the actual cranks under the bending load (Section 2, Figure 10 and Section 2, Figure 11).

Namely, the equivalent model shall result in the same bending deflections in the middle of the crank-pin as the real crank would. The difficulty that is now faced is that the crankshaft changes its angular position, and as it happens, the same load[4] acting on the particular crank pin will not result in the same bending deformation for different crankshaft angles. Moreover, the effect of the adjacent crank throws has to be considered as well. A different angular position of the crankshaft will redistribute the crank-mechanism load throughout the cranks.

FIGURE 9
Crankshaft – Equivalent Model for Shaft Alignment



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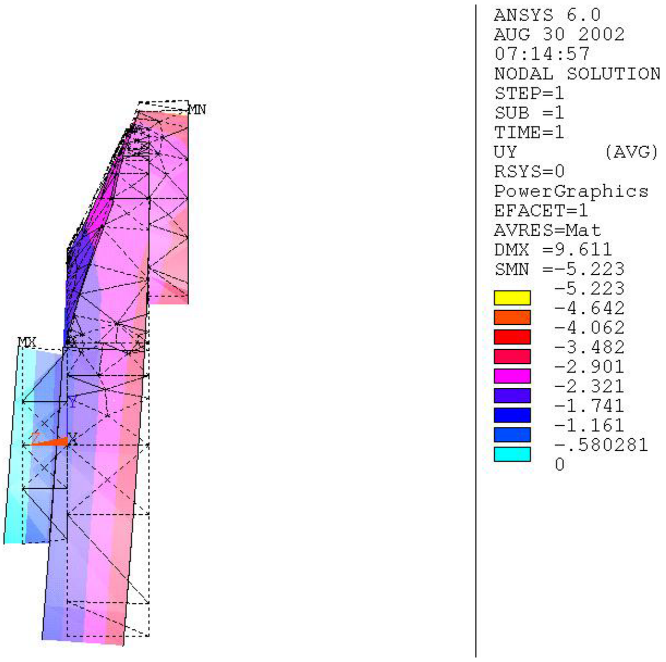
[4] Actual load on the crank-journal may not remain the same as the crankshaft changes its angular position. Friction in cylinder and cross-head mechanism may reduce the load as well.

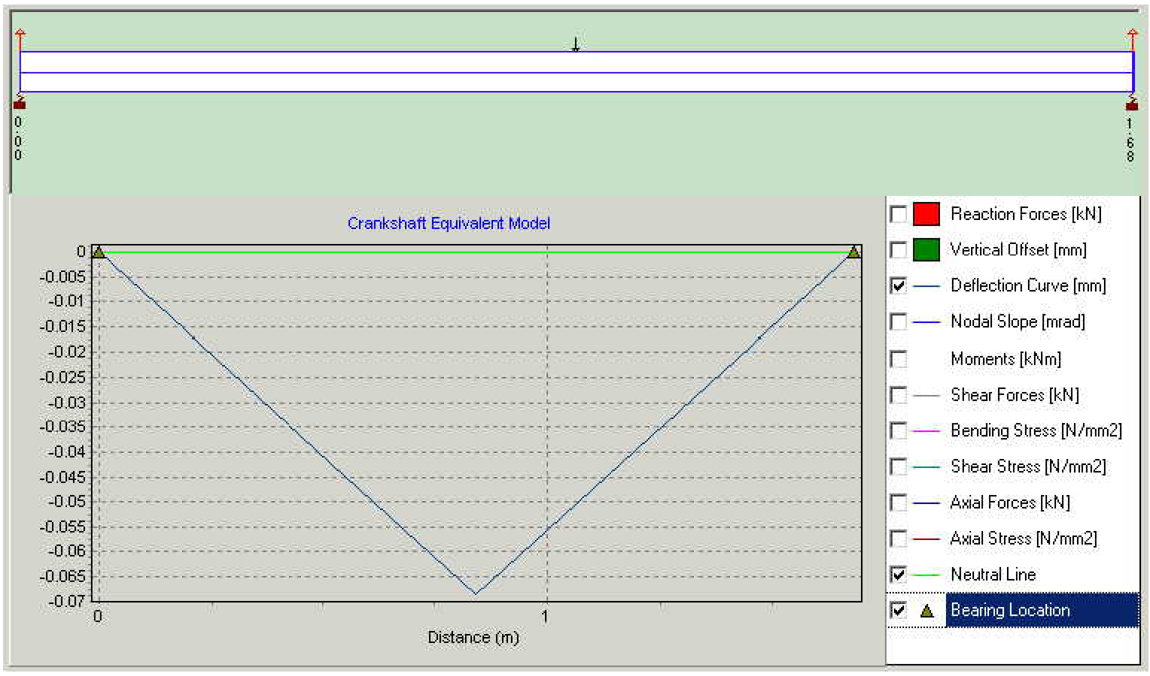
FIGURE 10
FE Model of Half of the Crank



Note: Section 2, Figure 10 shows only half of the single crank 3-D FE model which will not provide an accurate equivalent model. Whole crankshaft modeling will be necessary to establish interaction among cranks.

Moreover, crankshaft equivalent stiffness will vary with the relative angular position of the crank.

FIGURE 11
Defining Equivalent Model



☐ 🟥 Reaction Forces [kN]
☐ 🟩 Vertical Offset [mm]
☑ Deflection Curve [mm]
☐ Nodal Slope [mrad]
☐ Moments [kNm]
☐ Shear Forces [kN]
☐ Bending Stress [N/mm2]
☐ Shear Stress [N/mm2]
☐ Axial Forces [kN]
☐ Axial Stress [N/mm2]
☑ Neutral Line
☑ ▲ Bearing Location

Example: When cylinder No. 1 is in the TDC, the bending deflections of the node in the middle of the crank journal will be different than for the 90º crank throw position. The consequence will also be different bearing reactions for a different crankshaft angular position. How large the difference in deflections and in reactions will be will depend on the particular crankshaft's design.

Note: The variation of the bearing reactions due to the stiffness variation of the crankshaft as the crankshaft's angular position changes from 0º– 360º (for further information, refer to 5/2.1) is normally expected to be:

- up to 10% at the two aftmost M/E bearings
- up to 20% on the bearings within the engine

From the above discussion, it appears that the issue of the crankshaft modeling is fairly complex. There is a simple solution, as given below:

- First of all, be aware of the constraints that the simplified crankshaft modeling imposes.
- Always consider the error that the simplified analytical model may result in.
- Verify those analytical cases where bearing reactions are low by M/E bearing reaction measurements. The bearing reactions are deemed low if the 10 – 20% change in reaction on the adjacent bearing may result in the particular bearing unloading.

4.5 Applying a Partial Equivalent Model of the Crankshaft

Related topics:

- Sag and Gap measurement (Subsection 5/7)
- Crankshaft modeling (2/4.4)

When the partial modeling of the crankshaft is applied, only the few aftmost crankshaft bearings are considered in the alignment analysis. Sometimes the crankshaft model is reduced to as little as two bearings, and in some cases, even the load from the crank mechanism is completely neglected. With a stripped crankshaft model like this, it is obvious that the alignment designers completely excluded the diesel engine from the alignment evaluation and concentrated only on the shafting. The adopted crankshaft model serves only to minimize the error in reaction evaluation on the foremost line shaft bearings.

The question here is whether such a modeling should be acceptable. It is not recommended because experience shows that the consequences of not evaluating loading condition for at least the two aftmost M/E bearing (which require a crankshaft model of a minimum of four bearings) may eventually result in damage to the engine and costly resource engagement from all involved parties. Consequently, if the modeling of the engine is reduced to the bare minimum, it is only coincidental that the M/E bearings ended up one way or another.

Summarizing the above:

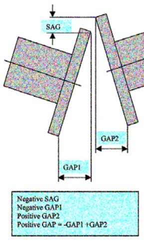
- The equivalent model, even when it represents the full crankshaft, cannot provide completely accurate information of M/E bearing loading (it was mentioned in the previous Paragraph that the bearing reaction estimate error may be up to 20% at the two aftmost M/E bearings).
- However, even if the information on the load condition is not completely accurate, the error margin is still within the acceptable limits to evaluate engine bearings correctly. Normally, the primary interest would be in the several aftmost M/E bearings only, as those can be affected by the intermediate shaft bearing position adjustment.
- If the model is reduced to less then four bearings, and particularly when no load is accounted for, the result of the bearing reactions, as well as the Sag and Gap data, will most likely be inaccurate.

4.5.1 Example

The partial crankshaft modeling (Section 2, Figure 12 and Section 2, Figure 13) may result in incorrect prediction of the crankshaft aft-flange sagging. The calculation accuracy may be particularly affected when the model includes less then four bearings and when load acting on the flange and aftmost crank-journals are not taken into account.

- Difference in estimated sags is 0.03 mm
- Difference in estimated gaps is 0.067 mm

FIGURE 12
Reduced Crankshaft Model – 2 M/E Bearings Only



Reduced crankshaft model
Sag and gap @ int-M/E flange:
SAG = -1.2616
Gap1 = -1.2228
Gap2 = 0.0166
Gap1 + Gap2 = 1.2394 (below flange)
Aftmost M/E bearing reaction: 173.7 [kN]

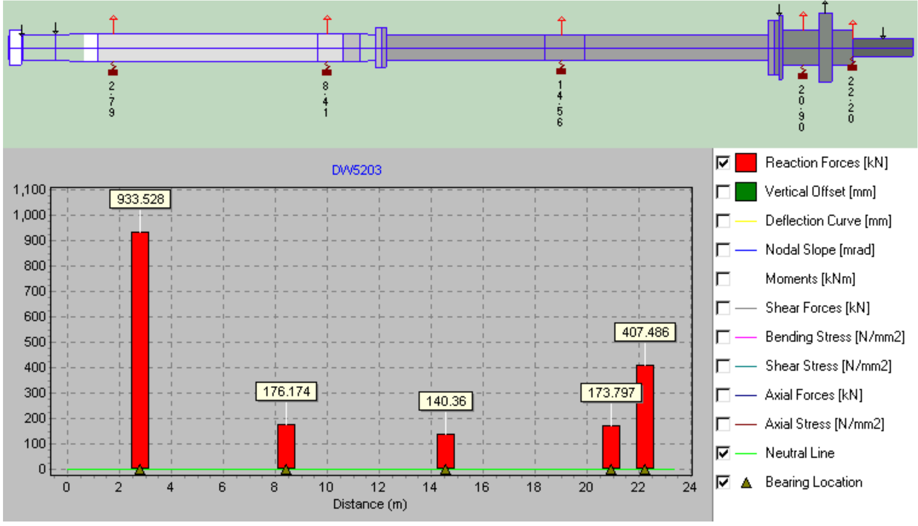
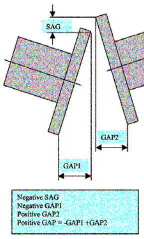
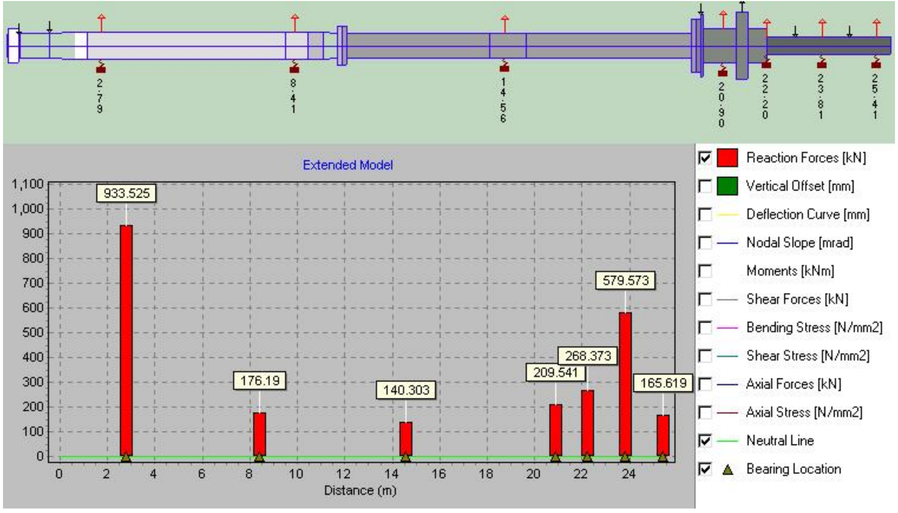


FIGURE 13
Reduced Crankshaft Model – 4 M/E Bearings



Extended model crankshaft
Sag and gap @ int-M/E flange:
SAG = -1.2301
Gap1 = -1.2228
Gap2 = 0.0832
Gap1 + Gap2 = 1.3060 (below flange)
Aftmost M/E bearing reaction: 209.5 [kN]



The Sag and Gap is a procedure conducted prior to the shafting assembly (Subsection 5/7). It consists of measurements of sags and gaps between mating flanges and verification of the system's compliance with calculated data. However, if Sag and Gap is erroneously defined, the yard will not be able to comply with requirements without readjusting offset of one or more bearings. By doing so, the system's alignment will be incorrectly conducted from the very beginning with very small possibility of rectifying it.

Actual Sag and Gap values are expected to be similar to the results of the second model with extended crankshaft. However, if the crew conducting the alignment is given the data as per the first model, the alignment, which may actually be correct, will be adjusted to the incorrect Sag and Gap values. As the adjustment is normally conducted by changing the intermediate-shaft bearing offset, the consequence (after the shafts are assembled) will be bearing reactions which do not match the analytical predictions.

Note: Although ABS does not endorse the Sag and Gap as an accurate method in the shaft alignment procedure, and would not advise any alignment rectification be conducted based on the Sag and Gap readings, the same method is still in use in the industry and the subject example is therefore presented here to warn of possible problems that may arise from its application.

4.6 Engine Bearing Misalignment

Related topics:

- Diesel Engine Alignment (Subsection 3/11)
- Intermediate Bearing Offset Adjustment (Subsection 3/10)
- Crankshaft deflection measurement (Subsection 5/5)
- Diesel engine bearing reaction measurement (Subsection 5/2)

It may be difficult to analytically predict the engine bearing misalignment condition with the commercial shaft alignment software. However, a possible bearing unloading inside of the main engine can be predicted, and then awareness of the misalignment possibility can be raised.

Again, it is to be noted that the crankshaft modeling (that most commercial shaft alignment software applies), may result in 10% to 20% error in reaction prediction. Accordingly, the same error will exist in predicting the possible misalignment between the crankshaft journal and the M/E bearing.

The engine bearing unloading and the possibility of the misalignment between the bearing and the crankshaft are further addressed in Subsection 3/11, where an example is given of the problems that may be expected in cases where the bearing condition is not recognized in time and corrective actions are not undertaken.

Main engine bearing misalignment is normally not a problem in diesel engines. However, in cases when any of the bearings get unloaded, the most likely scenario to expect is that the adjacent bearings will be damaged due to the misalignment and the edge loading problem, rather than the one that is unloaded.

The reason for possible M/E bearing edge loading is almost solely because of disturbances coming from the shaft line. There are probably rare occasions where the internal engine misalignment itself may cause the bearing unloading.

4.7 Bearing Clearance

Related topics:

- Crankshaft modeling (2/4.4)

In some alignment designs (for example, VLCC vessels) when hull deflections are initially accounted for, the second aftmost main engine bearing may be intentionally unloaded when alignment is conducted in the dry dock or when the vessel is at very light ballast. This unloaded bearing condition is expected to be rectified as the vessel becomes exposed to additional hull deflections once it gets loaded. Neglecting bearing clearance may result in negative bearing reactions on the bearings which would otherwise be unloaded. As a consequence, false information will be provided for bearing condition verification (reaction measurements). Moreover, when Sag and Gap is calculated, if any of the main engine bearings are unloaded and no clearance is taken into consideration, the Sag and Gap data will be mistakenly obtained (see 2/4.4).

On smaller vessels where the shaft is supported in roller bearings, negative bearing reactions are possible and shall be considered.

4.8 Bearing Elasticity

Related topics:

- Stern tube bearing contact modeling (2/4.3)

In the static condition, bearing elasticity will depend on the contact area between the shaft and the bearing. Therefore, the bearing stiffness will not be simple to define, as it is not solely related to the material property and the load, but is also a function of the constantly changing contact area. The contact area will change with bearing load redistribution. Load redistribution may result mainly from external disturbances such as:

- Hull deflections, and/or
- Thermal effects on the bearing offset

As the bearing offset changes with external disturbances, the misalignment angle between bearing and the shaft will also be affected. This will consequently result in a changed contact area between the shaft and the bearing. The shaft's sagging into the bearing will be proportional to the area of contact.

In real life, the shaft finds its static equilibrium immediately. In analytical modeling, it is necessary to find the equilibrium solution which will need to balance load at the bearing, the misalignment angle, the contact area and the shaft's penetration into the bearing. Although it is possible to find the solution analytically, it is not worth the effort. The simpler way is to apply an iterative process. A number of iterations are applied until the stable bearing reactions for the respective contact area are obtained.

It is left to the designer's judgment whether it is necessary to conduct the iteration. If the decision is taken to perform the iteration, the following procedure is suggested when the ABS shaft alignment program is utilized:

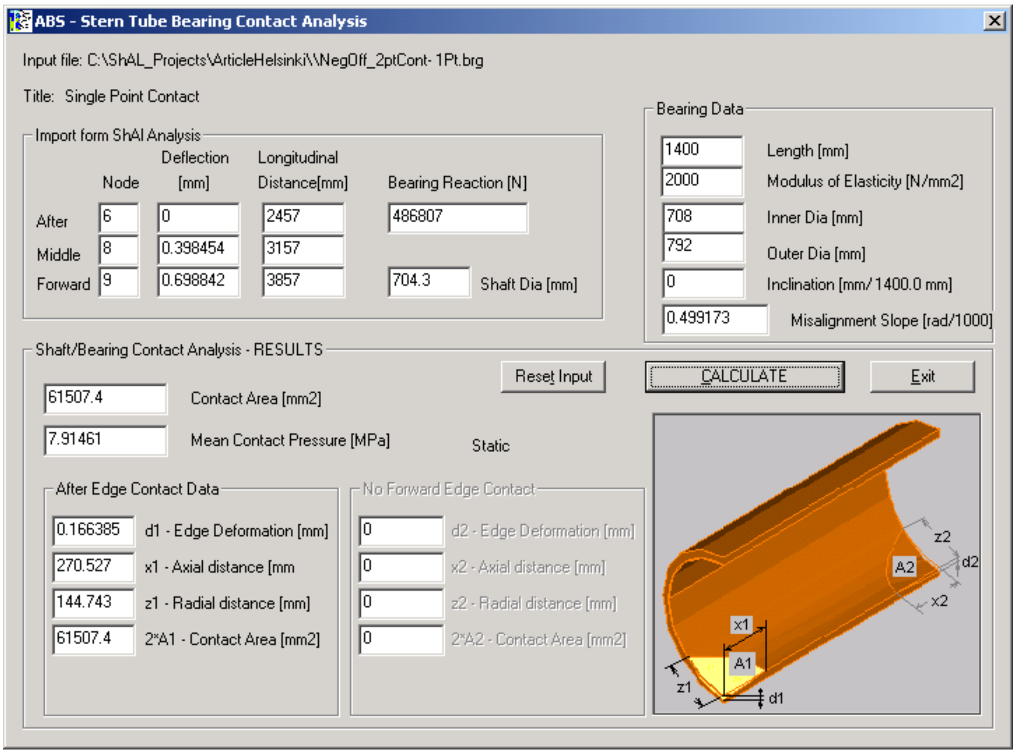
1. For initially defined parameters, define the S/T bearing contact area and the shaft's sagging into the bearing (S/T bearing evaluation interface Section 2, Figure 14 must be invoked in ShAl program).
2. Use the contact area information to establish actual position of the reaction load (half the length of the contact area can be presumed at the point where bearing reaction will act), and correct the S/T bearing horizontal location, accordingly.
3. Use the sagging information to correct the vertical position of the S/T bearing in the ShAl input file (lower the bearing down for the half of the sagging value).
4. Rerun the alignment analysis program and bearing evaluation interface with the new set of data.
5. Verify the shaft's sagging into the bearing in the middle of the contact area. If the sag is changed insignificantly, the results are acceptable. Otherwise, repeat steps 2) to 5).

This procedure is time-consuming and may not be necessary if the designer considers it as a possible disturbance while optimizing the alignment (see Section 7).

ABS shaft alignment software provides an interface to evaluate the bearing contact condition (see ABS shaft alignment program Users Manual):

Note: The approach where structural and bearing elasticity are applied as constant values may not yield more preferable results than the solution where the bearing elasticity is neglected completely.

FIGURE 14
ABS Bearing Evaluation Interface



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

Title: Single Point Contact

Import form 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	

Shaft Dia [mm]: 704.3

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]

4.9 Bearing Wear Down

Related topics:

- Bearing wear down survey and inspection (4/2.4)

Bearing wear down is a parameter that does not immediately affect the alignment condition. The wear of the bearing material progresses with time, and it largely depends on the shaft-bearing misalignment angle. Misalignment angle defines the contact condition between the shaft and the bearing and, accordingly, the revolution at which the shaft's lift will occur.

Although the wear down is undesired in all of the bearings, the after stern tube (S/T) bearing condition is the primary concern. After stern tube bearing is adversely loaded by the overhung propeller which loads the bearing heavily at its after edge. Bending curvature of the shaft is also high and the contact between the shaft and the bearing may often require corrections, which are normally performed by slope boring.

It is impossible to verify the S/T bearing's actual condition. However, the amount that the shaft drops with time can be indirectly measured. This measurement is regularly performed during the special surveys, and it is conducted with a poker gauge.

Bearing wear down is one of the issues which should be considered when alignment is designed. A good and robust alignment design should account for wear down. Alignment optimization is particularly helpful to account for this kind of influence.

4.10 Gear Meshes

Related topics:

- Gear contact misalignment measurement (Subsection 5/6)

Gear driven propulsion installations, where a propeller is directly connected to the gearbox, may be significantly affected by the shafting alignment condition, resulting in:

- Gear meshes misalignment
- Gear shaft bearing adverse loading condition

Requirements imposed on the gear contact are very stringent:

- Uniform contact across 90% of the effective face width of the gear teeth is required.

With regard to the above, in installations with reduction gears, it is important to inquire the alignment influence on the gear-pinion misalignment (Section 2, Figure 16 and Section 2, Figure 15), and ensure that it is maintained within allowable tolerances. Tolerances are expected to be defined by the gear manufacturer.

There are other practices in the marine industry which are taking indirect routes in addressing the issue, and not directly investigating the effect of the misalignment angle on the gear tooth contact. One of the commonly applied approaches is to investigate the gear shaft bearings reaction difference, and maintain it within 20% of each other (Section 2, Figure 15). This approach may be acceptable only when zero moment and shear force is maintained at the flange connecting to the line shaft. Otherwise, there will be no assurance that the misalignment angle is within acceptable limits – the bearing reactions themselves will be no guarantee of it.

FIGURE 15
Gear Driven Propulsion – Equal Gear Shaft Bearing Reactions
0.21 mrad Gear Misalignment Angle

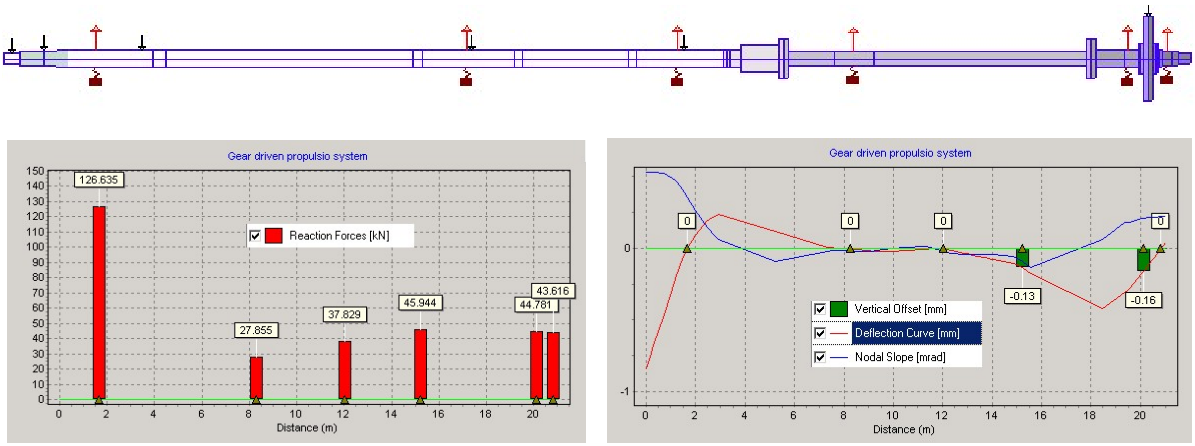
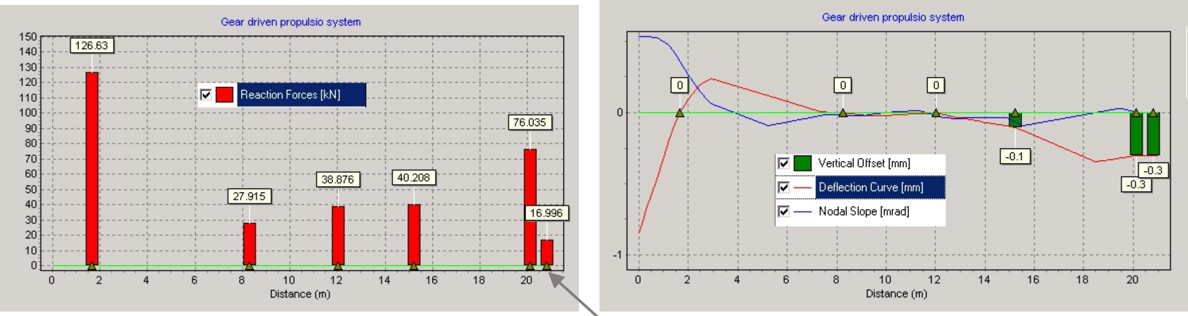


FIGURE 16
Gear Driven Propulsion – Uneven Gear Shaft Bearing Reactions Zero Misalignment Angle at Gear Wheel



Section 2, Figure 16 and Section 2, Figure 15 show that an appropriate selection of bearing offsets can bring the gear misalignment angle to almost zero angle (Section 2, Figure 16 no-misalignment). However, when concentrating on misalignment angle, the gear-shaft bearing reactions are most probably going to be much more apart than 20% as some industry practices will require. This eventually does not matter as long as one of the bearings is not overloaded or unloaded when the running condition is analyzed.

Note: ABS considers the approach where a misalignment angle between gear meshes is controlled and maintained as close to zero as possible to be a correct way to address the alignment of the gears in contact.

4.10.1 Hybrid Analysis, Quasi-Dynamic Analysis

In the case of geared installations, it may be advisable to perform a quasi-dynamic analysis in addition to the static investigation. A common procedure is to incorporate acting dynamic loads on top of the existing static forces into the static shafting alignment model. It is suggested that steady dynamic loads from the gears in contact, as well as propeller thrust load, be included.

The results obtained by the quasi-dynamic analysis should be cautiously considered and primarily used to investigate the gear load and misalignment condition. Attempts to design the slope boring for the model where dynamic loads are incorporated are not endorsed by ABS.

In cases where dynamic load are included, the loads at the gear shaft bearings may not always be positive[5]. Depending on the gearbox design and operating condition, the reaction load at the gear shaft bearings may overcome the gravity forces and result in negative bearing reactions. Accordingly, ABS shafting alignment rules may not apply for those analyses.

Note: The above comments on dynamic load application do not wave the ABS requirement that the static analysis should be submitted for plan review, satisfying appropriate ABS Rule requirements.

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[5] ABS sign convention considers bearing reactions loads to be positive if they act in opposite direction to the gravity loads.

SECTION 3 Shaft Alignment Procedure

1 General

As already mentioned, the propulsion shafting alignment process consists of the design, analysis, and the alignment procedure and measurements. The alignment procedure is the executable part of the alignment process where the alignment is performed in accordance with the requirements defined by the alignment designer. The alignment procedure is not uniformly defined and applied in the industry. The procedure often depends on shipbuilders' practices, experiences, and even more so on the production schedule of the particular builder.

It is not intended to address each particular practice present in the industry, or to judge the efficiency and validity of different approaches, but rather, in this Section, an alignment procedure will be established which, if properly followed, will have a high probability of success. This is not going to be an instruction for an ideal solution to all alignment problems, as there are production differences among shipbuilders, as well as differences in experience and skills of the personnel conducting the alignment. Instead, this is a proposal for a safe and practical way to conduct the alignment procedure, which will more likely avoid dire straits in the post alignment search for a solution.

2 Shaft Alignment Procedure

The shaft alignment procedure is not expected to start before the vessel stern blocks are fully welded and all of the heavy stern structure is in place. Only then should the reference line for positioning the shafts, bearings, main engine and gear box be established. This is not always the case, however. Some yards do start the procedure much earlier, even during block stage, or without a fully welded stern area of the vessel, or/and with no superstructure in place. These different practices will be addressed later in the text and discuss possible consequences which such approaches in alignment procedure may yield, along with solutions to the possible problems.

After the sighting through is finished, the established shafting reference line is further rectified (if necessary) by a slope boring or inclination of the stern tube bearing.

Vessel is now ready for shafts to be put in place, propeller installation and system assembly (connecting the engine and gearbox, where applicable).

When shafts are positioned in place, if necessary, the additional (temporary) bearings are used to assist the assembly. Propeller is connected and, if required, the load is applied at the forward end of the tail shaft to hold it in contact with the forward stern tube bearing before assembling. At this stage, it is normal practice for the yard to verify pre-assembly alignment condition of the shafting by conducting a so-called "Sag and Gap" procedure.

Sag and gap is verified between mating flanges, and has to comply with appropriate, analytically obtained, values. If sag and gap is conducted in the dry dock, the yard should be able to fully control the alignment, meaning that the measured values of sags and gaps should be verified quite accurately against the analytically predicted values. If sag and gap is conducted on a waterborne vessel, then the accuracy of analysis may be in question, as the hull deflection effect needs to be considered.

It is therefore desired to conduct as much of the alignment procedure as possible while the vessel is in the dry dock. Accordingly, if plausible, the reaction verification and the bearing-shaft contact condition should be verified when the vessel is in the dry dock. By doing so, the shipyard can ensure very good control of the alignment procedure against the analysis. It is again important to highlight that the issue of controlling the alignment is in direct relation to the completion of the structural work of the vessel.

Further verification of the alignment condition should proceed with the vessel afloat. On a waterborne vessel, it is more difficult to ensure compliance with the calculated alignment, as the hull deflections are difficult to predict accurately. However, with the controlled dry dock alignment, any deviation in bearing reactions from calculated to measured values should be attributed to hull deflections.

The strongest argument that the opposition may have to the above proposed procedure is the builder's inability to ensure actual alignment compliance with theoretical requirements, even for the relatively stable vessel condition in the dry dock. Therefore, if the shipyard finds the alignment conditions to be "impossible" to control, what is the point of investing precious time into a procedure that fails anyhow? Accordingly, opponents will argue further, the alignment shall be conducted by roughly following the requirements, and only fine-tuned when the vessel is afloat and if the bearing reactions significantly differ from the analytical predictions.

The general policy of the classification societies is to accept the procedures which result in a satisfactory solution. The problem in the alignment case is that the complexity of the procedure provides insufficient guaranty that initial nonconformance with alignment requirements (sighting through in particular) in the dry dock can be eventually rectified to comply with requirements as the vessel is waterborne.

The propulsion shafting alignment procedure can be summarized in the following activities:

- Sighting through (bore sighting)
- Bearing slope boring or bearing inclination
- Engine bedplate pre sagging
- Sag and Gap
- Reactions measurements
- Bearing-shaft misalignment evaluation
- Shaft eccentricity (runout) verification
- Intermediate shaft bearing offset readjustment

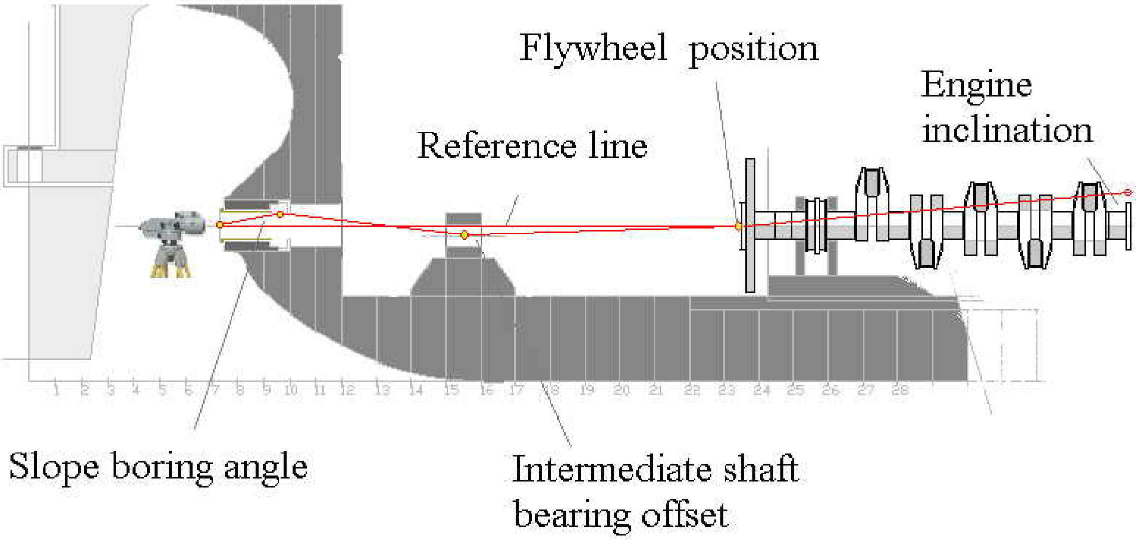
The alignment verification is also part of the alignment procedure to which a separate Section in these Guidance Notes is dedicated. It consists of

- Crankshaft deflection measurements
- Engine bedplate deflections measurement
- Gear contact evaluation (where applicable)
- Gear-shaft bearings reaction measurements

3 Sighting Through (Boresighting)

The process of establishing the reference line is often called sighting through or bore sighting. The procedure is conducted by optical instruments (Section 3, Figure 1), laser or a piano wire (Section 3, Figure 2).

FIGURE 1
Example of Optical/Laser Sighting Through



Sighting through procedure is commonly conducted as follows:

- Telescope, laser or piano wire is normally positioned in front of the after stern tube bearing.
- Reference line is defined so as to match the center line of the after stern tube bearing.
- Target points are then defined at the location of the intermediate shaft bearings, gearbox flange or main engine flange.
- Target points are offset for values corresponding to the prescribed bearing offsets for the dry dock condition.
- Shaftline bearings and gearbox or main engine are then positioned into place.
- Slope boring angles are marked. If bearing inclination is conducted instead of slope boring, the inclination angle is applied to the S/T bearing and bearing is fixed in place inclined, ready for the epoxy resin casting.

In order to prevent or minimize disturbances of the established bearing location, engine position and S/T bearing inclination, the following is required:

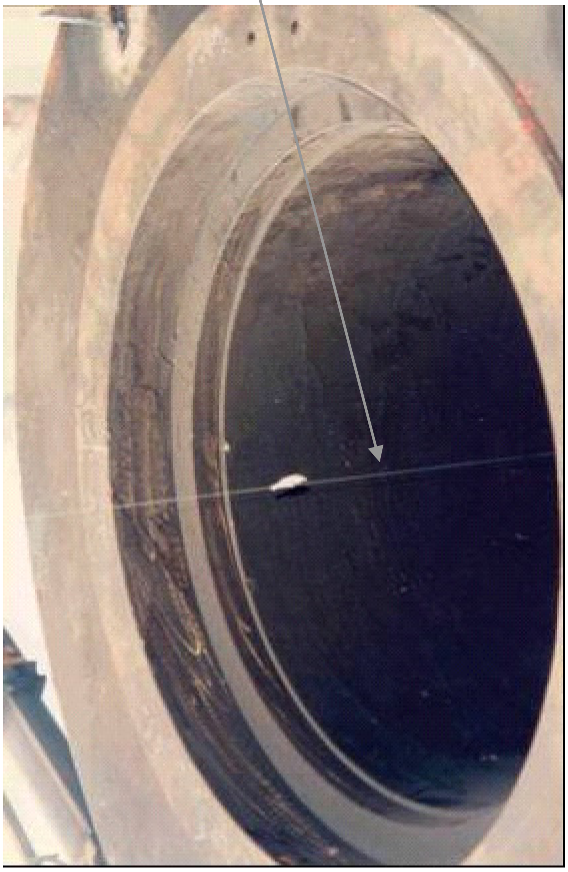
- Temperature of the vessel's structure must be stable and as even as possible. For that reason, boresighting is normally conducted in early morning hours before the sunrise.
- At this point of the vessel construction, the major welding work should be completed on the stern block of the vessel. This is to prevent eventual structural deformation which may result from excessive welding.
- Heavy structural parts and equipment shall be installed on the vessel (superstructure, main engine, etc.).

If the above recommendations are fully complied with, at this stage of construction, no hull deformations are expected to adversely affect the established prealignment condition. Later on, when the vessel is launched, the initial alignment is expected to be disturbed by hull girder deflections as a result of the buoyancy forces.

3.1 Piano Wire Application

Section 3, Figure 2 below shows a piano wire application in a “sighting through” procedure of establishing a center line of the shafting. The wire enters the aft S/T bearing from the stern (see figure below) and is pulled straight to the main engine flange.

FIGURE 2
Piano Wire Application



Prescribed bearing offset is now applied by measuring the vertical distance from the piano wire to the location of the particular intermediate shaft bearing.

Positions of the bearings and a slope boring angle are defined using a piano wire as a reference.

When applying the prescribed displacement and slope, the theoretical data must be corrected for piano wire sagging.

When the piano method is used, one needs to apply the correction for the piano wire sagging. The following is the formula for piano wire sag:

$$\delta = r^2 \cdot \pi \cdot \frac{\rho \cdot x}{2000 \cdot F} \cdot g$$

where

δ = piano wire sag, in mm, at distance x

ρ = specific gravity of the piano wire material (7860 kg/m^3)

r = piano wire diameter, in mm. (0.5 mm piano wire is normally used – however, 0.6 and even 0.7 mm diameter wire may also be applied)

x = distance, in m

F = tensioning force, in N

g = gravity constant 9.8066 m/s^2

4 Slope Boring – Bearing Inclination

One of the most important issues in the alignment process is to ensure the proper operating condition of the stern tube bearing, meaning that the load exerted on the bearing from the shaft is distributed as evenly as possible along the bearing length. The bearing problem is significant because of the following:

- Propeller load results in large bending deformation of the after portion of the tail shaft.
- Large shaft's bending reduces the area of static contact with the bearing.
- Bearing central axes and the shaft center axes misalign (relative misalignment) due to the shaft deformation[6], as well as due to the bearing offset change[7].
- Relative misalignment causes further contact area reduction as the contact normally shifts to one or the other edge of the bearing (mostly after edge of the bearing).
- Moreover, after the shafting is put in place, the stern tube bearing is inaccessible for alignment condition modifications, adjustment, damage repairs and condition monitoring. For that reason, it is important to have the alignment conducted properly and in a controlled manner to ensure provisions for acceptable bearing operation in the whole range of the vessel's operating conditions.

The slope boring or bearing inclination is a procedure which is commonly applied to ensure the satisfactory operation of stern tube bearing. The slope boring or bearing inclination is a process by which the after stern tube bearing center line (and sometimes the forward stern tube bearing, as well) is inclined to reduce misalignment between the bearing shell and the shaft. The procedure is applied in the very early stage of the alignment process before shafts are put in place. Initial work related to the slope boring or bearing inclination starts as early as the sighting through process.

Slope boring has an advantage over the bearing inclination as it can be conducted with multiple slopes. Multiple slopes are desired as the bearing running condition may significantly improve with earlier developed hydrodynamic lift and more even load distribution in operating condition. Drawback of the multiple slopes is that it requires a longer time for machining, and accordingly, it is a more expensive procedure.

Note: Slope boring or bearing inclination is to be considered when calculated misalignment between the shaft and the bearing's center line is greater than 0.3 mrad.

The difference between slope boring and bearing inclination is:

i) *Slope boring* (Section 3, Figure 3 and Section 3, Figure 4):

Slope boring is a process where the bearing shell is machined so as to ensure that the center line of the bearing's inner bore is misaligned to the desired angle (defined by shaft alignment analysis, Section 3, Figure 3). To allow provision for slope boring, the inner bearing diameter is initially pre-machined to the smaller diameter. The special boring machine (Section 3, Figure 4) is then attached to the stern block and aligned so as to match the required misalignment angle. Machining is then conducted by boring through the bearing in several passes, if required. Multiple passes may be necessary when larger amounts of bearing material are to be taken away because of a danger of bearing material overheating, as well as to ensure required machining tolerances.

---

[6] Shaft deformation is caused by static forces: shafts own weight, propeller, generators, gears, flywheels, crank mechanism, etc.

[7] Bearing offset changes mostly as a result of hull girder deflection and thermal expansion.

FIGURE 3
Slope Boring Arrangement

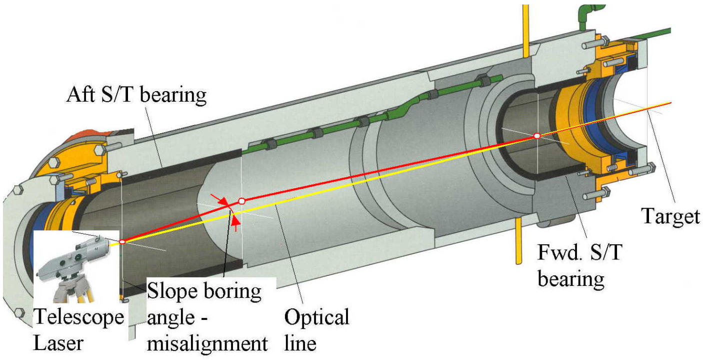
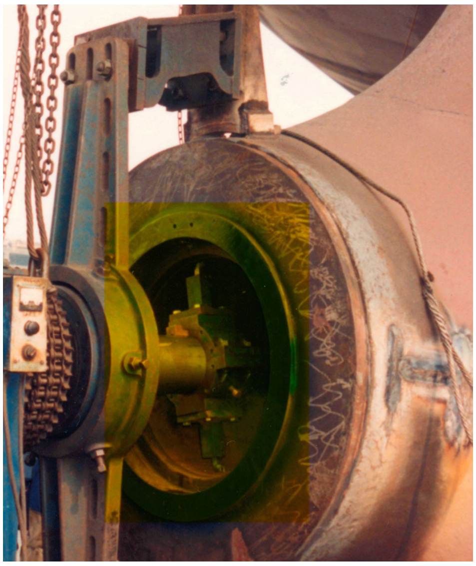


FIGURE 4
Slope Boring Machine



The drawbacks of the slope boring are:

- Very slow and sensitive process
- Requires specially designed equipment
- Machining precision may be reduced on lengthy bearings

Due to the length of time for machining, which can take several days, the procedure may be affected by structural work and vibrations.

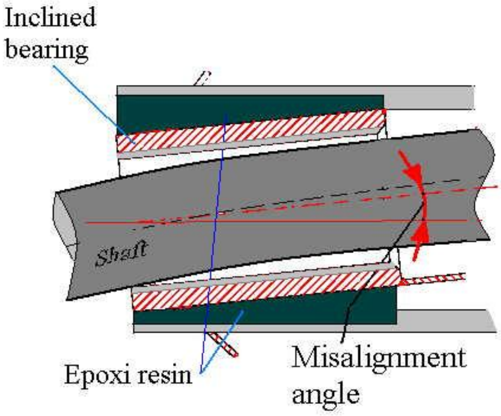
ii) *Bearing inclination* (Section 3, Figure 5):

Bearing inclination is another method of reduction of the misalignment angle which is becoming more and more common.

- Instead of machining the bearing after installation, the bearing is machined to its final diameter and placed inclined into the stern block.
- The bearing's casing is fixed to the stern block, not by shrink fit (as is done when slope boring is performed), but by bearing epoxy resin.

- Bearing is inclined to the required angle, fixed in place with temporary connections to the stern block.
- Epoxy resin is then cast to bond the bearing to the stern block.

FIGURE 5
Bearing Inclination



Slope boring and bearing inclination are analytically defined. The question is for which vessel condition? Is it for ballast, laden or the dry dock? The alignment and the S/T bearing slope can be optimized only for one condition of the vessel loading (i.e., hull deflections).

Presumably, one would desire to have an optimum alignment design for laden vessel. Therefore, it would be expected that the slope is defined and machined in accordance with results obtained by shaft alignment analysis which included hull girder deflections of the fully loaded vessel. However, the optimum slope for laden vessel may not result in an acceptable bearing loading for ballast, for example. Therefore, the misalignment slope shall be a tradeoff between a desired misalignment angle for the whole spectrum of operating conditions.

Note: To summarize, the misalignment-slope will vary with change in the loading condition of the vessel and the environmental condition (temperature in particular) around and inside the vessel.

Therefore, it is more important to predict the trend of misalignment-slope-change than to define one optimum angle which will ideally suit only one alignment condition. When alignment is calculated, the trend of the misalignment angle change is to be observed, and the slope should be defined so as to ensure that slope change will not deteriorate the bearing condition to the point of unacceptable bearing loads. The condition is to be acceptable for all different vessel loadings.

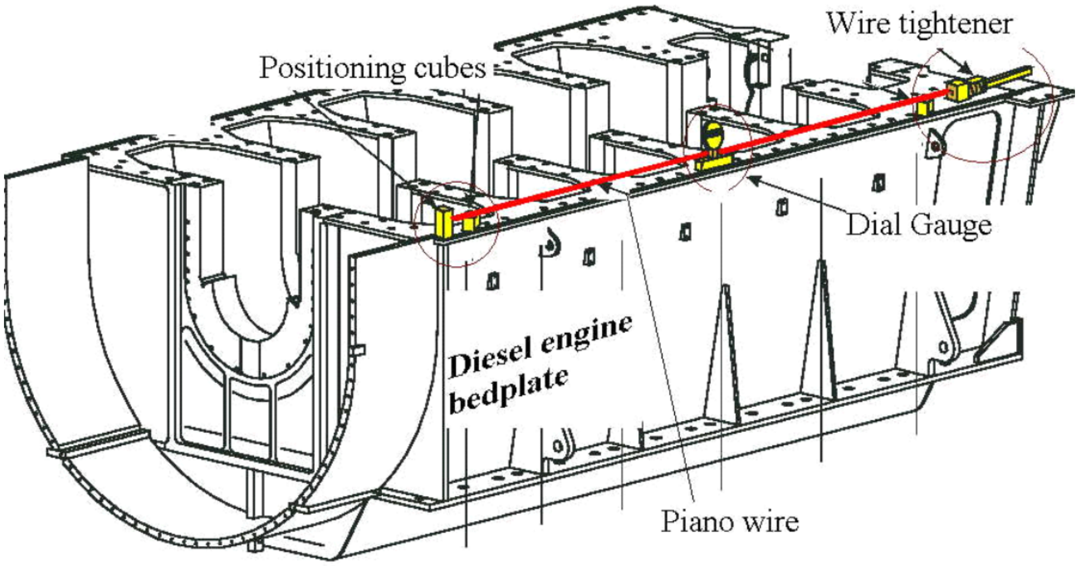
The Surveyor's presence is advisable for the final slope boring or bearing inclination verification, which is often conducted as a part of the sighting through process.

5 Engine Bedplate Pre-sagging

Related topic:

- Hull girder deflections (Section 6)

FIGURE 6
Bedplate Sagging Measurement Using Piano Wire



Large two-stroke low-speed cross-head diesel engines have a relatively flexible structure, which is therefore susceptible to disturbances which can result from ship's hull deflections and temperature change.

To prevent M/E bearing and crankshaft damage, the large two-stroke diesel engine designers normally require that the engine bedplate be pre-sagged when the engine is installed on the vessel.

The pre-sagging procedure consists of the following:

- Engine is installed when the vessel is in dry dock (preferable) or afloat at very light ballast condition.
- It is expected that the effect of the bedplate presagging will be annihilated due to the:
  - Deflection of the hull structure of the vessel
  - Thermal rise of the engine's bedplate

  (This is expected behavior on tankers and bulk carriers in particular – Section 6, Figure 1.)
- Smaller engines (e.g., 4, 5, 6 cylinders of diameter 600 mm or less) may be pre-sagged by letting the bedplate bend freely (catenary curve). The bedplate is supported by the bolts only at the forward and after ends of the bedplate. Using this procedure, it is not possible to control the bending. However, as long as the crankshaft deflections are satisfactory (with a trend to improve as the hull deflections increase), the procedure is acceptable.

This procedure is normally required to be confirmed by the engine manufacturer for each particular installation.

6 Sag and Gap

Related topic:

- Sag and Gap measurements (Subsection 5/7)

The Sag and Gap procedure is commonly applied as an alignment verification method prior to the shafting assembly. The Sag and Gap should not be regarded as an acceptable method of confirming the final alignment condition, but rather as a cursory check of the pre-assembly condition of the shafting. This is because of the relative inaccuracy and inconsistency of the Sag and Gap measurement itself, as well as the difficulties in knowing which condition is actually being measured. The accuracy of the method is a problem because it is often conducted using filler gauges.

The vessel condition during the measurement is often quite different from the analytical model for which the calculated values of the Sag and Gap are defined.

Moreover, in very rigid propulsion shafting systems (common in tankers and bulkers), the deflection values are very small, and the bearing reactions are very susceptible to small deviations in vertical position of the bearings. This is reflected in the Sag and Gap procedures, as well. Reactions at the bearings will be quite different for very small deviations in the Gap and Sag values.

Question: What is the procedure if Sag and Gap, as measured, do not comply with the calculated values? Should the bearing offset be corrected to obtain better agreement with the analytical data, or should it just be recorded and the eventual adjustment left for after the bearing reaction measurement?

> *The Answer:* It is strongly suggested that the bearing offset, and engine position, or gearbox position not be amended based solely on the Sag and Gap measurements. As mentioned above, the accuracy of the method is not sufficient to ensure that the alignment is being improved. It may well be that the alignment will worsen by readjusting the bearing offsets in order to obtain the Sag and Gap values which are neither accurately measured or not calculated for the particular vessel condition.

It is recommended not to commence with the Sag and Gap procedure before the following is completed:

- Engine and reduction gear are installed.
- Temporary supports are installed.
- Shafts are placed inside the vessel and propeller is mounted.
- Propeller shaft is in contact with a bottom shell at the foremost stern tube.

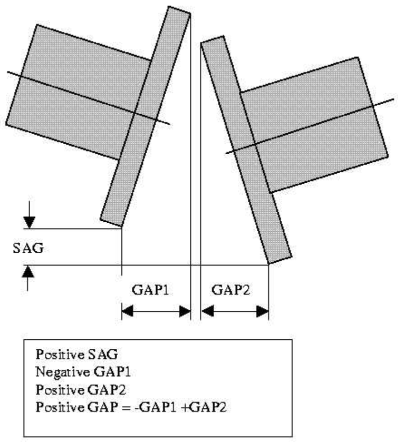
Note: It is desired to have major structural work completed before sighting through, as the bore sighting condition may be significantly disturbed by substantial welding and addition of heavy masses in the stern part of the vessel.

6.1 Theoretical Background

The theory behind the procedure is the same beam theory applied in shaft analysis of the whole – assembled system, and the calculation is conducted as follows:

- Alignment is defined and calculated for the assembled system.
- Position and offset of the temporary bearings are defined.
- Assembled system is detached at flanges and each shaft is analyzed separately; displacements and slope at the each end of the shaft (flange connection) are calculated.

Sag is now calculated by taking the bending displacement at each flange location and subtracting the same from the deflection of the mating flange.

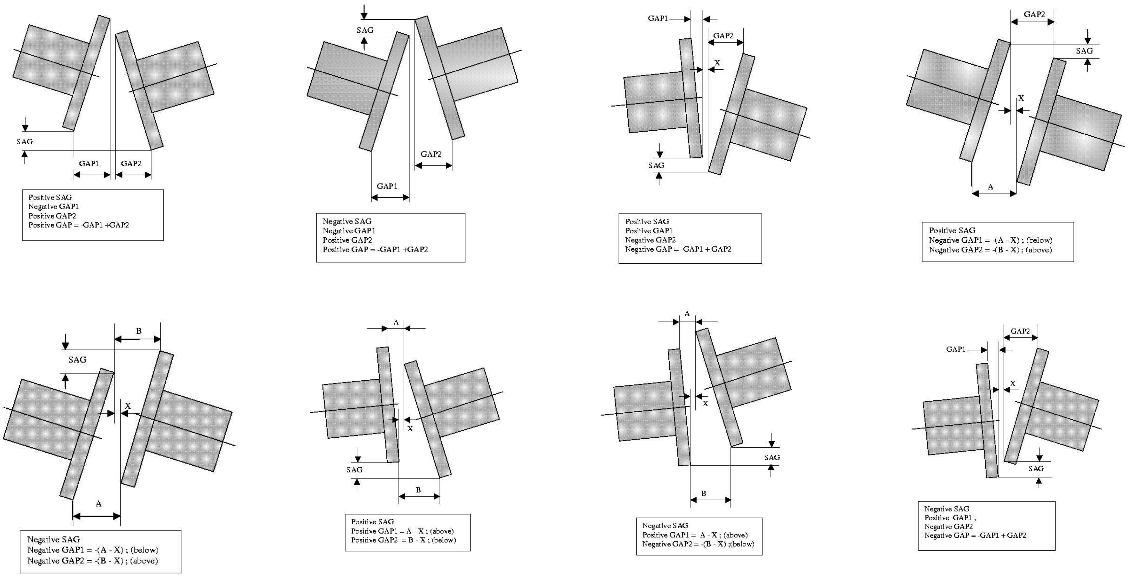


Gap is defined as the difference in distance between the top or bottom edges of the unconnected flange pair. Gap at each flange is calculated from the angular inclination of the shaft (at flange location) and the flange diameter. Total gap is obtained by linear summation of the gaps at both flanges.

In the ABS Sag and Gap analysis, sign convention was defined in order to uniquely define the Sag and Gap information.

Flanges, corresponding to one to another, can take eight different positions. The Sag and Gap calculation will differ depending on the same arrangement as shown in Section 3, Figure 7.

FIGURE 7
Flange Arrangement in Sag and Gap Analysis



Sag and Gap needs to be verified by measurements. Details of the measurements are given in Subsection 5/7.

7 Reactions Measurement

Related topics:

- Jack-up measurement (5/2.1)
- Strain gauge measurement (5/2.2)
- Sag and Gap measurement (Subsection 5/7)
- Sag and Gap procedure (Subsection 3/6)

In Section 1, the propulsion shafting alignment was defined as a static condition observed at the bearings which support the propulsion shafting. Accordingly, to verify the alignment, the bearing condition is to be evaluated and measured, namely:

- The bearing reactions
- The bearing shaft misalignment

Bearing reactions are measured directly and indirectly. The most commonly applied methods that measure the alignment condition are:

- Sag and Gap
- Jack-up
- Strain gauge method

The Sag and Gap and the strain gauge procedures are indirect methods to measure the deflections and strain in the shaft and correlate those measurements to the bearing reactions.

Jack-up measurement is a direct reaction measurement where a hydraulic jack is used to lift the shaft and measure the load at the particular bearing.

The above three bearing reaction measurement procedures are described in detail in Subsection 5/2.

8 Bearing-Shaft Misalignment Measurement

Related topics:

- Slope boring – bearing inclination (Subsection 3/4)
- Bearing misalignment measurement (Subsection 5/4)
- Diesel engine alignment: Crankshaft deflections vs. M/E bearing reactions (3/11.1)

The misalignment condition between the shaft and the bearing is another important piece of information that is to be verified. Bearing reactions will provide information on load acting on the bearing. However, the more important information will be how this load is distributed along the bearing length.

A misalignment between the shaft and the bearing is always present to some extent. The problem is when misalignment is so excessive as to result in the heavy edge contact at the bearing, thus preventing the oil film from being developed in the running condition.

The larger the misalignment angle, the more the shaft is sagging into the bearing, and the faster speed of the shaft will be needed to develop the hydrodynamic oil lift. In extreme cases, the oil film may not develop at all, which will result in immediate bearing damage and failure.

The bearing shaft misalignment is addressed in great detail in the discussion of the stern tube bearing alignment analysis. Although the after stern tube bearing[8] is expected to be more affected by its misalignment with the shaft, the other bearings can experience misalignment-related problems, as well.

---

[8] In case of the after stern tube bearing criteria for allowable misalignment is set to value of 0.3 mrad, above which alignment is deemed unacceptable. After stern tube bearing misalignment condition is difficult to measure and is not conducted on commercial vessels.

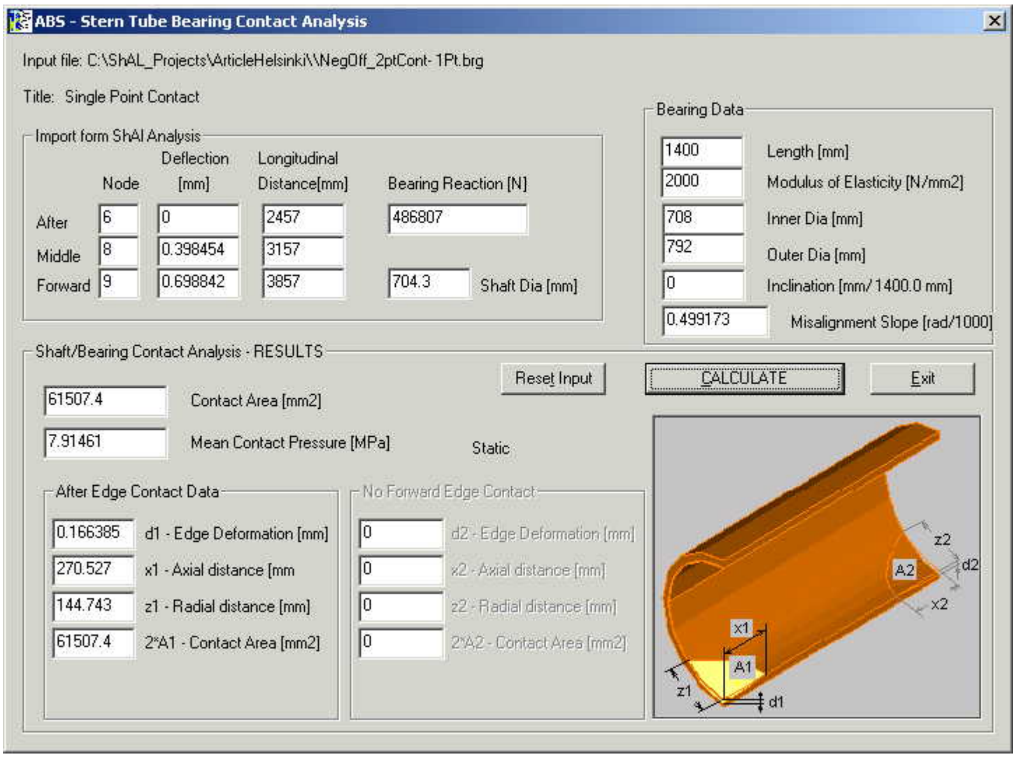
The misalignment problem at the intermediate shaft bearings can be controlled and corrected by clearance measurement between the shaft and the bearing shell.

In the case of the intermediate shaft bearing, it may be appropriate to consider the metallic chocks instead of epoxy resin ones. If there is a need for bearing inclination or offset readjustment, the metallic chocks can be re-machined much easier then the epoxy resin can be recast.

The other place where the shaft-bearing misalignment problems may be expected is at diesel engine. The misalignment in the engine may be a problem in cases where one of the bearings is unloaded, and the bearing adjacent to the unloaded one may result in heavy edge loading.

The ABS shaft alignment software is capable of statically addressing the bearing misalignment problem. The bearing contact evaluation interface defines the actual contact area between the shaft and the bearing. See the sample analysis in Section 3, Figure 8.

FIGURE 8
Stern Tube Bearing Contact Condition Evaluation – Sample Analysis



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

Title: Single Point Contact

Import form 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	

Shaft Dia [mm]: 704.3

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]

9 Shaft Eccentricity

Related topic:

- Shaft alignment eccentricity (Subsection 5/8)

Shaft eccentricity may be a cause of the misalignment problem and may result in dynamic instability of the shafting. It is important to ensure shaft's eccentricity is kept within some acceptable limits.

ABS has no specific requirements for the allowable limits on shaft eccentricity. However, the recommendations and requirements addressing the shaft eccentricity may be found in the industry.

For reference, requirements DEF STAN 02–304 Part 4/ Issue 2 (NES 304 Part 4) issued by the Defense Procurement Agency, An Executive Agency of The Ministry of Defense, UK Defense Standardization have been selected:

> Quote
>
> "Each shaft is to be supported between lathe centres and checked for concentricity after all machining is complete. No auxiliary supports are permitted during the check and the following limits are to apply:
>
> (1) The outside diameter of each shaft section is to be concentric with the axis of rotation within 0.38 mm 'Total Indicator Reading' (TIR). The change in concentricity in any metre of shaft length is not to exceed 0.08 mm TIR;
>
> (2) Shaft tapers are to be concentric with the axis of rotation within 0.05 mm TIR;
>
> (3) The periphery of each flange or sleeve coupling is to be concentric with the axis of rotation within 0.05 mm TIR;
>
> (4) Bearing journal, sleeve journal and sleeve outside diameters are to be concentric with the axis of rotation within 0.05 mm TIR.
>
> Surveyor's presence would be required only if there is suspicion that run-out may be a problem. It is, however, considered a good practice for the shipyard to verify the bending condition of the line shafting."
>
> Unquote

Requirements from other institutions may be different, allowing less stringent tolerances.

Shaft eccentricity can be measured as explained in Section 5.

Shafts that are found to have eccentricity outside of the required limits may require straightening. The straightening may be:

- Thermal
- Mechanical

Thermal straightening is normally preferred to cold mechanical straightening. The stresses imposed by the mechanical straightening can be dangerously high, particularly when shaft materials are of high yield strength.

10 Intermediate Bearing Offset Adjustment

Related topics:

- Influence coefficient matrix (2/3.4.1)
- Diesel Engine Alignment (Subsection 3/11)

The intermediate-shaft bearing offset is often adjusted when:

- Forward stern tube bearing reaction is too low.
- Main engine bearing reaction measurements show unacceptably large deviation from calculated values.
- Crankshaft deflections are not within manufacturer's limits.

Note: Crankshaft deflections and main engine bearing reactions are correlated. Adjustment of the one directly influences the other. Accordingly, the adjustment of the aftmost intermediate shaft bearing influences the condition of both. One has to be aware that correcting one parameter may result in worsening the other.

To show how the intermediate shaft bearing adjustment may affect the shaft alignment, the shafting system analysis was performed as per Section 2, Figure 7. Namely, a Negative-Offset solution to the alignment was arbitrarily selected, and two propulsion system designs were considered:

- With forward stern tube bearing
- Without forward stern tube bearing

Both designs are further analyzed for their sensitivity to the intermediate shaft bearing offset change (Section 3, Figure 9 and Section 3, Figure 11).

Upward and downward adjustments of the intermediate shaft bearing offset of 0.1, 0.2, 0.5 and 1.0 mm from the initially prescribed baseline were investigated.

The offset change influence on the following bearings is evaluated:

- Tail shaft bearing – change in misalignment slope
- Diesel engine aftmost bearing (M/E Brg. 1) – reaction change
- Diesel engine second aftmost bearing (M/E Brg. 2) – reaction change

The above three bearings are particularly considered because of their high sensitivity to the changes of the alignment condition and the seriousness of the consequences when damages and failures happen.

Both analyses, with and without forward stern tube bearing (Section 3, Figure 9 and Section 3, Figure 11, respectively), resulted in the aftmost M/E bearing unloading when the intermediate shaft bearing was raised more than 0.5 mm (it would be easy to predict this happening by inspecting the influence coefficients matrices – see further explanation below). On Section 3, Figure 9 and Section 3, Figure 11, it can be observed how the bearing reactions at two M/E aftmost bearings vary as the offset at the intermediate shaft bearing changes from –1 mm to +1 mm from the designed reference line. The change in gradient of the particular line indicates the load transfer from one bearing onto the other, as the bearings unload and load again.

The third curve on Section 3, Figure 9 and Section 3, Figure 11 shows how the misalignment angle varies as the offset changes at intermediate shaft bearing.

Remark: The design without forward stern tube bearing would normally have the intermediate shaft bearing in a different location (moved toward the stern) in order to maintain proper load distribution among the supporting bearings. For the purpose of this investigation, the intermediate shaft bearing location was not changed.

10.1 System with Forward S/T Bearing

(Section 3, Figure 9): By adjusting the intermediate shaft bearing offset, the desired influence on the M/E Brgs. 1 and 2 was achieved, which did not significantly affect the tail shaft bearing slope. As noted from Section 3, Figure 9, the aft S/T bearing misalignment angle increases relatively little as the intermediate bearing is being lowered. By increasing the offset at intermediate shaft bearing, the S/T bearing misalignment slope improves (i.e., slope lowers) as long as the shaft maintains contact with the forward S/T bearing. Once the contact with the forward S/T bearing is lost, the installation behaves as if no forward S/T bearing is installed.

The advantages and disadvantages of the system with forward S/T bearing can be summarized as follows:

Advantages:

- Preferred due to sensitivity of the after stern tube bearing misalignment to the adjustment of the intermediate bearing.
- The misalignment angle of the after S/T bearing will be less affected by change in intermediate bearing offset.

Disadvantages:

- System is more rigid, therefore, less compliant with hull deflections.
- The same intensity of hull deflections will more adversely affect the alignment, and the bearing reactions variation will be much larger for the same change in the bearing offset than in the system without forward S/T bearing.
- This arrangement will unload some of the bearings much sooner (at +0.2 mm and +0.5 offset change – Section 3, Figure 9) e.g., forward stern tube bearing and the aftmost M/E bearings.

FIGURE 9
System Sensitivity to Intermediate Shaft Bearing Offset Change – with Forward Stern Tube Bearing

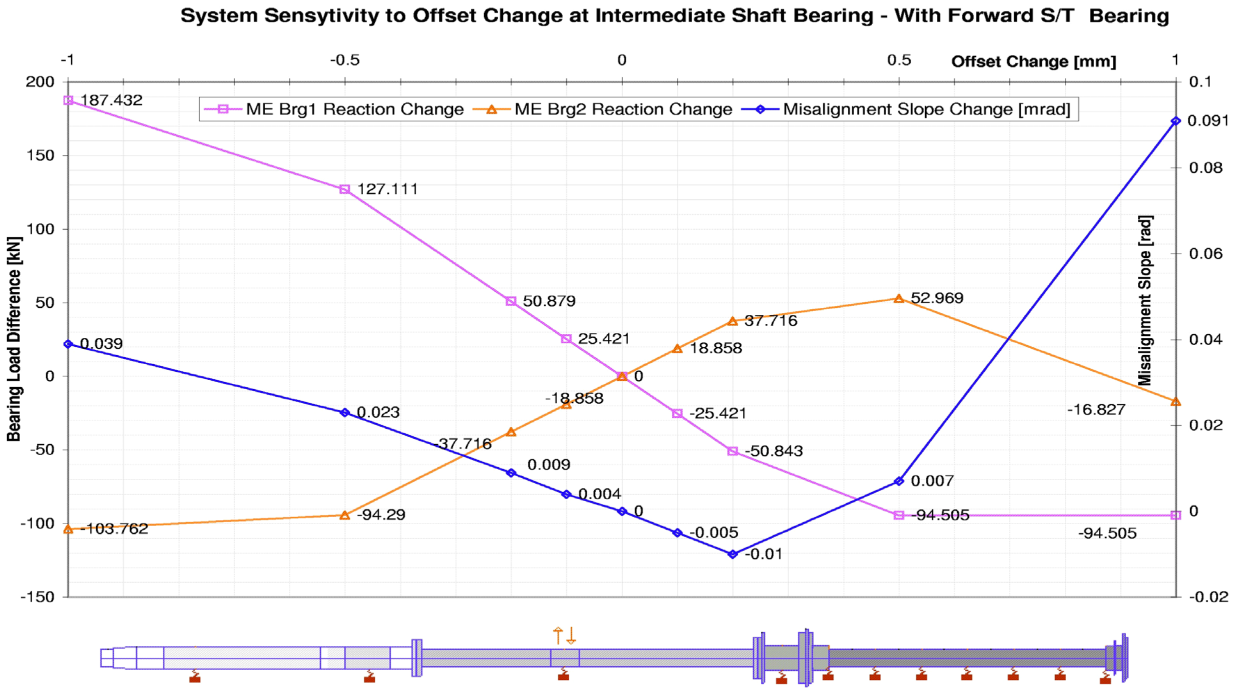
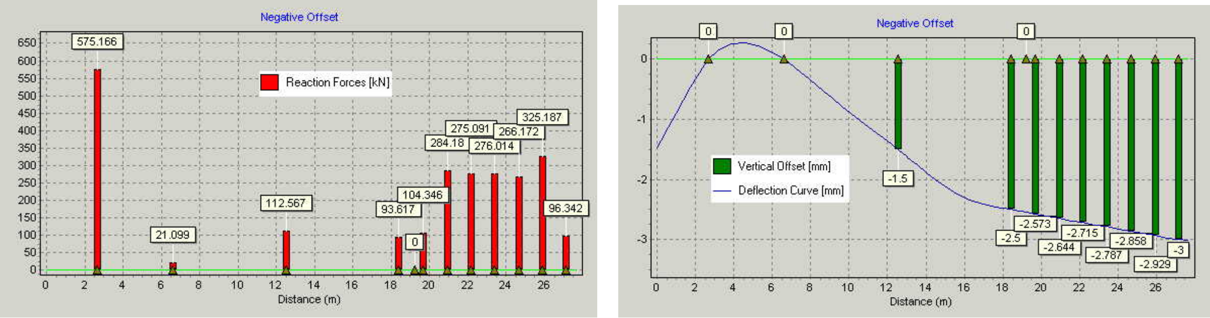


TABLE 1
Influence Coefficient Matrix – System with Forward Stern Tube Bearing

```
RELATIVE BEARING REACTIONS [kN] -> R[0.1-offset]-R[0-0ffset]
 Due to 0.1[mm] OFFSET relative to the ZERO bearing Offset
Node      |  <  7>     < 14>     < 27>     < 41>     < 45>     < 46>     < 48>     < 50>     < 52>     < 54>     < 56>     < 58>
     Supp.|    1         2         3         4         5         6         7         8         9        10        11        12
 -------------------------------------------------------------
<  7>    1 |    4.598    -8.354     4.963    -3.354     0.000     2.206    -0.072     0.015    -0.003     0.001    -0.000     0.000
< 14>    2 |   -8.354    16.063   -11.351    10.113     0.000    -6.653     0.218    -0.044     0.009    -0.002     0.000    -0.000
< 27>    3 |    4.963   -11.351    13.478   -25.460     0.000    18.883    -0.619     0.126    -0.026     0.005    -0.001     0.000
< 41>    4 |   -3.354    10.113   -25.460   166.620     0.000  -250.841   123.821   -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 |    2.206    -6.653    18.883  -250.841     0.000   511.836  -379.403   125.081   -25.395     5.148    -1.004     0.141
< 48>    7 |   -0.072     0.218    -0.619   123.821     0.000  -379.403   461.940  -295.733   108.086   -21.910     4.273    -0.599
< 50>    8 |    0.015    -0.044     0.126   -25.141     0.000   125.081  -295.733   389.320  -280.955   104.921   -20.460     2.870
< 52>    9 |   -0.003     0.009    -0.026     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
```

Column and row #3 in the above influence coefficient table represent the reaction load variation at all system bearings, as the offset at bearing #3 changes for 0.1 mm.

FIGURE 10
Bearing Reactions for Design Offset – with Forward Stern Tube Bearing



If the original design of the shafting resulted in bearing reactions, as per Section 3, Figure 10, it can be easily concluded by influence matrix inspection (Section 3, Table 1) that the offset increase by 0.1 mm at bearing number 3 (Section 3, Table 1 column/row three) will result in –25.46 [kN/mm] reaction change at bearing number 4, which is the aftmost M/E bearing. If the same intermediate shaft bearing is raised by 0.5 [mm], the reaction at the bearing will drop five times as much, i.e., –127.3 [kN]. Since the load at bearing 4 was only 93.6 [kN], with a 0.5 offset increase on the intermediate bearing, the M/E aftmost bearing (bearing #4) was completely unloaded. This is exactly the reason why there is a sudden change in gradient of the loading line due to the 0.5 [mm] offset change (Section 3, Figure 9).

If a similar analysis is conducted to investigate the condition of the forward stern tube bearing, it will be seen that the same also unloads, but it happens sooner. A raise in offset of 0.2 mm on intermediate shaft bearing will unload the bearing as the influence coefficient is –11.35 [kN/mm]. Total forward S/T bearing reaction change for the 0.2 [mm] change in offset is –22.7 [kN], which is greater than 21.1 [kN] reactions on the S/T bearing.

The unloading of the forward S/T bearing results in a sudden jump in the after stern tube bearing misalignment angle immediately after the forward S/T bearing becomes unloaded. Further increase in misalignment angle is noticed again after the main engine aftmost bearing unloads (when offset at intermediate shaft bearing increases beyond 0.5 [mm]). Although the gradient of the misalignment curvature in Section 3, Figure 9 changes sharply, this actually benefits the S/T bearing misalignment angle. Maximum difference in misalignment at the bearing is 0.101 [mrad], which is significantly less then in the case without the forward S/T bearing.

If there was no bearing unloading, all three lines would be almost straight with a constant gradient within the observed range of offset variation (i.e., –1 to +1 [mm]).

10.2 System with No Forward S/T Bearing

(Section 3, Figure 11): By adjusting the intermediate shaft bearing offset, a significant influence on M/E Brgs. 1 and 2 is achieved, as well as much higher sensitivity (relative to the previous case) of the tail shaft bearing slope. The reason for this higher sensitivity is a different load distribution among the bearings. The misalignment angle change at aft S/T bearing follows linearly the change in intermediate shaft bearing offset. The misalignment angle is reduced as the intermediate shaft bearing is lowered down, and increases with offset increase at intermediate bearing.

It can be concluded that the system is much more compliant in this arrangement.

The advantages and disadvantages of the system without the forward S/T bearing can be summarized as:

Advantages:

- System is more flexible, thus less susceptible to the hull deflections.
- For the same intensity of hull deflections, the bearing reactions will vary much less than in the case with forward S/T bearing, making it more difficult to unload the bearings along the shaftline (this may not be true for other than one, or maximum two aftmost M/E bearings).

Disadvantage:

- The misalignment angle at the after S/T bearing will be much more affected by change in the intermediate shaft bearing offset.

FIGURE 11
System Sensitivity to Intermediate Shaft Bearing Offset Change – without Forward Stern Tube Bearing

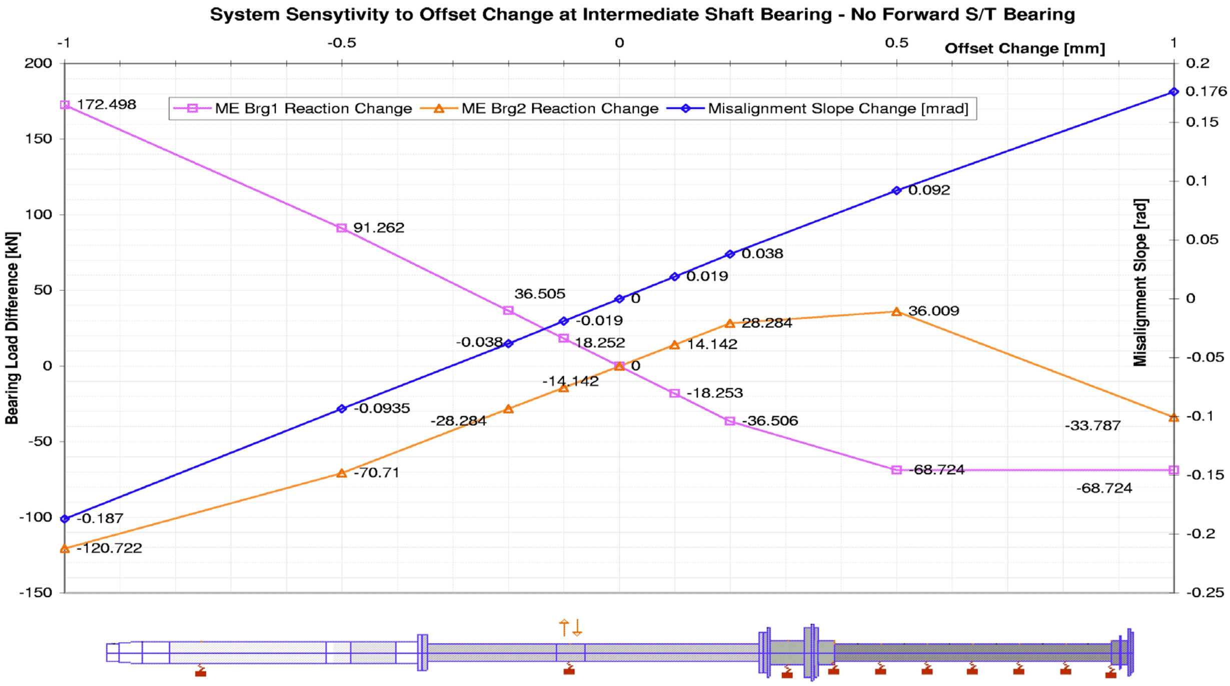
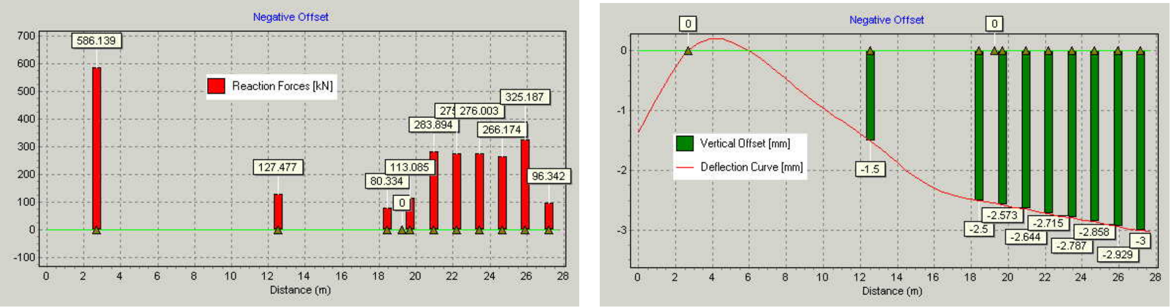


TABLE 2
Influence Coefficient Matrix – System without Forward Stern Tube Bearing

```
RELATIVE BEARING REACTIONS [kN] -> R[0.1-offset]-R[0-0ffset]
   Due to 0.1[mm] OFFSET relative to the ZERO bearing Offset
  Node      |  <  7>     < 27>     < 41>     < 45>     < 46>     < 48>     < 50>     < 52>     < 54>     < 56>     < 58>
      Supp.|     1         2         3         4         5         6         7         8         9        10        11
   -------------------------------------------------------------
 <  7>    1 |    0.254    -0.940     1.905     0.000    -1.253     0.041    -0.008     0.002    -0.000     0.000    -0.000
 < 27>    2 |   -0.940     5.458   -18.314     0.000    14.182    -0.465     0.094    -0.019     0.004    -0.001     0.000
 < 41>    3 |    1.905   -18.314   160.253     0.000  -246.653   123.683   -25.113     5.099    -1.034     0.202    -0.028
 < 45>    4 |    0.000     0.000     0.000     0.000     0.000    -0.000     0.000     0.000     0.000    -0.000    -0.000
 < 46>    5 |   -1.253    14.182  -246.653     0.000   509.081  -379.313   125.063   -25.391     5.147    -1.004     0.141
 < 48>    6 |    0.041    -0.465   123.683     0.000  -379.313   461.937  -295.732   108.085   -21.910     4.273    -0.599
 < 50>    7 |   -0.008     0.094   -25.113     0.000   125.063  -295.732   389.320  -280.955   104.921   -20.460     2.870
 < 52>    8 |    0.002    -0.019     5.099     0.000   -25.391   108.085  -280.955   386.156  -279.504   100.648   -14.120
 < 54>    9 |   -0.000     0.004    -1.034     0.000     5.147   -21.910   104.921  -279.504   381.883  -259.045    69.538
 < 56>   10 |    0.000    -0.001     0.202     0.000    -1.004     4.273   -20.460   100.648  -259.045   281.235  -105.848
 < 58>   11 |   -0.000     0.000    -0.028     0.000     0.141    -0.599     2.870   -14.120    69.538  -105.848    48.046
```

Column and row #2 in the above influence coefficient table represent the reaction load variation at all system bearings as the offset at bearing #2 changes for 0.1 mm.

FIGURE 12
Bearing Reactions for Design Offset – without Forward Stern Tube Bearing



If the original design of the shafting resulted in bearing reactions, as per Section 3, Figure 12, it can be easily concluded by influence matrix inspection (Section 3, Table 2) that offset increase of 0.1 [mm] at bearing number 2 (Section 3, Table 2 column/row two) will result in –18.3 [kN/mm] reaction change at bearing number 3, which is the aftmost M/E bearing. If the same intermediate shaft bearing is raised by 0.5 [mm], the reaction at the bearing will drop five times as much to –91.5 [kN]. Since the load at the bearing 4 was only 80.3 [kN] with 0.5 [mm] offset increase on intermediate bearing, the M/E aftmost bearing (bearing #4) was completely unloaded. This is why the gradient of the loading line (Section 3, Figure 11) changed for offsets greater then 0.5 [mm]. The proportional relationship between the misalignment angle at the after S/T bearing and the intermediate bearing offset variation does not benefit the misalignment condition, and the constant trend in gradient change results in a relatively high range of misalignment angles at the after S/T bearing.

In this case, it may be noted that the misalignment angle changes almost linearly with the intermediate shaft bearing offset within the whole range of offsets investigated. This is because the M/E bearing unloading does not significantly affect the misalignment.

10.3 Which Solution to Adopt

- If the shipyard is confident in obtaining a relatively good alignment and does not expect that alignment will need significant amendment of the intermediate shaft bearing offset, then the solution without forward stern tube bearing should be preferred. The solution is then expected to be less sensitive to hull deflections, as the shafting is more sensitive and compliant.
- However, if the shipyard expects difficulties in conducting the alignment, such as unloaded M/E bearings, and wants to ensure the provision of bearing offset adjustments, it may be safer in that case to opt for a solution with forward stern tube bearing. The system will be more sensitive to hull deflections, but after stern tube bearing, it will not be as sensitive to intermediate shaft bearing offset adjustment.

Eventually, the decision as to which design to select has to be made by the yard and the Owner.

Note: The above discussion is fully applicable to installations with only one intermediate shaft bearing, such as very short and compact propulsion arrangements (e.g., tankers, bulk carriers). However, on longer shafting systems (e.g., container vessels) where there are more then one intermediate shaft bearings in the system, the above may not hold fully.

11 Diesel Engine Alignment

Related topics:

- Intermediate bearing offset adjustment (Subsection 3/10)
- Diesel engine bearing misalignment (2/4.6)
- Crankshaft deflection measurement
- Bearing-Shaft misalignment measurement (Subsection 3/8)

The engine alignment problems are primarily experienced as:

- The main engine bearing reactions problem (aftmost engine bearing unloading)
- Inability to maintain the crankshaft deflections within the manufacturers' limits

Ensuring the satisfactory alignment of the diesel engine is becoming quite a challenging task as the engines get larger and more powerful. The problem is not the engine itself, but rather the sensitivity of the whole propulsion system, and the propulsion installation system's interaction with the hull structure.

Although the engine structure increases in flexibility with new engine designs, it is still much firmer than the structure supporting the shafting. The interface between the shafting and the engine is a particular issue which may result in engine alignment problems. Differences in structural stiffness below the line shaft and the engine supporting structure (including the engine structure itself) are relatively high, and the transition between the structures is sharp. Structurally, this sharp transition does not appear to be a problem, however, it does affect the alignment condition, in particular, the engine's aftmost bearing loading and the crankshaft deflections.

11.1 Crankshaft Deflections

Crankshaft deflections are an indirect method of verification of the crankshaft stress level. Deflections are measured between webs of the crankshaft for each cylinder, and the obtained values must be within limits established by the engine designer. As the crankshaft is rigidly connected to the shafting, any disturbance in the line shaft bearing offset will result in a crankshaft deflection change. The most affected bearings are the two aftmost M/E bearings.

Crankshaft deflections are initially adjusted by the engine manufacturer during the construction of the engine. M/E bearing vertical alignment is the parameter that controls the crankshaft deflections, and after the M/E bearing vertical position is set during the engine construction, there is no further possibility to change it after the engine is delivered. It is also recommended that the engine be delivered with crankshaft deflections as low as possible. Low crankshaft deflections will leave more space for the eventual bearing reaction adjustment at the M/E bearings.

Note: In an ideal situation, crankshaft deflections should be available prior to the commencement of the shaft alignment design. Knowing the initial crankshaft deflections can make a difference in deciding how to allow provision for positioning the engine vertically.

Section 3, Figure 13 shows the eight-cylinder crankshaft positioned on the engine's bedplate on the test bench. This is where the web deflections are fine-tuned and the bearings are verified to be in good contact with the crankshaft.

In some cases, however, the crankshaft deflections of the newly constructed engine are very close to the allowable tolerance, meaning that the provision for later correction of the alignment will be limited by this tolerance.

The engine bearing unloading, as mentioned in the example below, is not a problem in cases where the bearing condition is recognized in a timely manner and corrective actions are undertaken. The usual approach in correcting the M/E bearing loading condition is to adjust the foremost intermediate shaft bearing offset so as to obtain the desired load on the M/E bearings.

However, in some cases, it may not be possible to correct the engine bearing loading by adjusting the intermediate shaft bearing offset without causing problems somewhere else in the system, namely:

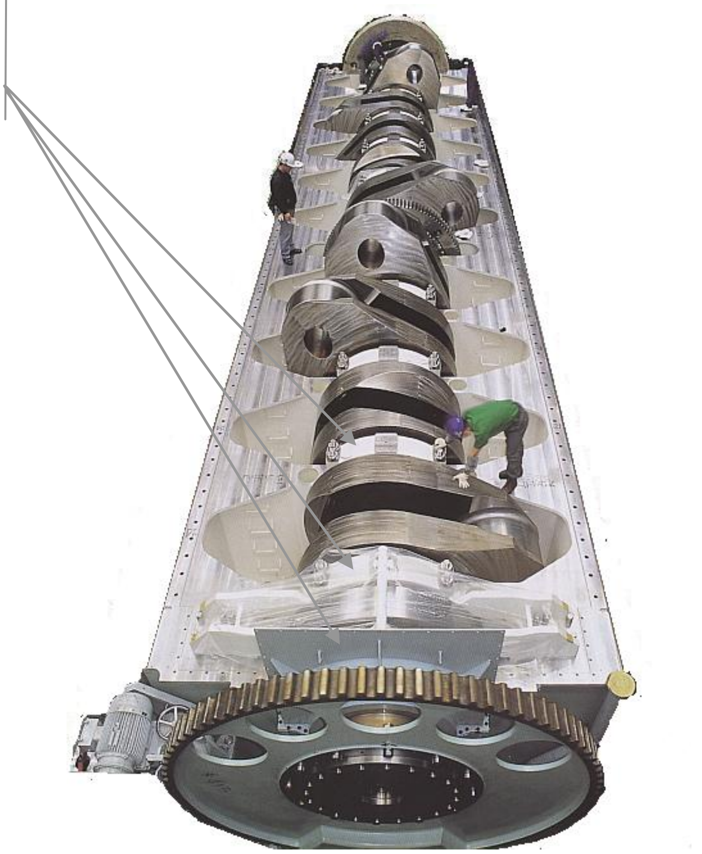
- *Crankshaft Deflections:* Originally, the crankshaft is delivered from the workshop with crankshaft deflections which are within tolerances defined by the engine designer. If the delivered crankshaft deflections are close to the tolerance limits, the interaction between the crankshaft and the rest of the propulsion system may easily result in crankshaft deflections exceeding the limits. Now, attempting to correct the unloaded M/E bearings by adjusting the intermediate shaft bearing offset may worsen the crankshaft deflections.
- *Stern Tube Bearing Load:* An attempt to rectify the crankshaft-deflections and the M/E bearing loading may result in worsening the stern tube bearing load distribution (relative misalignment between the bearing and the shaft). Particularly sensitive are installations without forward stern tube bearing.

Example: The alignment correction will be needed in cases when any of the engine bearings get unloaded.

The reason for M/E bearing unloading is almost exclusively caused by the disturbances coming from the shaft line (there are probably rare occasions where the cause of the internal engine misalignment is due to different reason – however, those exemptions will not be discussed here).

Accordingly, the alignment design is expected to affect main engine bearing loading of the three aftmost engine bearings. The most likely scenario is that the two aftmost engine bearings may get unloaded and the third one may encounter the edge load from the crankshaft.

FIGURE 13
Crankshaft Installation in the Engine



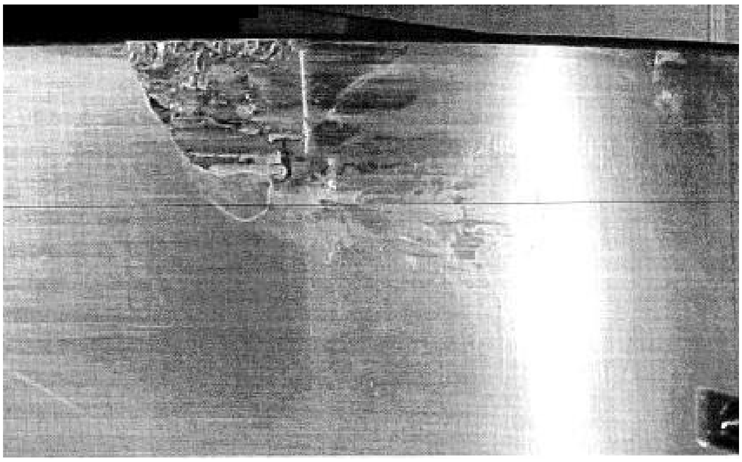
Unloading of the aftmost engine bearing may not be a problem per se, but it may result in overload on the bearing number 2 from the aft.

No load on the second aftmost bearing may have much more severe consequences from the combustion related pounding load, overload on the bearing No. 1 and 3, and the edge load on the bearing No.3.

Those bearings may get unloaded or lightly loaded which, in some cases, may have serious consequences if corrections are not applied.

Section 3, Figure 14 shows the damage of the lower shell of the M/E bearing, which is typical of hydraulic overloading (i.e., high oil film pressure). This may be an indication of significant crank-journal misalignment, and accordingly, high edge loading at the bearing.

FIGURE 14
Diesel Engine Bearing Damage due to Edge Loading



12 FAQ – Problems and Solution

Given below is a list of some very possible arguments and replies:

Problem: As measured, the dry dock alignment is very different from the calculated values for the dry dock condition.

> *Solution:* There are a number of factors which may deteriorate and change the alignment condition of the shafting in the dry dock. Primarily, the dry dock procedure (as proposed in Subsection 3/1 above) is strictly followed. Any deviation from it may result in a condition that cannot be easily rectified. The first problem is noncompliance and deviation from the primary requirement, that structural work on the stern part be completed to the extent to which it will not introduce significant disturbance into the bearing offset.

Problem: Even with sighting-through conducted with almost completed structural work, the bearing reactions are not adequately close to the calculated values.

> *Solution:* If the sighting through is conducted under certain thermal condition, the bearing offset, and accordingly, bearing reactions, may be affected if reaction measurement is conducted under different thermal conditions. The sighting through is normally conducted in the early morning hours before sunrise to ensure an even temperature distribution throughout the structure. If reaction measurement in the dry dock is conducted during the day when structural deformation due to the sun exposure affects the hull unevenly, the bearing reaction readings may be significantly different. It is therefore important either to account for these differences or to conduct the reaction measurements in the early morning hours, as well.

Problem: What is the point of conducting the thorough measurements in the dry dock if the alignment will change once the vessel is waterborne. Moreover, no information on the effect of hull girder deflection on bearing offset change is available.

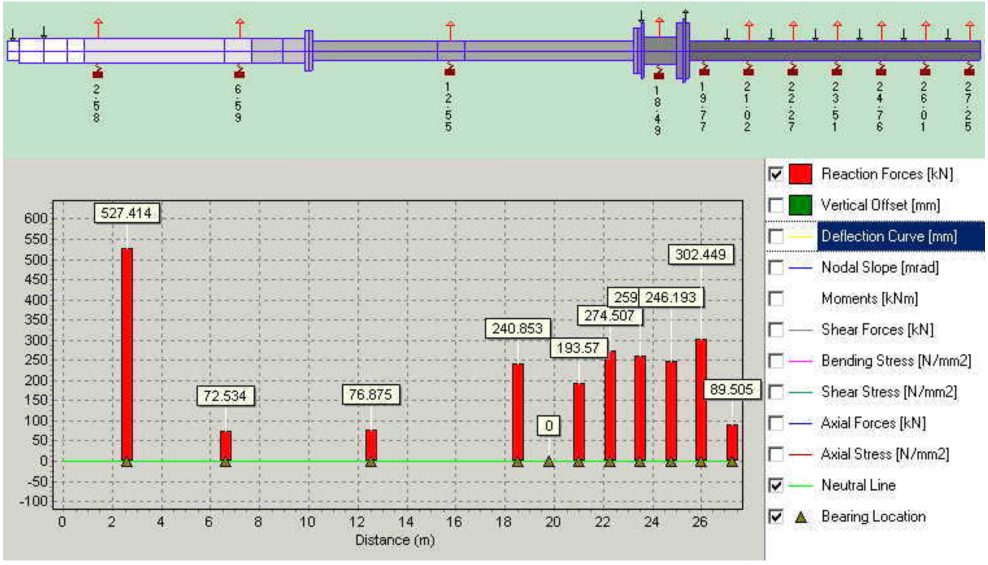
> *Solution:* If alignment analysis is conducted without hull girder deflection consideration, it is difficult to determine the alignment of a waterborne vessel without specialized software (such as finite element analysis, or the shafting alignment software which has ability of estimating hull deflections for certain categories of ships - see Section 6 and Section 7 for more details). The alignment condition then relies on the knowledge and experience of shipyard's production personnel.
>
> However, this does not necessarily renders dry dock alignment useless. Often the experienced designers, even though not directly accounting for hull deflections, will include some educated prediction of the expected waterborne alignment when designing the dry dock alignment. In other words, the alignment as designed for the dry dock may not look acceptable. However, if correctly designed, the shaft alignment will contain correction for the expected disturbances. (See example below.)

Example:

VLCC with directly coupled low speed diesel engine to the propeller.

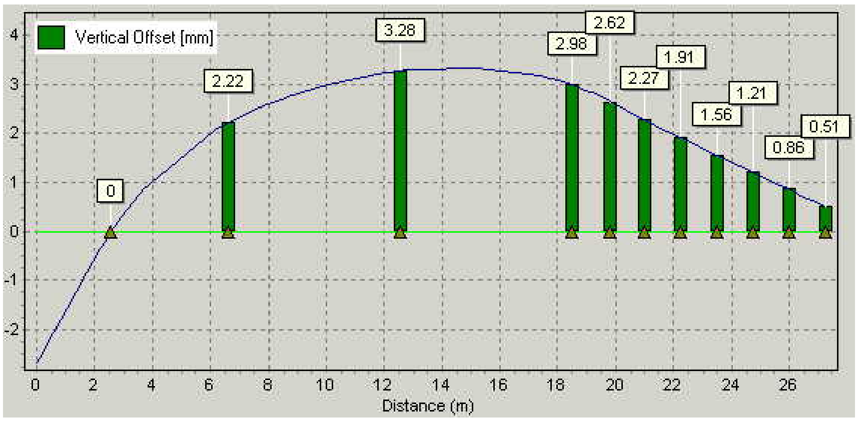
Dry dock alignment is conducted with an unloaded 2nd M/E bearing.

FIGURE 15
Bearing Reactions for a Dry Dock Alignment with Intentionally Unloaded Second Main Engine Bearing



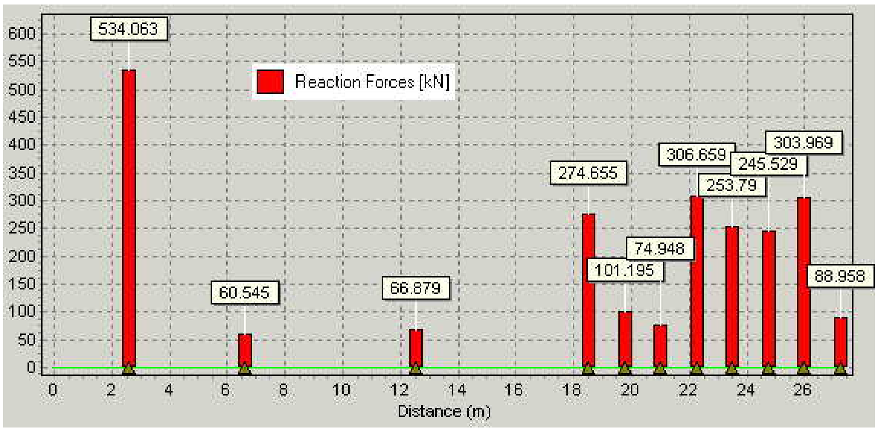
Prescribed displacements for which the above bearing reactions are obtained are selected as below.

FIGURE 16
Deflection Curve and Bearing Offset for Dry Dock Condition, which Resulted in Intentionally Unloaded Second Main Engine Bearing



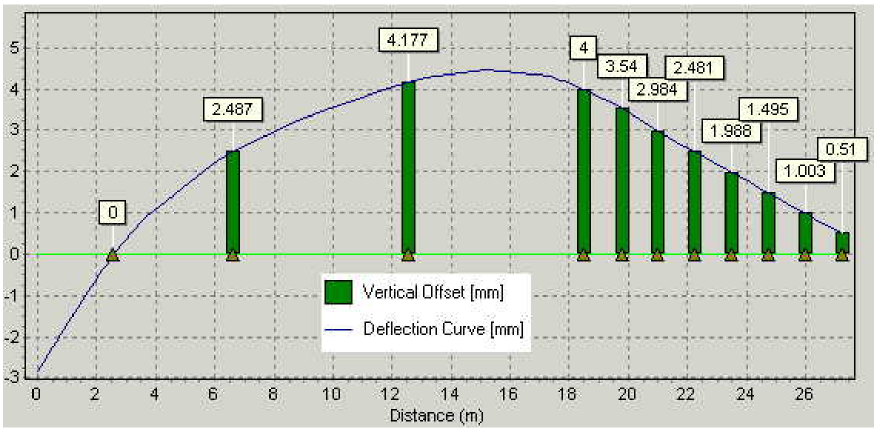
The above approach can be taken by an experienced designer who is able to predict that the 2nd M/E bearing will pick up load once the M/E bearing sagging is introduced and vessel is afloat[9]. In Section 3, Figure 17 below, it is shown how bearing reactions may change when the vessel waterborne condition is considered and the dry dock bearing offset is changed by the amount of hull deflections and engine bedplate sagging. (The particular example considers laden vessel deflections).

FIGURE 17
Bearing Reactions for a Waterborne Vessel – Rectified by Hull Deflections and Bedplate Sag



Hull deflection intensity will depend on the vessel loading condition (see Section 6, "Hull Girder Deflections" and Section 7, "Alignment Optimization"). Vertical offset for laden vessel will be quite different than for ballast vessel. Alignment needs to satisfy both conditions (Section 7).

FIGURE 18
Total Vertical Offset at the Bearings Including Prescribed Displacements, Hull Deflection Estimate and Bedplate Sag



The above shows exactly the reasons why the dry dock alignment is so important.

---

[9] Experience in alignment design is very important, however, even the experienced designers may have problems in ensuring acceptable alignment condition under all operating conditions of the vessel. This is where optimization software is an indispensable tool.

Question: Why is it recommended not to have engine/gear-box and bearings chocked before the waterborne alignment condition is verified?

> *Answer:* Even if the hull deflections are accounted for, and alignment in the dry dock is close to the analytical predictions, there is a need to ensure provision for alignment fine tuning and adjustment if, for some unpredictable reason, alignment in the afloat condition ends up being unacceptable. Accordingly, the alignment of the waterborne vessel needs to be verified and adjusted if necessary. For that reason, chocking of the engine and the intermediate shaft bearing shall be conducted only after the alignment is verified for waterborne vessel.

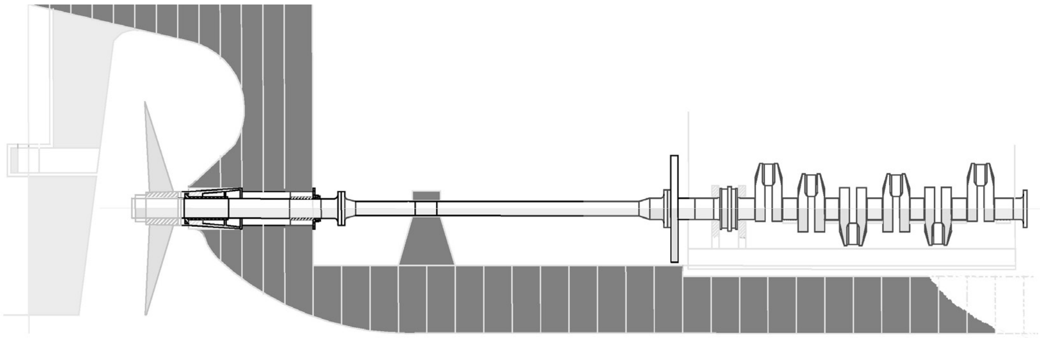
Question: What about a smaller vessel? Is the proposed procedure applicable to smaller vessels as well?

> *Answer:* The above procedure is applicable to smaller vessels too. However, smaller vessels historically have less severe alignment-related problems, as the propulsion shafting is more flexible and the structure more compact than in larger vessels.

Problem: If there is no easy way to evaluate hull deflections, why is it then required that shafting should comply with any specific requirement for the dry dock condition if it is known that hull deflections, once the vessel is afloat, will disturb it all to the point of resulting in unacceptable reactions?

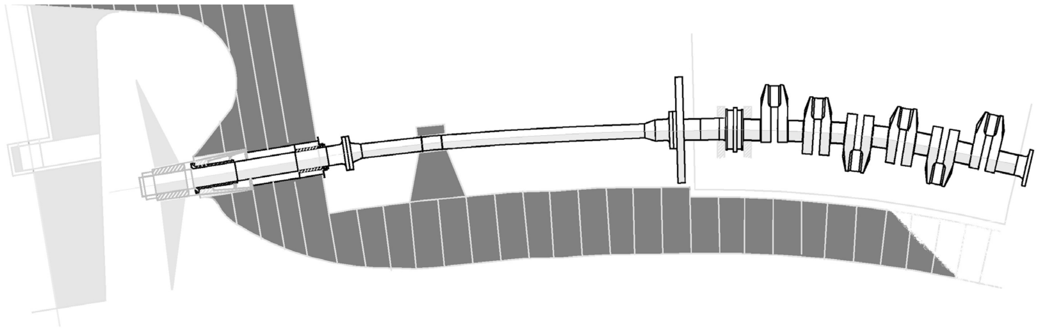
> *Solution:* It is the builder's responsibility to ensure sound and safe operating condition of the shafting, as well as the vessel as a whole. A mismatch between the alignment analysis and the procedure itself starts at the very beginning of the alignment process. The shaft alignment analysis and the procedure are often in conflict as the high accuracy requirements for the shaft alignment analysis on one side do not match the relaxed tolerances in vessel construction on the other. This would not be a problem had the alignment procedure been conducted under the following conditions:
>
> - With vessel completed to the extent where all major welding works are finished and all heavy loads are in place.
> - Hull deflections are known or evaluated with sufficient accuracy.
> - Alignment is conducted and verified in a controlled manner.
>
> As already mentioned, the ideal condition for performing the propulsion shafting alignment procedure would be in the dry dock before the vessel is launched. However, to be able to comfortably rely on dry dock alignment, it is necessary to be able to predict hull deflections with relatively high confidence, and to be able to design the dry dock alignment robustly enough to prevent minor disturbances that may adversely affect 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 ABS is now able to provide to the industry a state of the art shafting alignment optimization tool (Section 7).
>
> Accordingly, it is important to know/predict the hull deflections as accurately as possible. However, if the vessel is not in the dry dock, it is difficult to establish a reference line against which the alignment condition may be verified.
>
> An optical line of reference is established during the sighting process while the vessel was in the dry dock (Section 3, Figure 19). After the vessel is launched, this line is distorted due to the hull deflections. If it is not possible to accurately predict the extent of hull deflections, the reference line is essentially lost. Consequently, without knowledge of offset change with hull deflections, the alignment process may not be verified with the desired accuracy.

FIGURE 19
Vessel in Dry Dock



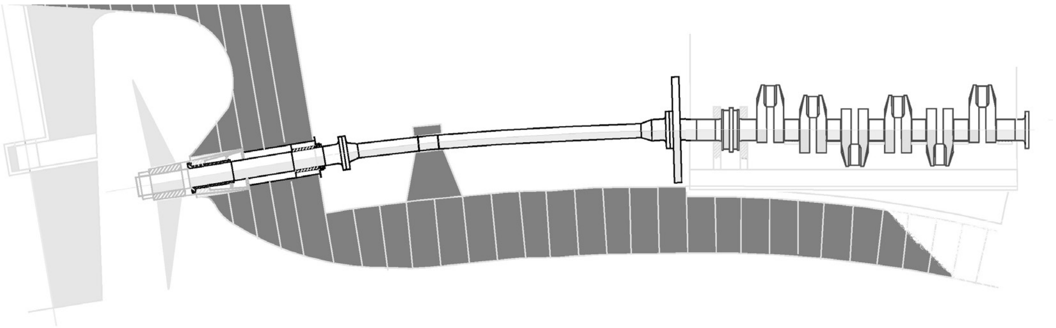
In order to protect the diesel engine from damages due to a possible inadequate alignment, engine designers normally require application of the engine's bedplate sagging after vessel is afloat (Section 3, Figure 20). The bedplate sagging is supposed to rectify and diminish hull deflection influence on the engine alignment. It is primarily meant to cancel out deflections that occur while the vessel is afloat, and further reduces the influence of the hull's hogging as the vessel gets loaded.

FIGURE 20
Vessel Waterborne – Hull Deflections Affect the Propulsion



However, this correction, applied to the engine after the vessel is afloat, results in an inconsistent alignment procedure (Section 3, Figure 21). The established dry dock reference line is now changed only in the section below the main engine (M/E). The rest of the propulsion system remains affected by the hull deflections. The shafting and the engine are now aligned to the different base lines (one which is known initially is defined in the dry dock, and the other one, essentially unknown, is established for engine realignment and bedplate sagging after the vessel is launched). The consequence is the shafting affected by hull deflections on one side, and the M/E on the other side rectified for the even keel condition.

FIGURE 21
Vessel Waterborne – Engine Sag Applied



What essentially happened is that control was gained over the engine alignment (engine reference line is now known), but the possibility of accurate control of the alignment condition of the shafting was practically lost, as well as the stern tube bearing condition.

The solution to the analysis-procedure inconsistency problem may be in conducting the whole shafting alignment procedure with the vessel in the dry dock where the procedure can be accurately verified against the analysis. In order to align the system in the dry dock, it is necessary to be able to:

- Estimate hull deflections, as the alignment needs to be satisfactory with vessel afloat.
- Define the optimal set of prescribed bearing displacements to ensure a robust alignment which is relatively unaffected by hull deflections when vessel is afloat.
- Conduct the whole alignment procedure in the dry dock.

In order to allow some provision for corrections, the shaft line bearings, as well as the diesel engine or gearbox, should not be chocked until the bearing condition is satisfactory in the afloat condition.

The final step in the alignment procedure is verification of the alignment condition, normally conducted by measuring bearing reactions. Section 5 is solely dedicated to alignment measurement.

*Question: S*hould the eccentric propeller thrust be included into the alignment calculation?

Answer: Propeller thrust should be part of the investigation of the shafting behavior. There is no problem if the dynamic thrust from the propeller and all the other significant dynamic actions are accounted for in proper dynamic analysis. ABS Rules also require that whirling and lateral vibration be investigated.

There is a problem when dynamic forces are taken as a pure static action in static analysis, and results are even used to contradict the pure static calculation.

ABS believes there should be three separate approaches:

- First is a static analysis
- Second may be a hybrid analysis where the static model utilizes dynamic loads as well, and
- Third should be a dynamic analysis.

ABS requires a static analysis because analytical data is needed which can be used to verify measurements. Measurements are conducted when shafting is at rest, so if dynamic loads are included in the analysis, there will be false and incomparable information.

A static condition to design the slope boring of the stern tube bearing will also be needed.

An acceptable static condition will normally yield satisfactory dynamic operation. Whirling and lateral vibration is very much dependent on bearing position (vertical as well as horizontal). If there are dynamic problems suspected, the full-scale dynamic analysis should be conducted.

ABS accepts application of dynamic loads in static analysis as a good practice. ABS would agree that a simplified approach with dynamic forces (acting on gears and propeller) may, and does, provide sufficiently good data for strength estimate, or evaluation of the thrust block stiffness, etc. However, getting into fractions of millimeters precision that alignment requires with dynamic-loads in static model should not be acceptable without scrutiny, as the results of this kind of analysis could easily be misleading.

Dynamic analysis should definitely be an area in which to look for answers on dynamic actions if potential problems using hybrid models are noticed.

Comment: Special care should be taken for tolerances in GAP/SAG values. The effect of minimum tolerances to alignment should be checked. A limitation for minimum tolerances should be given. This would ensure the alignment work is practicable and that sensitivity (influence numbers) of alignment is reasonable.

Answer: Sag and gap is considered to be a good check method to verify the pre-assembly condition. The problem with sag and gap is the inaccuracy of the procedure itself, which is more pronounced on shafts of larger diameter.

Accuracy of the method is limited because of the aspect ratio between the system geometry (large diameters of flanges - over 1 meter, and Gap and Sag values that are measured in millimeters or fractions of millimeters.

The tolerances for sag and gap are limited to the equipment used in verification of the same. The dial gauge accuracy is up to 0.001 [mm], and the filler gauge accuracy cannot be obtained greater than 0.05 [mm]. It is often difficult to measure precisely with filler gauges, and gaps are almost exclusively measured with them. Errors of 0.1 [mm] or greater are very common.

Question: Why is there no criteria distinguishing shafting systems which are sensitive to the alignment problems from those that are less or not sensitive? It would be useful for the industry if for the shafting segments between the bearings some kind of acceptability factor/ratio is established, correlating influence coefficient factor and the length of the subject segment.

Answer: We consider it difficult to establish numerical factors which would consistently distinguish alignment-sensitive propulsion systems from those that are not. The primary problem in establishing such numerical values is that the sensitivity of the alignment is not only related to shafting itself, but to the hull structure flexibility as well. Namely, the shafting may be relatively rigid, but if the hull structure stiffness is high as well, the propulsion system may not be more sensitive to the hull deflection than when more elastic shafting is installed.

SECTION 4 Shaft Alignment Survey

1 General

As per ABS Rules, the shaft alignment is to be carried out in the presence of a Surveyor. Alignment is normally to be verified in the afloat condition with superstructure in place. 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 data are to be verified and recorded by appropriate measurement procedures in the presence and to the satisfaction of a Surveyor.

The above Rule requirement is a general statement which primarily obligates the shipbuilder to ensure the presence of the Class Society during the alignment procedure. However, when it comes to acceptance criteria, there may be quite a few questions that need to be answered. These Guidance Notes will try to address some of the most important ones:

- When is Surveyor's attendance required?
- Which information is Surveyor to be familiar with when attending alignment?
- What is an appropriate measurement procedure?
- Should the alignment be accepted if verified in dry dock condition only?
- Is alignment acceptable if bearing positioning and slope boring are conducted with substantially incomplete welding, and/or no superstructure in place?
- Is Sag and Gap measurement sufficient procedure for alignment verification?
- Is it sufficient to verify bearing reaction for only one bearing, and based on it accept the alignment?
- What are the reaction measurements acceptability tolerances?
- When is slope boring required?
- How to address different construction practices?

2 Alignment Acceptance Criteria

Shaft alignment is acceptable for all operational conditions of the vessel, if the following is satisfactory:

- Bearing reactions are positive on all bearings.
- Misalignment slopes are acceptable.
- Crankshaft deflections are within engine maker's limits.
- Gear contact is acceptable.
- Stresses are not contributing significantly to the total stress level.

2.1 Attendance

When and where is Surveyor's attendance important?

What is important to be verified during the alignment procedure?

- Equipment calibration record
- Pre-shaft-assembly Survey
- Sighting through
- Slope boring
- Sag and Gap
- After-shaft-assembly Survey
- Bearing reaction
- Shaft runout
- Bearing-shaft misalignment (front aft, port-starboard)
- Crankshaft deflections
- Engine bedplate deflections
- Gear contact
- Gear shaft bearing reactions

2.2 Required Information

Surveyor needs to be provided with stamped alignment analysis, review letter and alignment procedure. The important details the Surveyor should become familiar with are:

- Prescribed bearing offset
- Bearing reactions
- Slope boring requirement
- Influence coefficient matrix
- Alignment procedure

2.3 Measurement Procedure

Any measurement procedure which directly or indirectly provides information on bearing reactions for any operating condition of the vessel is considered to be an acceptable method for reaction verification. In this regard, the jack-up and the strain gauge measurements are acceptable procedures, and the Sag and Gap is not.

Alignment condition of the main engine has to be balanced with the requirement on crankshaft deflections. If necessary, the shipbuilder will readjust the alignment in order to comply with crankshaft deflection requirements. If such a readjustment is conducted, the Surveyor may request repeated verification of the bearing reactions.

2.4 S/T Bearing Wear Down

The shafting alignment condition can also be assessed through the after stern tube bearing wear down measurement. This measurement will not provide much information about the rest of the shafting, however, it will be important information about stern tube bearing misalignment condition, and how it performs with time.

The measurement is regularly performed during the tailshaft surveys. It is conducted with a poker gauge located at the after seal. The amount of the shaft drop will indicate the wear down of the bearing.

2.5 Dry Dock Alignment

The alignment should not be accepted if verified in dry dock condition only. It should be verified for at least one afloat condition.

Moreover, as per ABS Rules, alignment needs to be satisfactory under all operating conditions (meaning for hot and cold engine and ballast and laden vessel). It is, however, at the discretion of the attending Surveyor to decide if the alignment can be accepted based on one or two sets of measurements only. The Surveyor's decision shall be made upon reviewing measurement compliance with respective analysis and in the Surveyor's confidence in shipyards' practices, and satisfactory experience with vessels of similar design.

2.6 Noncompliance with Construction Completion Requirements

The final alignment condition may vary significantly from its design condition if the stern structural blocks were not welded at the time that the alignment sighting through and Sag and Gap were conducted, as well as when significant weights were placed on the stern part of the structure after the alignment was conducted.

It is therefore strongly recommended to conduct the alignment starting from bore sighting with the stern of the vessel being as complete as possible.

2.7 Sag and Gap Acceptability

The Sag and Gap measurement is not a sufficient procedure for alignment verification, and it cannot be accepted as the sole means of alignment verification as the Sag and Gap accuracy is relatively low.

The Sag and Gap procedure, although not accurate, is a useful and fast way of confirming the alignment condition prior to shafting assembly, and if larger discrepancies from analytical values are noticed, it can indicate that the sighting through was significantly disturbed before the propulsion machinery installation, or the analysis was erroneously conducted.

2.8 Number of Bearings to be Verified

Verifying alignment condition by single bearing reaction measurement should not be an acceptable practice. In case the jack-up method is utilized in reaction verification, it is recommended that reactions are measured at forward stern tube bearing (if installed), intermediate shaft bearing, and depending on the propulsion system design, at least on one M/E bearing or gear shaft bearing.

2.9 Reaction Measurement Acceptability

In the shaft alignment analysis, it is suggested that the minimum bearing reaction be not smaller than 10% of the allowable load on the bearing (see 2/3.4.3). These criteria are set to prevent bearing unloading due to various reasons (e.g., installation errors, unexpected thermal influence, incorrect prediction of hull deflections, runout, etc.).

An acceptable limit for measured bearing reaction would be ±20% variation of the designed value. This would be a good match with a theoretical requirement being 10% of the allowable load at the bearing[10]. In that case, alignment may be considered acceptable without additional requirements.

However, the measured reaction deviation from the calculated value is often much greater than ±20%, and it can easily vary ±50% or more. In these cases, the Surveyor has to verify that the measurement condition of the vessel (dry dock, afloat, ballast, laden, propeller immersion, etc.) matches the condition that the analysis is conducted for. If no analysis is conducted for a particular vessel condition, the assurances that the alignment is acceptable may be required (i.e., measurements on additional bearings to confirm reaction load is acceptable, and an appropriate analysis for corresponding condition that is measured).

---

[10] Why is the measured tolerance ±20% of the calculated value, and theoretical minimum ±10% of the maximum allowable value? The actual bearing reaction is smaller than the maximum allowable value. Therefore, the actual load variation of ±20% at the bearing may be close to 10% of the maximum allowable load. In addition, if load at the particular bearing is ±20% reduced, this means that the adjacent bearings will share the extra load.

The reaction measurement indicates whether the bearing offsets are as designed or deviate from the original proposal. When measured reactions deviate from the design values, the offset will vary proportionally. This signifies that the bending curvature of the shaft is changed as well. The bending curvature is particularly important to be controlled at the after stern tube bearing. When bearing reaction deviation is large, it is important to inquire how the bearing reactions deviation (even when resulting in all positive bearing reactions) affects the bearing misalignment (consult Subsection 3/10).

It is suggested that the Surveyor consult the Influence Coefficient Matrix, as well as the Intermediate Bearing Offset Adjustment procedure (Subsection 3/10) to verify how the reaction change on a particular bearing influences the adjacent bearings. The reason that reactions vary significantly has to do with all of the problems related to the alignment design and procedure that have already been addressed in Sections 2 and 3.

2.10 Slope Boring

As per the ABS *Rules for Building and Classing Steel Vessels*, the shipbuilder is advised to consider the slope boring of the after stern tube bearing in cases where the shaft to bearing relative misalignment exceeds 0.3×10^{-3} rad (see Subsection 3/4).

2.11 Dry Dock Alignment

If an alignment is conducted and verified in the dry dock, at least one bearing condition should also be verified when the vessel is waterborne.

2.12 Shaft Runout

Shaft runout may significantly affect bearing condition, and in extreme cases may result in failure of the bearing or the stern tube seal. If bearing reactions are measured using strain gauges, it is straight forward to verify runout of the shaft. The shaft runout can be verified by dial gauges simultaneously measuring shaft movement as the shaft slowly rotates.

2.13 Construction Practices

Some shipbuilder’s construction practices are more prompt to alignment problems than others. Ideally, the builders would be expected to conduct the alignment after all major work of the vessel’s stern part are completed (i.e., welding of the main seams is completed, and all heavy structure and equipment is in place). Deviation from this may be acceptable in some cases if the Surveyor is confident that the builder is capable of controlling alignment and ensuring that the final alignment is in compliance with the Rules.

The way that the Surveyor may ensure compliance with the Rules in cases when not satisfied with the shipyard’s alignment procedure, is to request verification of the bearing location and confirmation of the stern tube bearing slope after the stern-block is welded to the vessel’s structure (verification is standard sighting through procedure prior to the shafting being placed into the vessel).

SECTION 5 Alignment Measurements

1 General

Although the propulsion shaft alignment measurement is considered to be an integral part of the shaft alignment procedure, for the reader's convenience, this Section is dedicated to elaborate on the measurement particulars.

The propulsion shaft alignment is defined as a static condition observed at the bearings supporting the propulsion shafting. To verify acceptability of alignment, it must be confirmed that the following minimum set of parameters are acceptable:

- Bearing reactions
- Bearing vertical offset
- Misalignment angles
- Crankshaft's web deflections (indirect confirmation of the crankshaft strength)
- Gear misalignment (indirect confirmation of the gear load)

All of the above have already been addressed from another angle in previous Sections, including the design and the construction process. This Section will tackle the same issues from the point of view of condition confirmation after construction. Moreover, this Section will also provide some requirements on:

- Sag and Gap
- Shaft eccentricity
- Stress measurement in shafting (bending moment, shear force)

Not all of the above measurements are required or conducted on every vessel. Normally, the following measurements are performed:

- Sag and Gap
- Bearing reactions
- Crankshaft deflections
- Bearing misalignment
- Gear misalignment (where applicable)

2 Bearing Reaction Measurements

Bearing reactions are generally measured utilizing:

- Hydraulic jacks, or
- Strain gauges.

2.1 Jack-up Method

Related topics:

- Reactions Measurement (Subsection 3/7)
- Hull Deflection Measurements (Paragraph 6/3.2)

Jack-up method is a direct way to check bearing reactions. Due to its simplicity, it is the most widely applied method in the industry. Measurements are conducted by hydraulic jacks which are placed in close proximity to the bearing which reaction is to be measured. It is strongly recommended to use hydraulic jacks in combination with the load cell, as the measurement accuracy will significantly improve.

The advantages of the jack-up method are:

- It uses simple measuring equipment such as hydraulic jack and the dial gauge.
- Accuracy is significantly improved in combination with load cell measurement.
- It is the only method that provides reaction load directly.

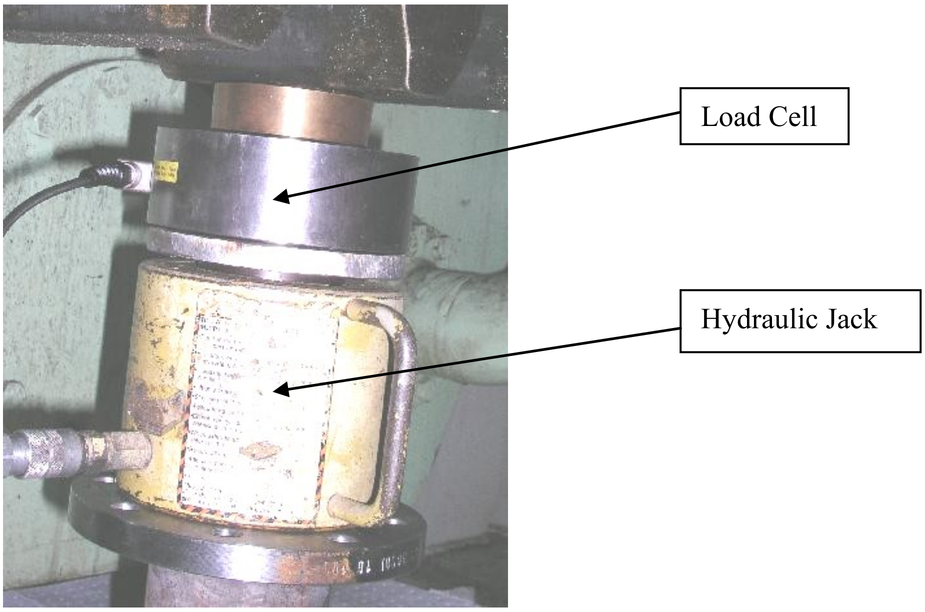
The disadvantages of the jack-up method are:

- It requires the same preparation time for each repeated measurement.
- Measurement results in wide hysteresis if load cell is not used.
- Installation inaccuracies due to:
    - Misalignment of the hydraulic jack
    - Misalignment of the dial gauge
- Although it directly records the load, jack-up method does not measure bearing reaction directly, as the jack is lifting next to the bearing location. This requires correction factors to be applied which introduce some error as well.

The method requires the following equipment:

- Hydraulic jack (ram)
- Load cell
- Dial gauge

FIGURE 1
Hydraulic Jack with Load Cell



Hydraulic jack should be located as close to the bearing as possible. The foundation on which the jack is placed should be sufficiently stiff.

Jack-up measurement may also be used for the shaft runout verification. However, the jack-up method is not very suitable for it since the shaft rotation can be applied only in steps, one angle of rotation at the time.

When engine aftmost bearing reaction is measured, attention should be paid that the turning gear being declutched from the flywheel. If this is not ensured, bearing reactions may be incorrectly obtained as the turning gear introduces significant horizontal force which consequently moves the crankshaft contact with the aftmost bearing sideways.

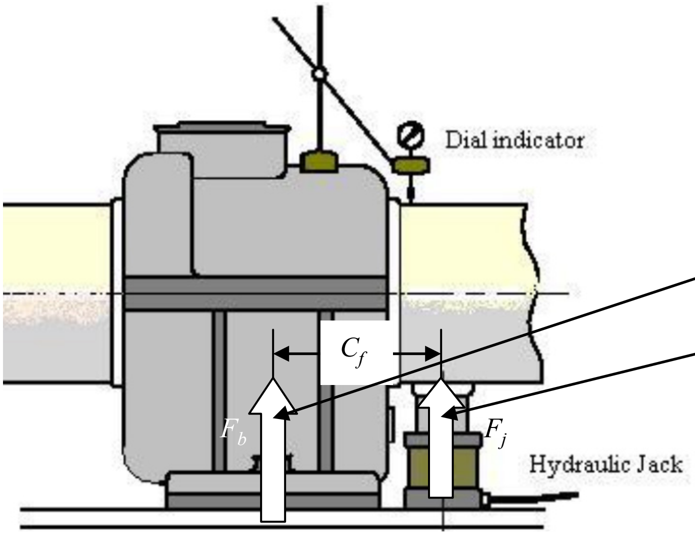
The load redistribution problem may also be related to the turning gear lock-up. The turning gear not only moves the shaft horizontally, but also locks some portion of the reaction at the contact point between gears.

FIGURE 2
Digital Dial Gauge

The dial gauge should be anchored on the structure which is not affected by the lifting. If the structure is too flexible, the jack load can move the dial gauge anchor as well, thus resulting in erroneous readings.

When the jack-up procedure is performed, it is suggested that the displacement of the top of the shaft be controlled and the load read for each step on the dial gauge. A smoother curve may be generated by applying this procedure, which will eventually provide more accurate recalculation of the bearing reactions.

FIGURE 3
Reaction Measurement at Intermediate Shaft Bearing



Although the hydraulic jack records the load directly, it does not measure the bearing reaction directly.

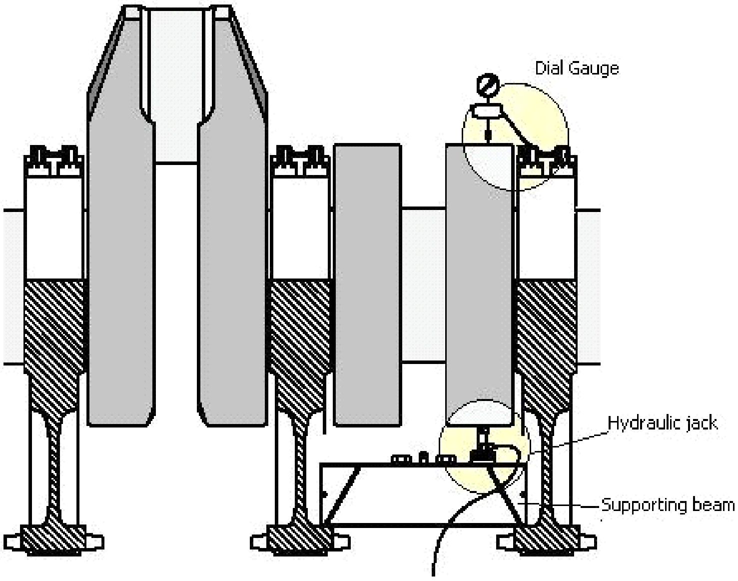
Jack is placed near the bearing and the actual reaction

(F_b) can be correlated to jack reaction

(F_j) via a correction factor (C_f):

$$F_b = C_f \cdot F_j$$

FIGURE 4
Jack-up Measurement of the Bearing Reactions Inside Diesel Engine



Compliance of the jack-up procedure with the analytical model can easily be verified by observing the jack-up procedure gradient. The jack-up gradient is an angle of the lifting/lowering curve. The jack-up gradient is normally expressed as change in lifting force over change in vertical offset. Gradient values are normally given as a regular output of the shaft alignment analysis.

Jack-up gradients are often called Influence Coefficient values and are presented in the form of a influence coefficient matrix.

2.1.1 Example:

The influence coefficient matrix below is produced by ABS shaft alignment software for a five bearing system.

TABLE 1
Sample Influence Coefficient Matrix

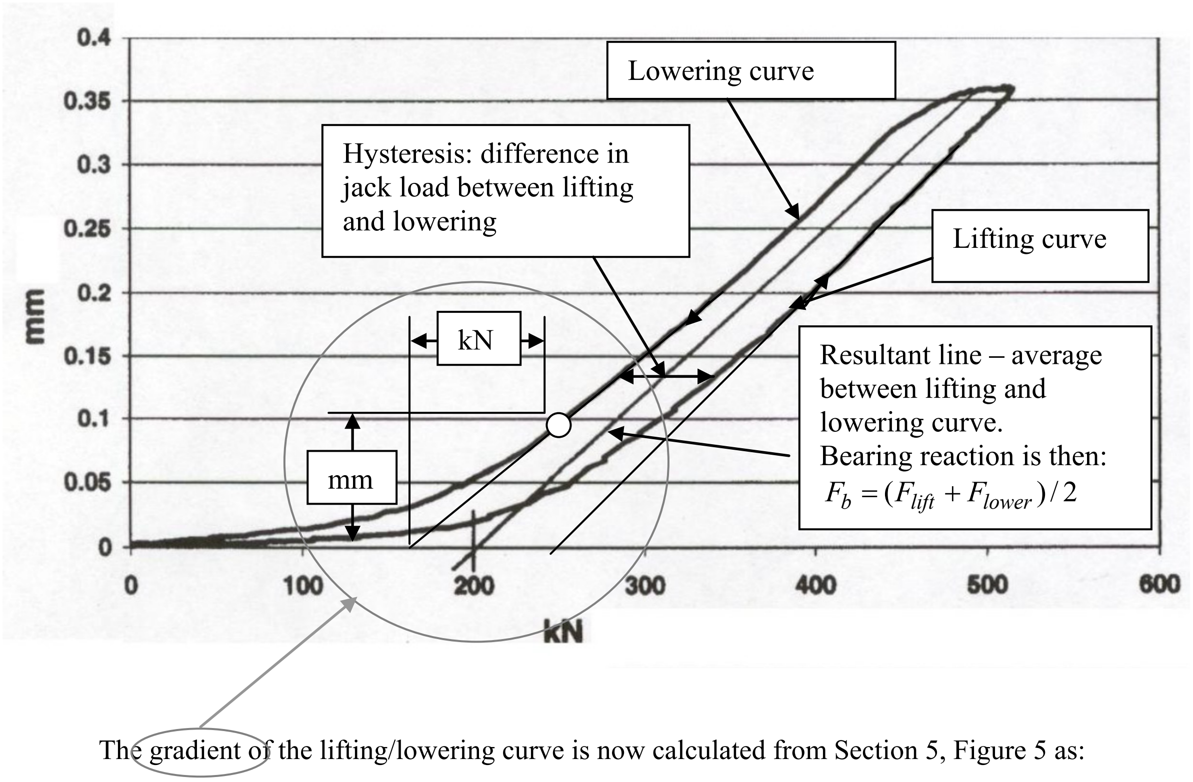
```
RELATIVE BEARING REACTIONS [kN] -> R[0.1-offset]-R[0-0ffset]
   Due to 0.1[mm] OFFSET relative to the ZERO bearing Offset
  Node      |  <  7>     < 14>     < 27>     < 41>      < 46>
       Supp.|     1         2         3         4          5
   ------------------------------------------------------------
 <  7>    1 |    4.289    -7.896     4.768    -3.222      2.120
 < 14>    2 |   -7.896    15.425   -11.112     9.951     -6.546
 < 27>    3 |    4.768   -11.112    13.421   -25.421     18.858
 < 41>    4 |   -3.222     9.951   -25.421   166.594   -250.824
 < 46>    5 |    2.120    -6.546    18.858  -250.824    511.825
```

```
Each column provides bearing reactions 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)
```

The rounded value in Section 5, Table 1 represents the gradient of the jack-up curve when bearing #3 is lifted.

The influence coefficient matrix can also be used to verify accuracy of the jack-up procedure. The matrix is generated to provide information on reaction change due to the unit lift applied to a particular bearing. This information may also be obtained from the jack-up curve and those numbers easily compared with analytical values. However, an influence coefficient matrix generated for the location of the jacks is needed.

FIGURE 5
Jack-up Curve



The gradient of the lifting/lowering curve is now calculated from Section 5, Figure 5 as:

$$\text{Gradient} = \frac{\text{Force Change}}{\text{Displacement Change}} \frac{\text{kN}}{\text{mm}}$$

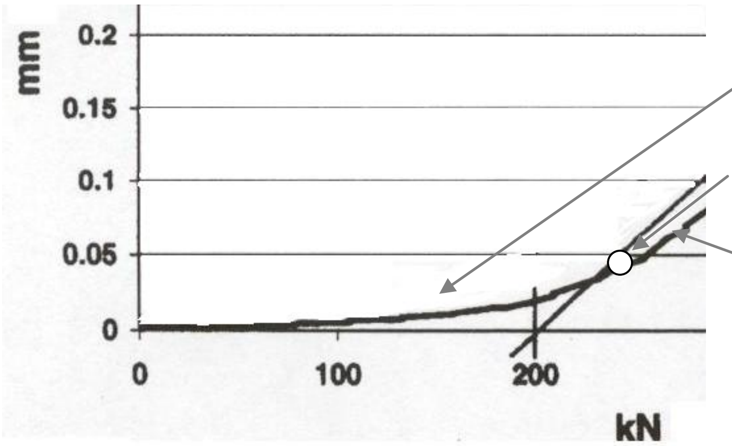
The resultant line which represents an average between the lifting and lowering curve needs to have a gradient, as defined by Influence Coefficient Matrix as well.

For example, if bearing #3 reaction is measured, the expected jack-up gradient can be found from the influence coefficient matrix (Section 5, Table 1) by intersecting row #3 and the column #3.

The value obtained by reaction measurement should be close to the calculated value.

2.1.2 Lifting

The following behavior can be seen during lifting of the shaft:

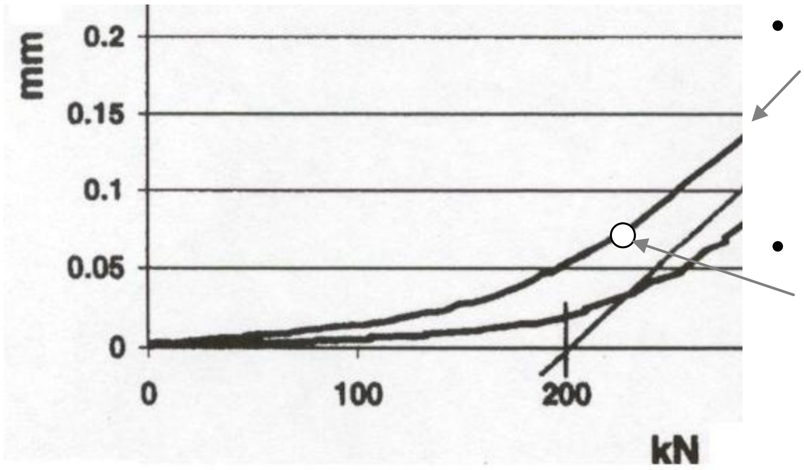


- Initially, when the hydraulic jack starts taking the load, the bearing is still carrying some load. This stage is represented by a relatively flat curve.
- Until load is completely transferred to the hydraulic jack, lifting curve gradient increases slowly.
- This is a breaking point when jack completely detaches the shaft from the bearing.
- As the lifting continues, the lifting curve becomes much steeper with gradient being relatively constant.

Lifting stops after a sufficient number of points are obtained to define the gradient of the jacking curve. The process then reverses and the hydraulic jack lowering starts. Again, the same number of points is recorded as during the lift.

2.1.3 Lowering

At the start of unloading of the hydraulic jack, the path that will be obtained will not be the same as that for lifting. The reason for this difference is friction in the hydraulic jack. Lowering shaft curve is similar in shape to the lifting curve. The lifting shaft curve is shifted left due to the following:



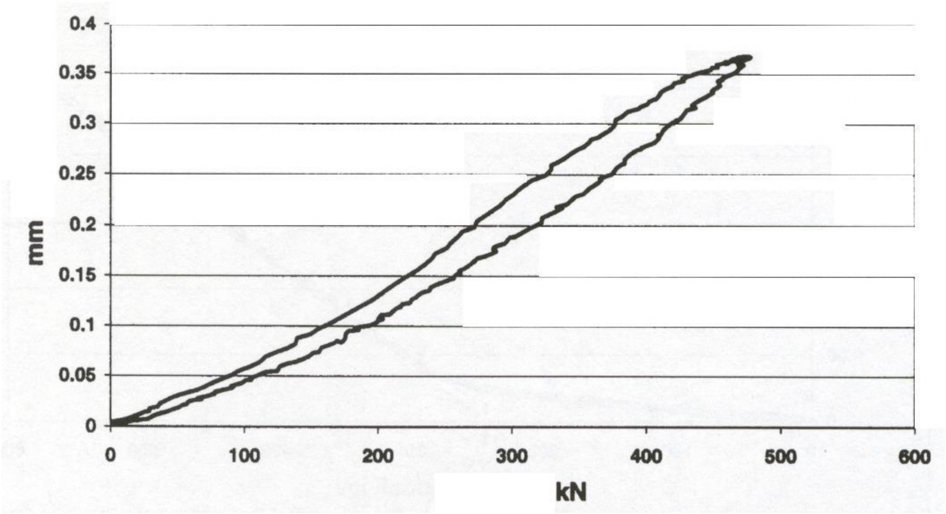
- Load reduces linearly as a vertical offset of the jack lowers. Gradient of the lowering curve is constant until the point where bearing starts picking the load again is reached.
- This is a breaking point from which the bearing starts picking up the load. From there on, the gradient of the lowering curve changes nonlinearly.

2.1.4 Unloaded Bearing

In the case that the bearing that is measured using the jack-up method is unloaded, the following pattern will be observed:

- There is no transition period of relatively low gradient.
- Jack immediately picks up the load and the gradient of the lifting/lowering curve remains relatively constant throughout the measurement.

FIGURE 6
Jack-up Curve for Unloaded Bearing



2.2 Strain Gauge Method

Related topics:

- Reactions Measurement (Subsection 3/7)
- Hull Deflection Measurements (Paragraph 6/3.1)

The advantages of the strain gauge method are:

- It can provide relatively accurate information on the loading condition of the bearings not accessible for jack-up measurements.
- Once the strain gauges are mounted, measurement can be easily repeated within a very short time.
- It can provide data about vertical and horizontal load at the bearings.
- It can provide simultaneous information on more than one bearing load.
- Measured strains and the corresponding bending moments provide invaluable information on shaft bending curvature, which can be further utilized in so-called "reverse calculation" of the actual bearing position.

The disadvantages of the strain gauge method are:

- It requires a relatively long time for equipment installation (approximately one hour per measurement point).
- Accuracy of the data depends on system modeling.
- It requires relatively sophisticated and expensive equipment for measurement.

The strain gauge technique for shaft bending moment measurement is based on a basic beam relationship

$$M = E \cdot W_p \cdot \varepsilon$$

where

E = Young's modulus

ε = strain

W_p = section modulus (for circular shape = $\pi \frac{D^3}{32}$).

Strain gauges measure strain. The shaft's flexion deforms, strains the gauges glued on the shaft's surface, thus changing the gauges' resistance. Accordingly, the strain can be calculated:

$$\varepsilon = \frac{V_o}{V_{ek}} \cdot \frac{1}{k}$$

$$\varepsilon = \frac{\Delta R}{R} \cdot \frac{1}{k}$$

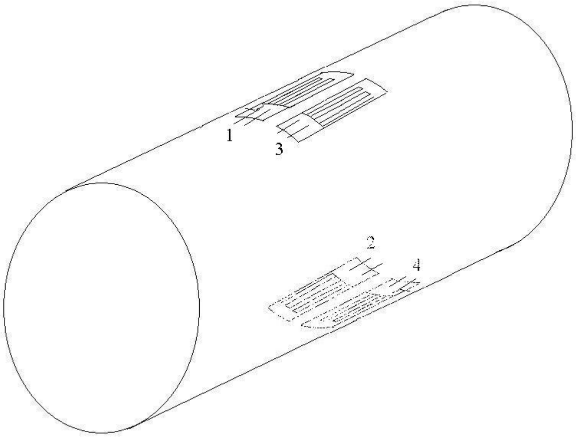
where

R = is bridge resistance, in Ω

ΔR = change in bridge resistance, in Ω

k = bridge factor (a common value for bridge factor is 2)

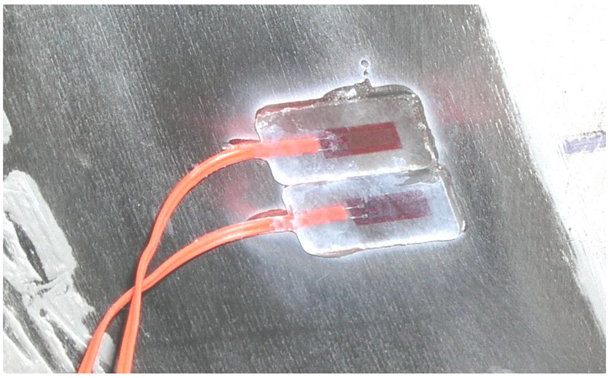
FIGURE 7
Strain Gauge Installation



To increase the precision (error correction) of the measurements, more than one gauge can be installed to measure the strain at the same location. Usually, there are four gauges installed in the so called Wheatstone bridge. Two pairs of gauges should be applied 180° apart from each other (Section 5, Figure 7), and connected in Wheatstone bridge as shown on Section 5, Figure 9.

Section 5, Figure 8 shows how a pair of uniaxial gauges is installed on the shaft to measure tension in longitudinal direction.

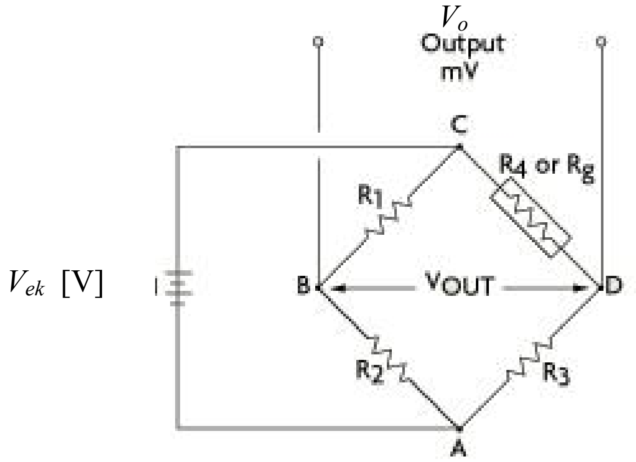
FIGURE 8
Pair of Uniaxial Gauges



Another pair of gauges is placed 180° apart. Signals from all four gauges are collected to increase measurement precision.

Applying fixed V_{ek} voltage to two opposite corners of the bridge, V_o changes could be measured.

FIGURE 9
Wheatstone Bridge



$$V_{OUT} = V_{IN}\left[\frac{R_3}{R_3 + R_g} - \frac{R_2}{R_1 + R_2}\right]$$

Voltage and resistance are then connected as follows:

$$\frac{\Delta R}{R} = \frac{V_o}{V_{ek}}$$

Combining the above relationships, the shaft bending moment can be determined by applying the following equation:

$$M = E \cdot W_p \cdot \frac{\Delta R}{R} \cdot \frac{1}{k} = E \cdot W_p \cdot \frac{V_o}{V_{ek}} \cdot \frac{1}{k}$$

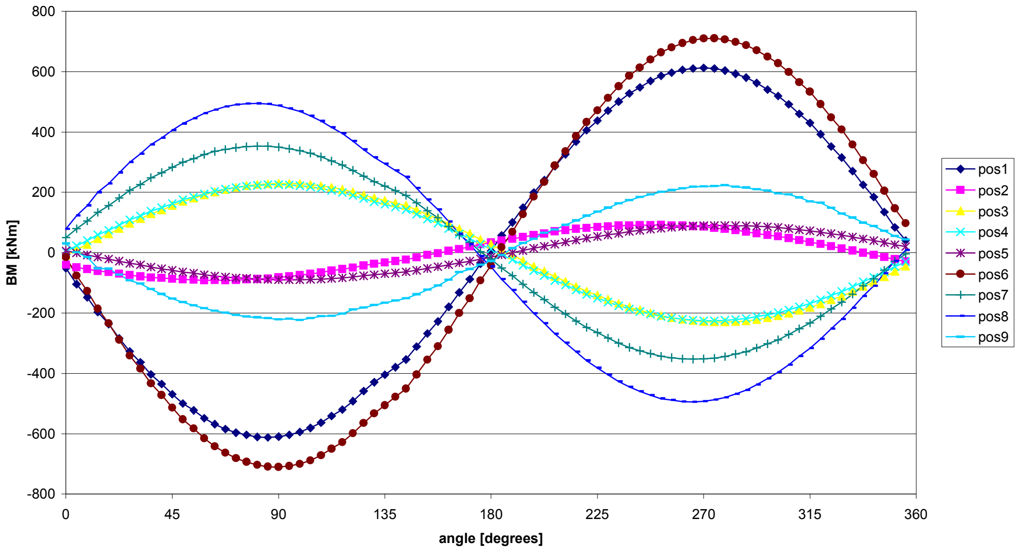
If the shaft is rotated for a full circle, each of the strain gauges will be exposed to deformation proportional to two times the bending moment. A simple analysis of continuous full circle measurements will separate vertical and horizontal bending moments.

2.2.1 Example

Nine bending moment curves taken at nine different locations along the line shaft are shown in Section 5, Figure 10, below. All of the measurement locations are placed along the same imaginary line perpendicular to the center line of the shaft. At each location, four uniaxial gauges are placed to measure longitudinal tension. Gauges are placed in pairs 180° apart.

It may be noted from Section 5, Figure 10 that extreme values of curves do not occur at the same phase angle. This indicates a possible existence of the horizontal load acting on the shaft and/or possible gauge misalignment.

FIGURE 10
Bending Moments Measured at Nine Different Locations Along the Shaft Line



Once information on bending moment(s) is obtained, bearing reactions can be recalculated. A principle to applying to recalculate bearing reactions from measured bending moment(s) is basically a set of equilibrium equations which are transformed so as to provide bearing reactions from input moments. This set of equations uniquely define bearing reactions with moments at any location on the shafting. This correlation can be established analytically.

2.2.2 Mathematical Representation

As described above, a system of linear equations should be generated first, from which bearing reactions could be obtained.

For each measurement point and respective bending moment, a linear equation is defined:

$$M_{mi} - M_{ei} - M_{0i} = K_{i1}\Delta R_1 + K_{i2}\Delta R_2 + K_{i3}\Delta R_3 + \ldots + K_{N}\Delta R_{N},\ i = 1\ldots N_m$$

where

N_m = number of bending moment's measurement points

i = measurement point number

M_m = measured bending moment

M_0 = initial bending moment (calculated or measured)

K = calculated bending moment's influence factor

R_m = bearing reaction

Using matrix notation, an expression is then written as:

$$[M_m] - [M_0] = [K] * [\Delta R]$$

If the number of equations is equal to the number of unknowns, the above system of equations could be solved by applying simple matrix inversion. For cases with more equations than unknowns, the solution to the above system can be obtained using the least square method.

Solving the equation for ΔR:

$$[\Delta R] = [K]^{-1} \cdot ([M_m] - [M_0])$$

Normally, the case is that the number of measurement locations is less then the number of bearings. Thus, a unique relationship to obtain reactions cannot be established from only a few measured moments. In that case, there is a need to combine analytically obtained data that was obtained by measurement.

3 Bearing Vertical Offset Measurements

Related topics:

- Intermediate Bearing Offset Adjustment (Subsection 3/10)
- Diesel engine bearing misalignment (2/4.6)
- Bearing-Shaft misalignment measurement (Subsection 3/8)
- Hull Deflection Measurements (Subsection 6/3)
- Alignment Optimization (Section 7)

The shafting bearing vertical position is set during the bore sighting procedure. During that procedure, laser, optical or piano-wire equipment is utilized. However, this initial presetting is often disturbed due to numerous reasons as mentioned in the text above (unfinished construction work, hull deflections, thermal influence, etc.). Therefore, the actual bearing position needs to be investigated in order to gain knowledge of how the offset changes and what its influence is on the bearing reactions.

Several methods may be applied:

- Optical
- Laser
- Piano wire
- Hydraulic jacks
- Strain gauges
- Crankshaft deflections
- Combined method, hydraulic jacks, strain gauges, and crankshaft deflections

Optical and laser methods are restricted to the systems where visual contact can be established. These methods can be applied to the crankshafts with hollow journals. The methods are relatively inaccurate. Moreover, the methods themselves are not providing information on the whole system, but rather on the segment of the system which is optically accessible.

The piano wire readings are much more inaccurate then the other methods. The accuracy improved somewhat with digital dial gauges, however, measurements are still hampered by problems that are difficult to prevent. (clean surface, wire vibration, tension…).

Hydraulic Jack-up: The jack-up method can be used to recalculate (reverse analysis) the bearing offset. However, the method itself cannot uniquely define the curvature of the shafting and therefore may provide false results. The jack-up method is also restricted by bearing's accessibility (e.g., aft stern tube bearing). This problem may be resolved if the jack-up method is combined with the strain gauge method.

Strain Gauge: The strain gauge method is the most reliable approach to investigate actual bearing position. It can also provide information on the bearings that normally are not accessible by other methods, and information on bending curvature of the shafting. However, the strain gauges themselves are not easily applicable to the crankshaft, thus this method needs to be combined with the jack-up measurement of the M/E bearing reactions and the crankshaft deflection measurements.

Crankshaft Deflections: Crankshaft deflection measurements are necessary for obtaining crankshaft bending curvature. Crankshaft deflections can be utilized in reverse analysis as well if the 3D crankshaft model is available.

Combined Measurements: Combined method is desired in investigation of the actual bearing position. This method uses measured data obtained by strain gauges, bearing reactions and crankshaft deflections and utilizes them simultaneously in recalculating the bearing offsets (see also Section 7, Paragraph 3).

3.1 Reverse Shafting Alignment Calculation of the Bearing Offsets

In conventional shafting alignment analysis, the bearing reactions, bending curvature, bending moments, etc. are calculated for the given bearing offset. Reverse shafting alignment analysis is a process where bearing offset is recalculated for the given bearing reactions, bending moments and crankshaft deflections.

Issues associated with accurately conducting reverse calculation are as follows.

- Inability to measure aft stern tube bearing reaction.
- Difficulty in accurately measuring diesel engine bearing reactions
- Strain gauge measurements can be taken only on accessible portions along the line shafting.

ABS's shaft alignment reverse analysis software is based on the following dual platform:

- The software evaluates the bearing offsets by using the analytical model and bending moments and bearing reactions,
- A best-fit, least square probability function is used to define bearing offset which will fit within given constraints of the measured bearing reactions, bending moments and crankshaft deflections.

The best-fit approach defines the bearing offset with maximum probability that the selected offset will result in the least square difference between the reverse-analysis calculated bearing reactions and measured reactions, and between reverse-analysis calculated bending moments and measured bending moments. The probability function is selected as an objective function which is to be maximized in order to obtain the best fit between measured and reverse-analysis recalculated reactions and moments.

In conducting the measurements obtained, readings may be corrupted for a variety of reasons. Reaction measurements are expected to be more sensitive to erroneous readings than the strain gauge measurements. Reactions measurements at the bearings inside the main engine are particularly sensitive, as the bearings are very close to each other. Moreover, reaction measurements, especially when hysteresis is high, are prone to individual interpretation of results which may vary significantly. To account for those inaccuracies, the ABS reverse analysis software incorporated a confidentiality function which can be assigned to each measured data. Accordingly, the measured values with higher confidence margin are given a higher fitness function.

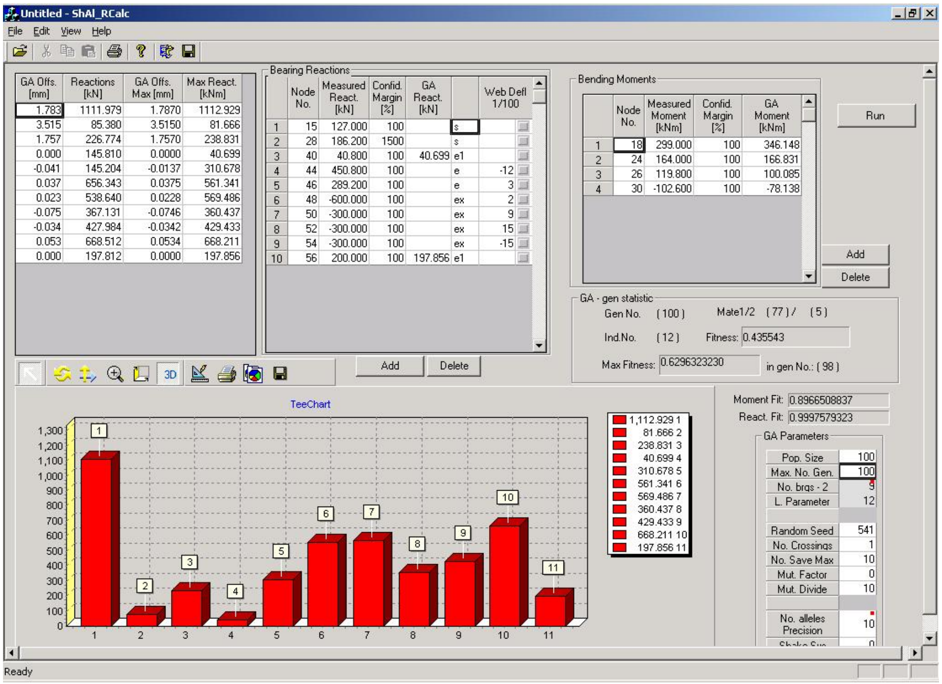
The following example shows the bearing offset as recalculated for given measured reactions, moments and crankshaft deflections.

3.1.1 Example

Displacement of the ship	320,000 DWT
Shafting length	19.8 [m]
Propeller	9.9 [m] diameter single screw
Engine	6 Cylinder MCR 30,000 kW @ 76 rpm

Reverse analysis is conducted for the dry dock, ballast and full loaded vessel. The reverse analysis GUI is shown in Section 5, Figure 11 for the dry dock analysis. The similar analyses are performed for other measurements (e.g., ballast, and laden).

FIGURE 11
Reverse Analysis I/O Interface



GA Offs. [mm]	Reactions [kN]	GA Offs. Max [mm]	Max React. [kNm]
1.783	1111.979	1.7870	1112.929
3.515	85.380	3.5150	81.666
1.757	226.774	1.7570	238.831
0.000	145.810	0.0000	40.699
-0.041	145.204	-0.0137	310.678
0.037	656.343	0.0375	561.341
0.023	538.640	0.0228	569.486
-0.075	367.131	-0.0746	360.437
-0.034	427.984	-0.0342	429.433
0.053	668.512	0.0534	668.211
0.000	197.812	0.0000	197.856

Bearing Reactions

	Node No.	Measured React. [kN]	Confid. Margin [%]	GA React. [kN]		Web Defl 1/100
1	15	127.000	100		s	
2	28	186.200	1500		s	
3	40	40.800	100	40.699	e1	
4	44	450.800	100		e	-12
5	46	289.200	100		e	3
6	48	-600.000	100		ex	2
7	50	-300.000	100		ex	9
8	52	-300.000	100		ex	15
9	54	-300.000	100		ex	-15
10	56	200.000	100	197.856	e1	

Bending Moments

	Node No.	Measured Moment [kNm]	Confid. Margin [%]	GA Moment [kNm]
1	18	299.000	100	346.148
2	24	164.000	100	166.831
3	26	119.800	100	100.085
4	30	-102.600	100	-78.138

GA - gen statistic

Gen No. (100) Mate1/2 (77) / (5)

Ind.No. (12) Fitness: 0.435543

Max Fitness: 0.6296323230 in gen No.: (98)

Moment Fit: 0.8966508837

React. Fit: 0.9997579323

GA Parameters

Pop. Size	100
Max. No. Gen.	100
No. brgs - 2	9
L. Parameter	12
Random Seed	541
No. Crossings	1
No. Save Max	10
Mut. Factor	0
Mut. Divide	10
No. alleles Precision	10

Bearing offset obtained by reverse analysis is further mapped into the desired coordinate system in order to present data in a convenient manner for further analysis.

Three charts below show the bearing offset obtained by reverse analysis for the dry dock, ballast and fully loaded vessel. Bearing offset is mapped into a coordinate system suitable to compare the reverse calculated bearing offset (obtained from measured moments and reaction measurements) with as-designed bearing offsets.

FIGURE 12
Dry Dock – Bearing Offset – Reverse Analysis vs. As-designed Offset Comparison

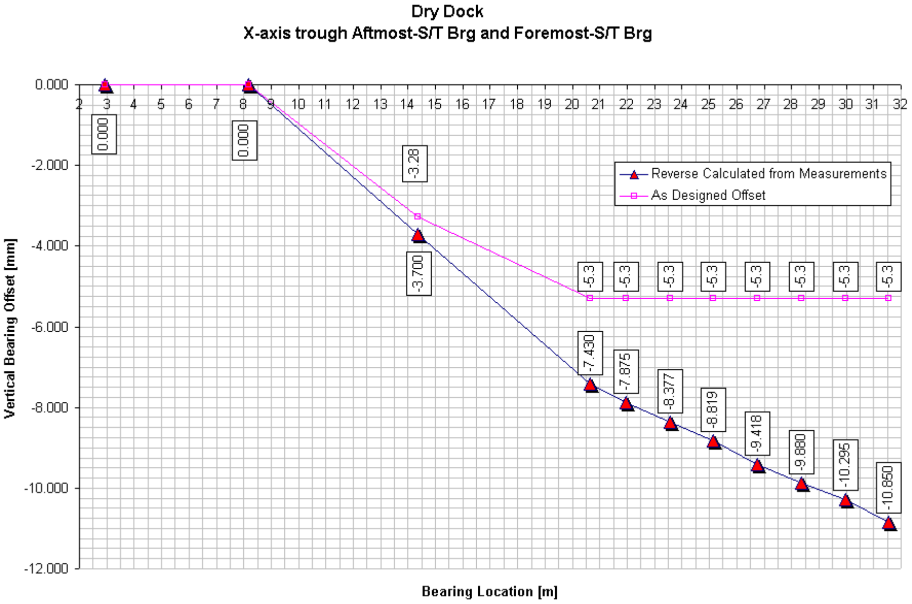


FIGURE 13
Ballast – Bearing Offset – Reverse Analysis vs. As-designed Offset Comparison

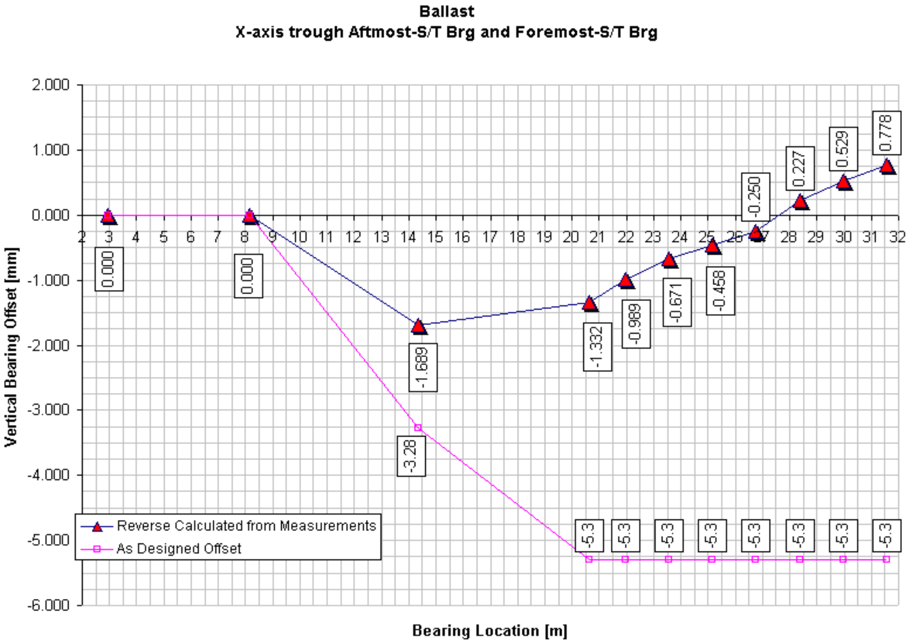
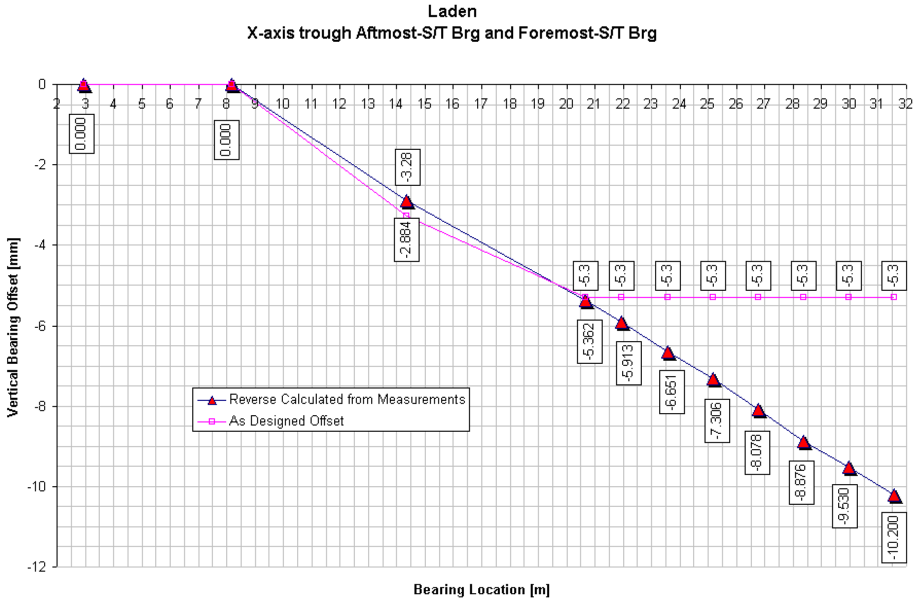


FIGURE 14
Full Load – Bearing Offset – Reverse Analysis vs. As-designed Offset Comparison



The same bearing offset on the charts above is shown in Section 5, Table 2 below in the form of offset vectors for the dry-dock, ballast and laden condition. These tabulated data are intended to be used in optimization software, and for that purpose, X-axis (longitudinal axis) is set to zero-in the after stern tube bearing and forward diesel engine bearing.

TABLE 2
Offset Vector Spectrum

Bearing Location	*Offset Vector Spectrum [mm]*		
	Offset Vector Dry Dock	*Offset Vector Ballast*	*Offset Vector Laden*
$S/T-aft$	0.000	0.000	0.000
$S/T-fore$	1.984	-0.142	1.865
$Int.Sh.brg$	0.631	-2.000	1.188
$ME8$	-0.714	-1.813	0.951
$ME7$	-0.667	-1.506	0.863
$ME6$ ⇒	-0.562	-1.231	0.695
$ME5$	-0.397	-1.061	0.611
$ME4$	-0.389	-0.897	0.410
$ME3$	-0.244	-0.463	0.182
$ME2$	-0.051	-0.205	0.099
$ME1$	0.000	0.000	0.000
	$_{1x11}$	$_{1x11}$	$_{1x11}$ $_{3x11}$

4 Bearing Misalignment Measurements

Related topic:

- Bearing-Shaft Misalignment Measurement (Subsection 3/8)

Bearing misalignment is defined as an angular difference between center lines of the shaft and the bearing. Ideally, when center lines match, the angle is zero. In real life, however, there are normally vertical and horizontal misalignments.

A misalignment at the bearings, which are physically accessible for measurements, is easily evaluated by filler gauges. Horizontal misalignment is measured at the port and starboard side of the bearing, and vertical misalignment is checked at the forward and after edge of the bearing (Section 5, Figure 15).

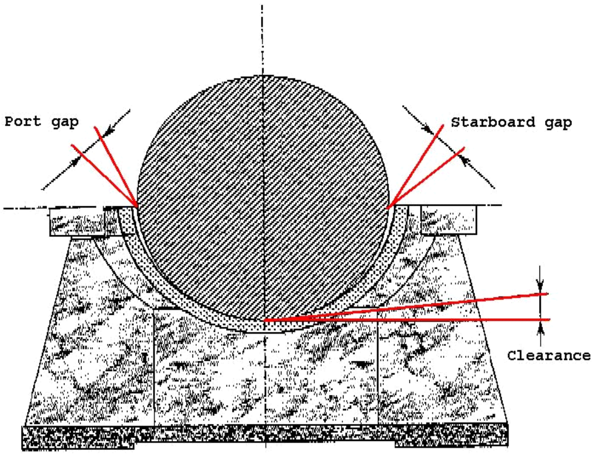
It is advisable to conduct the measurement several times within one shaft revolution. This will indicate if the measured misalignment is a result of the shaft's runout or actual bearing misalignment.

The runout can be verified by other methods as well, and corrected as explained in detail in Subsection 5/8 and Subsection 3/9.

If the bearing misalignment is found to be a problem, the possibility of correcting it will depend on which bearing is out of line. The solution will be simple only in the case of intermediate shaft bearings not cast in epoxy resin.

If bearings are cast in resin, it is recommended to do so only after the misalignment is verified and confirmed acceptable.

FIGURE 15
Intermediate Shaft Bottom Clearance and Runout Measurement

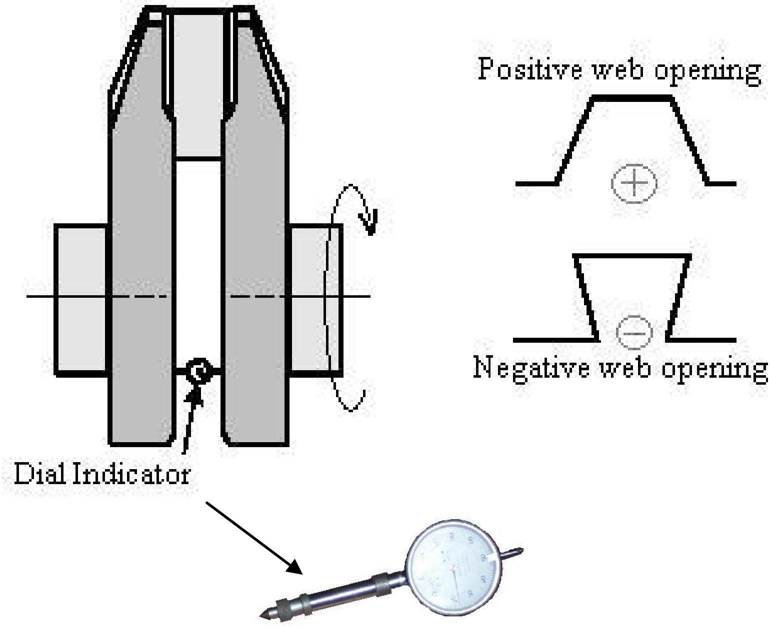


5 Crankshaft Deflection Measurement

Crankshaft deflections are an indirect confirmation of the stress level in the crankshaft. However, the crankshaft deflections can be utilized as an indication of the crankshaft bearing loading as well. The crankshaft deflections are important to be verified as a part of the alignment procedure, therefore, when the alignment procedure is performed, and if the bearing offset is changed, the crankshaft deflections need to be confirmed to be within the engine manufacturer-required limits.

Crankshaft deflection measurement is conducted with a dial indicator being placed at a predefined location between crank webs. The crankshaft is then rotated and the readings are taken at the prescribed angular locations. Web deflections between each cylinder are measured.

FIGURE 16
Crankshaft Deflection Measurements



Crankshaft deflection limits and tolerances are defined by the engine manufacturers for each particular engine.

6 Gear Contact Misalignment Measurement

Related topic:

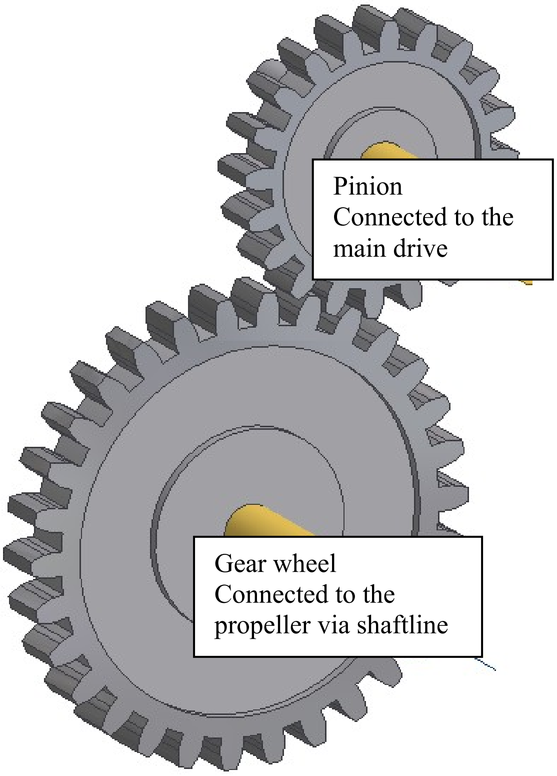
- Gear Meshes (2/4.10)

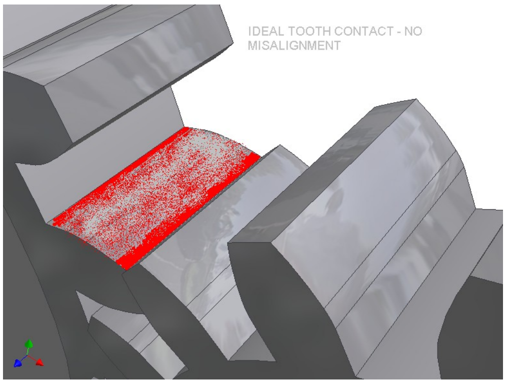
Section 5, Figure 13 shows gear tooth contact for:

- Case A) ideal (zero) misalignment between gear and pinion
- Case B) large misalignment between gear and pinion

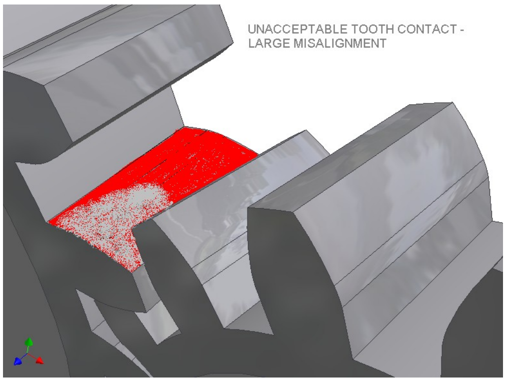
In both cases, the red color (dark) area represents dye penetrant painted over the teeth of the gears. The gray (light) area within the red (dark) penetrant represents the area of contact. Obviously, when the misalignment angle is small, the contact marks will be visible along the whole length of the teeth, as in contact Case A. In Case B, the gray (light) area is visible only on one side of the teeth in contact, thus indicating heavily misaligned gear mesh.

FIGURE 17
Gear Contact





Case A) Ideal contact - No misalignment



Case B) Unacceptable contact – Large misalignment

7 Sag and Gap Measurement

Related topics:

- Sag and Gap (Subsection 3/6)

The Sag and Gap shaft alignment method is commonly used to verify the preassembly condition of the propulsion shafting in new constructions and repairs. The method is simple, fast and requires no special equipment or gauges. However, due to the procedure's questionable accuracy, it should be used only as a cursory check. It is not recommended to use the Sag and Gap method either for final verification of the alignment or to rectify the existing alignment condition.

Although the Sag and Gap procedure is not endorsed as an accurate method, it still has its purpose as it may indicate possible problems in the preassembly stage of propulsion shafting setup.

The advantage of the Gap and Sag method is:

- It uses simple measuring equipment such as dial gauges and feeler gauges.

The disadvantages of the Gap and Sag method are:

- It cannot verify the condition of the assembled system.
- Its accuracy is limited because of the aspect ratio between the system geometry (large diameters of flanges and shafts – over 1 meter) and Gap and Sag values that are measured (in millimeters or fractions of millimeters).
- It does not allow easy measurement of the shaft's runout (shaft rotation is difficult if the system is not assembled).

The measurement tolerances will depend on the following:

- Dial gauge location
- Condition of the flanges where the gauges are placed
- Environmental condition (temperature, vibrations…)

The dial gauge accuracy is up to 0.001[mm], and the filler gauge accuracy cannot be obtained greater then 0.05[mm]. However, the equipment accuracy per se is not a problem, but rather the problem is the inability to take advantage of it.

It is often difficult to measure precisely with filler gauges, and gaps are almost exclusively measured with them. Errors of 0.1 [mm] or greater are very common.

Even with dial gauges, which are much more precise, the measurements may be tempered by inaccurate positioning of the gauges, difficulties in leveling the equipment, inaccuracies of the flange machining, cleanliness of the surface, etc.

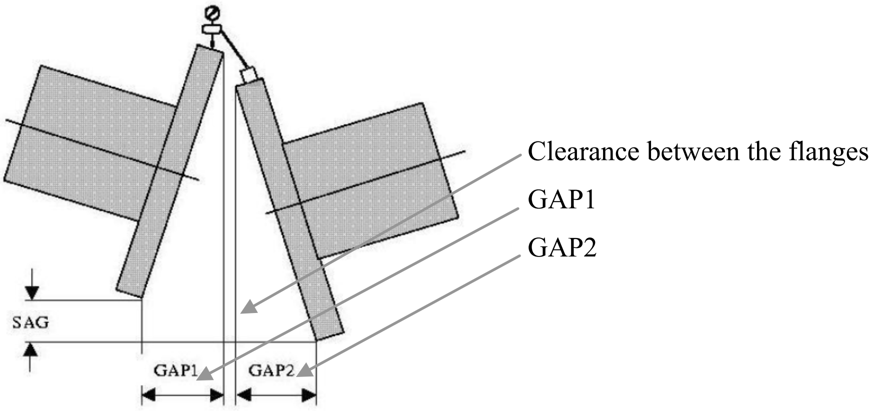
Another very important issue is that the Sag and Gap measurements have to match the appropriate analytical model. It is now known that the alignment condition changes significantly with the condition of the vessel (dry dock, waterborne, loaded, ballast), and if the Sag and Gap values are not given for a particular condition when the procedure is performed, the values cannot be verified appropriately.

A dial gauge is placed on the top of one flange and anchored on the top of the other. It is important to align the gauge and to anchor it properly to measure only vertical distance.

Filler gauges are to be placed in the gap between two flanges.

In Section 5, Figure 18, the flanges' positions are exaggerated for the purpose of indicating filler gauge measurement problems. Gap measurement will normally be conducted with a filler gauge that will measure the clearance between the flanges, GAP1 and GAP2. The clearance will introduce an error which is often difficult to prevent.

FIGURE 18
Sag and Gap Measurement

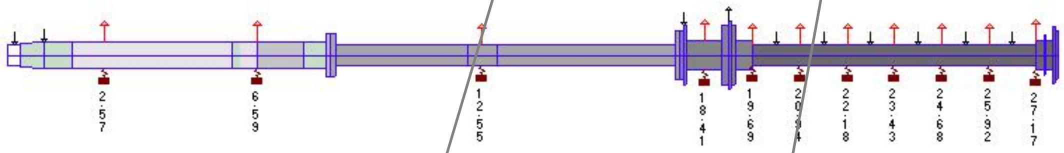


Example:

The table below is a standard output of the ABS shaft alignment software, and it provides all necessary data to verify the preassembly condition of the shafting, i.e., the Sag and Gap calculation.

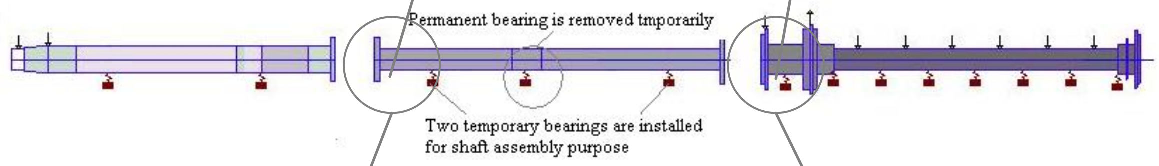
```
SAG and GAP ALIGNMENT DATA
          |           Between Shafts                  |
|  Node   | Shaft  Flange Dia| Shaft  Flange Dia|     SAG     |  Gap1       Gap2       GAP[mm]     |
|   No    |  No       [m]    |  No       [m]    |    [mm]     |  [mm]       [mm]       Gap1+Gap2   |
|----------------------------------------------------------------------------------------------|
|         |                  |                  |             |                       Above flanges |
|   18    |  1      1.1100   |  2      1.1100   |   1.7078    | 0.6997    -0.0745    -0.7742      |
|----------------------------------------------------------------------------------------------|
|         |                  |                  |             | Above       Below                |
|   38    |  2      1.2600   |  3      1.2600   |  -1.5681    | 0.0837     0.1414        N/A       |
|----------------------------------------------------------------------------------------------|
```

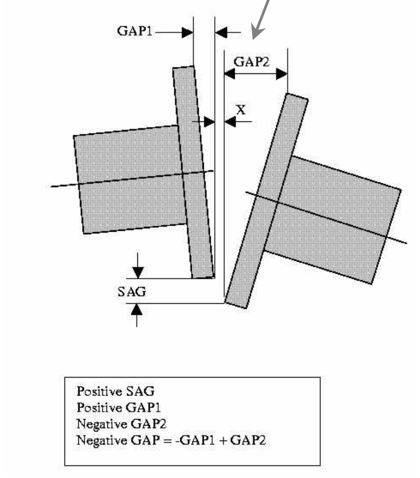
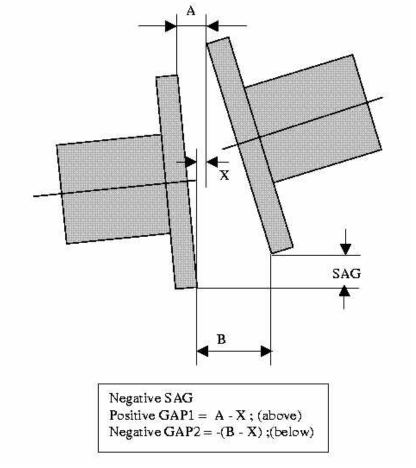
FIGURE 19
Assembled Shafting – Condition Desired After Sag and Gap is Verified



The desired alignment is defined for the assembled system. To obtain the desired bearing reactions of an assembled shafting, the preassembly condition is often verified by confirming the sagging among mating flanges and gaps between flanges (figures below).

FIGURE 20
Preassembly Shafting Setup – for Sag and Gap Measurement



Flanges' position between propeller shaft and the intermediate shaft	Flanges' position between intermediate shaft and the crankshaft
	

8 Eccentricity (Runout) Measurement of the Shaft

Related topic:

- Shaft alignment eccentricity (Subsection 3/9)

The shaft eccentricity may result in alignment problems. In the case of excessive runout of the shaft, the bearing load may significantly vary as the shaft rotates. The direction of the load will change as well, resulting in horizontal load at the bearing, which may have bearing damage and failure as a consequence. Moreover, the excessive runout may result in vibration and whirling problems.

To prevent possible problems, it is suggested to verify shafting runout when the shaft alignment procedure is conducted. Shaft eccentricity can be evaluated directly by dial indicator or indirectly by measuring bearing reaction change or strain in the shaft, for example. The shaft must be able to be rotated to conduct the runout measurements.

8.1 Dial Gauge Runout Measurements

Measurement utilizing dial gauges is conducted by placing one indicator in the vertical plane and another in the horizontal plane. As the shaft rotates, under ideal alignment conditions and no runout, the indicators will not change the initial value (normally set to zero). However, this ideal condition is not possible in practice. There is always going to be some deviation in recorded values which may not necessarily be a result of the runout. Some of the variation in readings may be attributed to hysteresis (internal friction) in the shaft, as well.

8.2 Runout Measurement in Lathe

For reference, DEF STAN 02–304 Part 4/ Issue 2 (NES 304 Part 4) requirements, issued by the Defence Procurement Agency, An Executive Agency of The Ministry of Defence, UK Defence Standardization were selected.

i) The shaft is to be mounted in a center lathe or similar device with one end gripped in a four-jaw chuck and the other end supported.

ii) Location stations are to be marked circumferentially at 300 mm centers.

iii) A dial gauge is to be set vertically below the centerline of the shaft to measure shaft eccentricity at each station.

iv) The shaft is to be rotated slowly and the indicator dial pointer displacement (M) between its extreme positions is to be recorded and the position of maximum eccentricity at each station is to be marked on the shaft.

v) M = Total Indicator Reading (TIR) = 2 * (actual shaft eccentricity).

vi) This procedure is to be repeated at each station.

vii) The station with the greatest shaft eccentricity is to be identified and the eccentricity then measured at further stations at 100 mm and 200 mm on each side of this station. From these measurements, the location and degree of maximum eccentricity is to be marked on the shaft and recorded.

viii) The shaft may remain in the lathe for straightening by thermal or mechanical methods.

9 Stress Measurements

Related topic:

- Strain gauge method (5/2.2)

9.1 Stress in the Shafting

The stress level in the shafting is seldom affected by shaft alignment. However, in some cases where the level of the stress in the shafting is already at the limit, the bending and shear stress introduced by the alignment condition may be a contributing factor.

Bending and shear stress in shafts can be easily measured using strain gauges.

9.2 Stress in the Bearing

In contrast to the shaft stress, the stress level in the bearings is dominated by the shaft alignment condition. A particularly important factor which defines stress distribution is the bearing-shaft misalignment. The misalignment angle is directly proportional to the contact area and, accordingly, to the stress as well.

Bearing stress measurement is an almost impossible task. It can only be indirectly evaluated by contact area examination when the bearing shell is removed for inspection.

SECTION 6 Hull Girder Deflections

1 General

Hull girder deflections are the most significant disturbance that affects the bearing offset and, accordingly, the shaft alignment after the vessel's construction. Inability to account for hull deflections may result in inappropriate alignment design with serious consequences on the life of the bearings. The problem, however, presents a difficulty in predicting and evaluating the hull deflections.

The ability to predict hull deflections with sufficient accuracy is of the foremost importance in order to ensure robust alignment design, and consequently, less alignment-related casualties.

In order to achieve the above objective, ABS conducted a series of hull girder deflection measurements on a number of vessels of different types and sizes. Collected data is to be applied in the ABS Shaft Alignment Optimization software to provide a basis for more robust shaft alignment design, which will be less susceptible to the alignment condition change during the operation of the vessel. The hull deflection data obtained by measurements or analyses would normally be utilized only on vessels of identical design. However, if a number of measurements and analyses are conducted for the same type of ships (e.g., tankers), but of different sizes/tonnage, then one can establish correlation among collected hull deflections and use the same data to predict the hull deflections of the newly designed vessel of the same type. The latter is exactly the approach that ABS is undertaking in predicting hull deflections on the new designs.

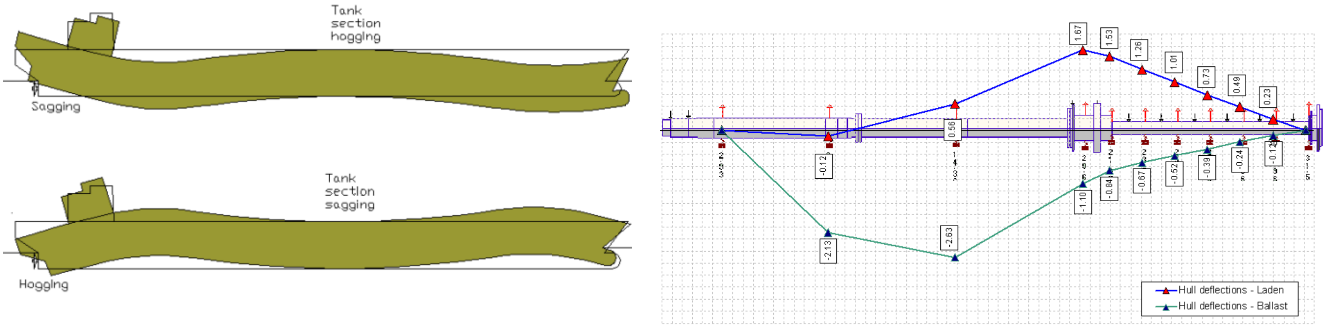
The above-stated principle of hull deflection estimate is imbedded in the ABS shaft alignment software, which enables alignment designs much less sensitive to possible disturbances of the bearing offsets. ABS software enables optimization of the dry dock bearing offset, considering the effect of the hull deflections. Designers of the shaft alignment are now able to obtain "optimum" bearing offset by inputting basic ship parameters in addition to the shafting geometry, loads and bearing location.

To optimize bearing offsets, designers will either need to input or let the software select the extreme disturbances affecting the bearing offsets. The dominant disturbances are hull deflections (two extreme hull deflections need to be defined - for ballast and for laden vessel) and thermal rise of the bearings. The prescribed offset of the bearings will then be selected by shafting alignment optimization software, alignment of these two extreme hull deflections, as well as for all hull deflections within (for details on optimization, see Section 7).

The vessels known to be particularly sensitive to hull girder deflection variation are large tankers and bulk carriers, primarily for the reason that those ships have short and very rigid shafting and are mainly direct-coupled diesel engine installations. However, we shall not exclude the large container ships from the "sensitive alignment" category because, although those ships have longer and more flexible shafting, the hull deflections are large and the effect on the alignment condition, in particular aftmost main engine bearings, is significant.

The schematic in Section 6, Figure 1 shows how tankers and bulk carriers are behaving under two extreme loading cases (ballast and laden).

FIGURE 1
Hull Girder Deflections Influence on Propulsion System



Typical hull girder deflections of a VLCC vessel under laden and ballast conditions.

Behavior of the shafting under laden and ballast conditions.

Hull deflections can be estimated:

- Analytically, or by
- Measurements

Both approaches are shown below in an example of a container vessel.

2 Analytical Approach

The analytical approach is time-consuming and expensive. It requires detailed modeling (e.g., finite element) of the vessel, in particular, the stern part, with a comprehensive model of the engine room, the engine and the shafting. The analytical approach is seldom undertaken solely for the purpose of investigating the hull deflections' effect on the alignment. It is more common to take advantage of the full-scale vessel modeling conducted for the dynamic loading analysis (or similar) to extract the data on hull deflections that may be applied in alignment analysis.

3 Hull Girder Deflection Measurements

Related topics:

- Bearing Vertical Offset Measurements (Subsection 5/3)

Hull girder deflection measurements are normally conducted for two reasons; to investigate particular shafting system sensitivity to hull deflection, and to acquire hull deflection data to be utilized on similar designs in future projects.

The hull girder deflections of interest comprise only the stern section of the ship, where the propulsion shafting is located, as the point of interest is the shafting alignment and it is affected by changes in hull deflections. Accordingly, to obtain information on hull deflections affecting the shafting, the propulsion shafting itself is utilized as a large gauge.

The propulsion shafting flexes and tries to follow the ship deformation as the ship condition changes due to the change in its loading condition. The change in ship deformation is directly reflected on the vertical offset of the bearings supporting the shafting. Therefore, knowing the vertical position of the bearing for certain vessel conditions (ballast, full load, etc.) will enable the definition of how the vertical offset of the bearings changes. This change in vertical offset from one vessel loading condition to another is going to be the actual information of interest: the hull deflection.

The problem that is faced now is how to measure the actual bearing position. Direct measurements are not possible since there is no clear optical line to simultaneously record the relative change in vertical position among bearings. Therefore, indirect methods of measurements of bending moment moments, bearing reactions and crankshaft deflections must be relied upon. Since the correlation between those measured parameters and the bearing offset are known, the so-called reverse analysis can be utilized to obtain bearing offsets. The particulars of the bending moment, bearing reaction and crankshaft deflection measurements for the purpose of the hull deflections investigation are given in the following paragraphs.

As explained in 5/3.1, the reverse analysis procedure will provide actual bearing offsets for given vessel condition. By knowing the offset for dry dock, ballast and laden vessel, the dry dock bearing offset can simply be subtracted from the ballast bearing offset to obtain the hull deflection effect on the initially established bearing offsets. The same procedure was repeated for the full loaded vessel and the desired hull deflections were obtained which can be utilized in the shafting alignment optimization procedure (Section 7).

In order to obtain sufficient information to define the hull deflection effect on the particular shafting alignment, a minimum of five sets of measurements need to be conducted. Namely, there is a need to collect information on bending moments, bearing reactions and crankshaft deflections for:

- The dry-dock condition,
- Immediately after launching (before any bearing adjustment)
- After bearing adjustment
- Ballast
- Full load.

Hull deflection measurements can be conducted by investigating the bearing offset change from one condition of the vessel to another. For such a task, a strain gauge measurement combined with the crankshaft deflection measurements and the M/E bearing reaction measurements is recommended to be applied.

As the bearing offset is normally readjusted after the launching, a reading needs to be taken before bearing adjustment and after in order to define the correction factors which should be applied when further measurements are conducted in ballast and laden vessel condition.

3.1 Bending Moment Measurements

Related topics:

- Bearing Reaction Measurements (Subsection 5/2.2)

Advantages of the strain gauge method are its ability to control the accuracy of the measurements and in providing information on the bending curvature of the shafting.

The error in the strain gauge measurement will be consistent throughout the repeated measurements. This is important because it can essentially minimize/eliminate the measurement error as consecutive readings (e.g., dry dock condition vs. different afloat condition – Section 6, Figure 5) are compared.

When the reverse analysis is conducted and the bearing offset from the measured moments, bearing reactions and crankshaft deflections are recalculated, the bending curvature of the shafting will be the essential information needed to obtain the actual position of the propulsion shafting bearings.

Depending on the propulsion shafting design, one should decide on the number of the strain gauge locations on the line shafting. Each strain gauge location would ideally be comprised of four strain gauges wired into the Wheatstone bridge.

Moreover, it would be desirable to place the strain gauges at locations where the moment is expected to be large. This is not always possible, due to the limited space on relatively short shafting, and obstructions and interferences with the other installed equipment. In principle, the more strain gauges installed, the higher accuracy of the reverse analysis results that will be possible. In practice, however, this is limited.

In the propulsion systems with one intermediate shaft bearing, it is suggested that strain gauges at a minimum of three locations be installed. However, due to the likely possibility that some of the strain gauges will not function properly, it is proposed that strain gauges be installed at at least five locations. In the case of longer shaft lines with more that one intermediate shaft bearing, it is suggested that the number of strain gauge locations be equal to a minimum of two times the number of the intermediate shaft bearings plus one.

At each defined location, the strain gauges are connected in the full Wheatstone bridge arrangement, one pair on the top of the shaft and the other pair 180° apart.

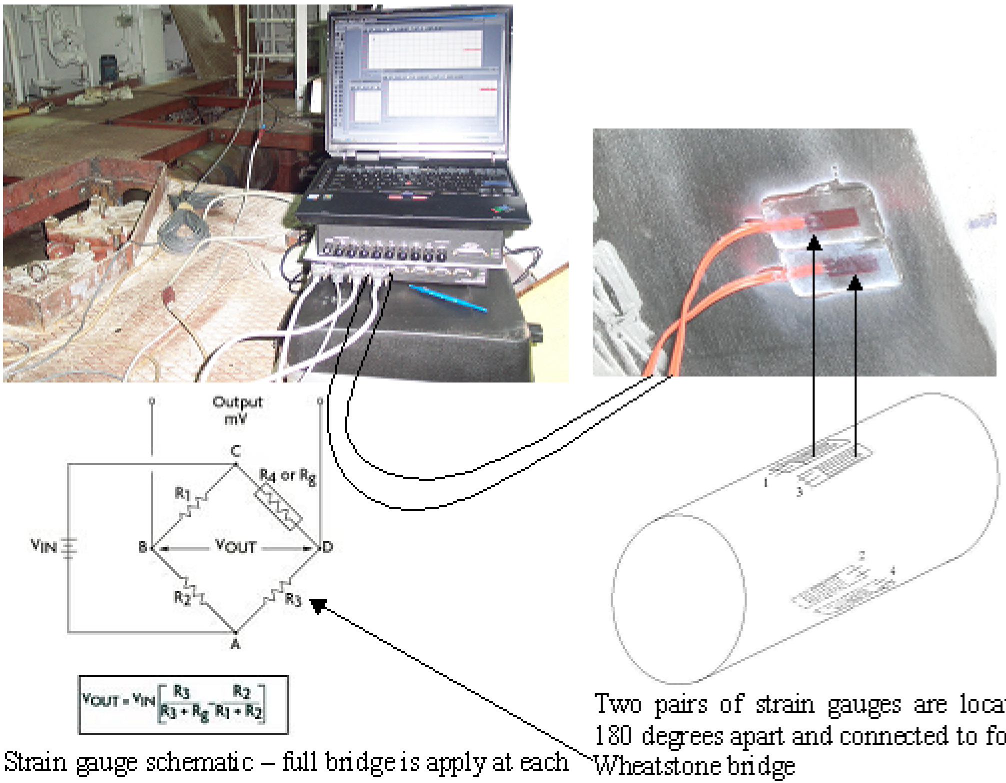
For each measurement, strains are recorded while the shaft is slowly rotating for two to three revolutions. The shaft is rotated first in the ahead direction and then in the astern. The resulting moments are the average between the two directions.

The signal from the strain gauges is further conditioned as it passes through the strain gauge module and is filtered and converted from the analog into a digital signal in the A/D converter.

From the A/D converter, the digital information is sent to the PC, where acquired data is further processed before being logged onto the computer's hard disk.

Data acquisition software on the PC controls the acquisition process and further samples, filters and maps the collected information into the moments. During the acquisition, data is continuously monitored on the screen and simultaneously stored on the disk.

FIGURE 2
Strain Gauge Measurement



$$V_{OUT} = V_{IN}\left[\frac{R_3}{R_3 + R_g} - \frac{R_2}{R_1 + R_2}\right]$$

Strain gauge schematic – full bridge is apply at each measurement location

Two pairs of strain gauges are located 180 degrees apart and connected to form Wheatstone bridge

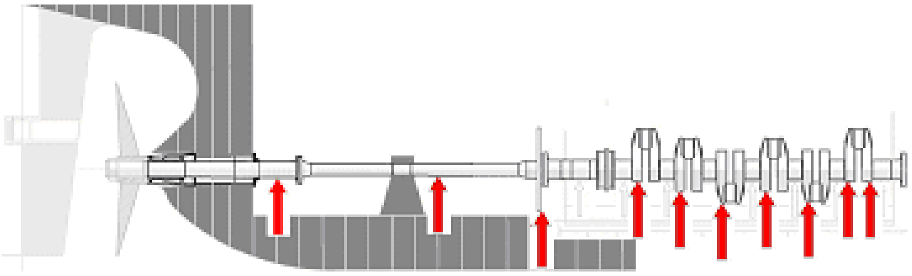
3.2 Bearing Reaction Measurements

Related topics:

- Bearing Reaction Measurements (5/2.1)

For the purposes of the hull deflection investigation, the bearing reactions are measured at all accessible bearings on the propulsion shafting; namely, forward stern tube bearing, intermediate shaft bearing(s) and after the M/E bearing (which can be measured at the engine's turning wheel). In installations driven by the directly coupled diesel engine, it is also desired to measure as many bearings inside the engine as possible (Section 6, Figure 3). In geared installations, if possible, both gear shaft bearings should be measured.

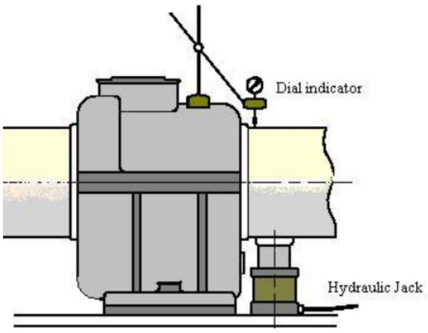
FIGURE 3
Hydraulic Jack Locations for Reaction Measurements on the Shafting and M/E Bearings



Normally, different jack sizes are utilized in order to obtain more precise readings (smaller hysteresis). For example, for the diesel engine bearings, larger jack sizes are used than for line shaft bearings.

Bearing reactions are measured not exactly at the bearing locations but as close to the bearing possible (as indicated in Section 6, Figure 4). By this approach, bearing reaction is not actually measured, and the obtained data must be corrected for that reason (Subsection 5/2).

FIGURE 4
Bearing Reactions are Measurements Using Hydraulic Jacks



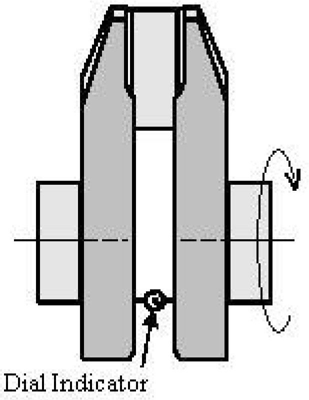
3.3 Crankshaft Deflection Measurements

Related topics:

- Crankshaft Deflection Measurements (Subsection 5/5)

Crankshaft deflection measurements are necessary for obtaining crankshaft bending curvature.

In ABS's reverse shafting alignment analysis, the bearing reaction measurements are utilized as the fitness function for the crankshaft bearing offset recalculation, and the crankshaft deflections are utilized to obtain a correct shape of the elastic line within the crankshaft.



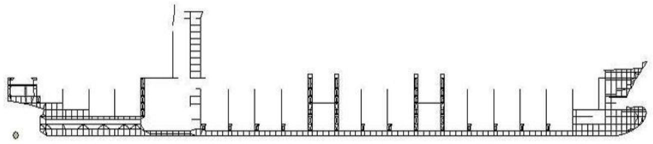
4 Example

4.1 Analytical Approach

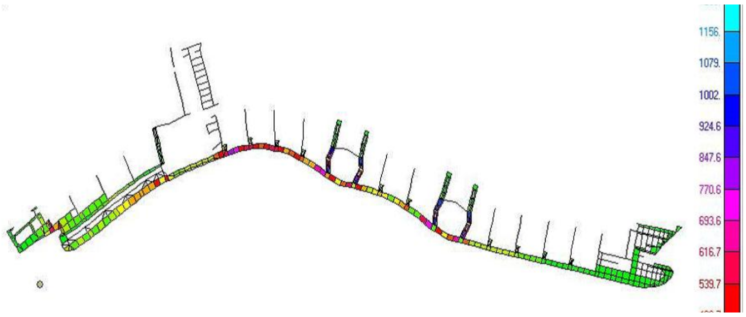
The container vessel example considered here indicates the importance of hull deflection consideration. When shaft alignment analysis is conducted without hull deflection consideration, there is no warning of possible problems. Eventually, when the analysis is repeated with hull deflections included, there is an indication that a problem may exist with the M/E bearing unloading in laden condition of the vessel.

The analyses shown here are for ballast and fully loaded ship. It is assumed that the dry dock hull girder deflections are negligible from the point of view of the propulsion shafting

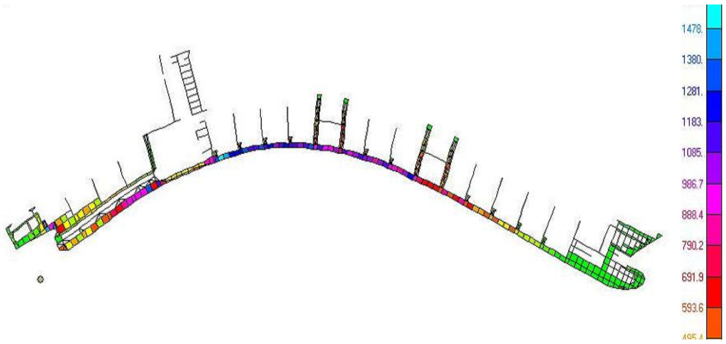
FIGURE 5
Vessel Deflections Change with Loading Condition



Dry dock – no hull deflections

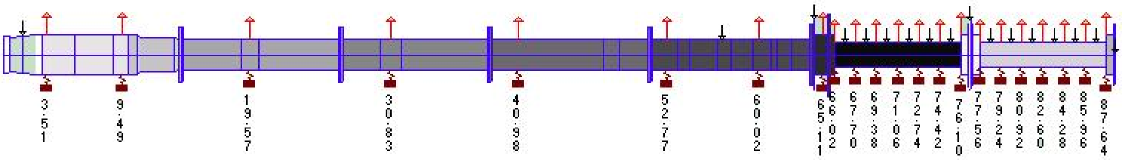


Ballast – still water deflections



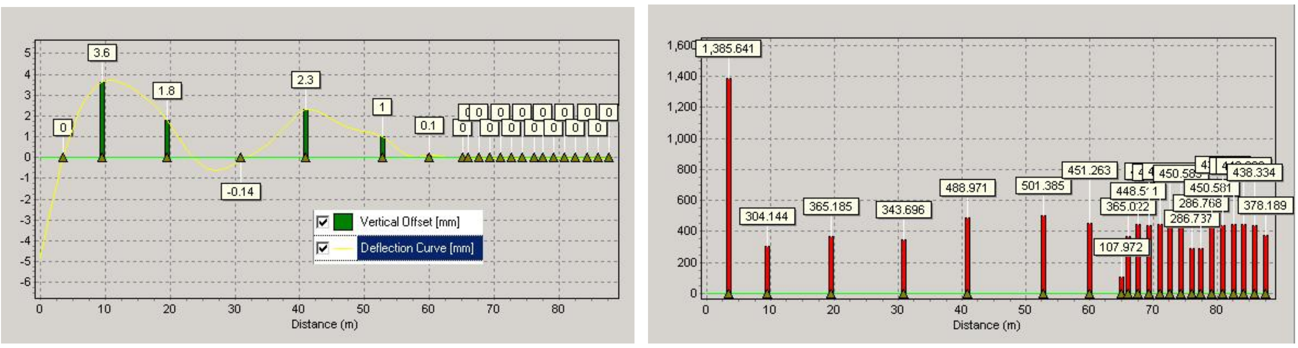
Laden – still water deflections

FIGURE 6
Large Container Vessel Shafting for Shaft Alignment Analysis Purpose



For prescribed bearing offsets below, the reactions in the bearings are almost ideally defined.

FIGURE 7
Shaft Alignment Design with No Hull Deflections Considered



If hull deflections for ballast and laden vessel (ABS dynamic loading analysis is applied for that purpose) are now investigated, the results obtained are as follows:

FIGURE 8
Still-water Deflections of the Vessel

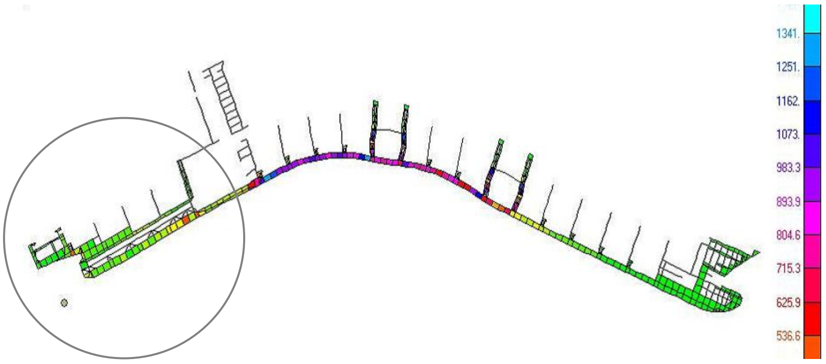
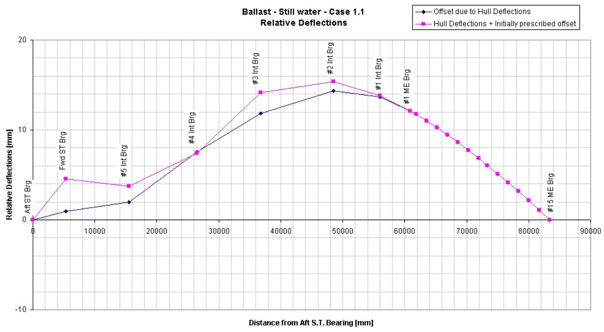


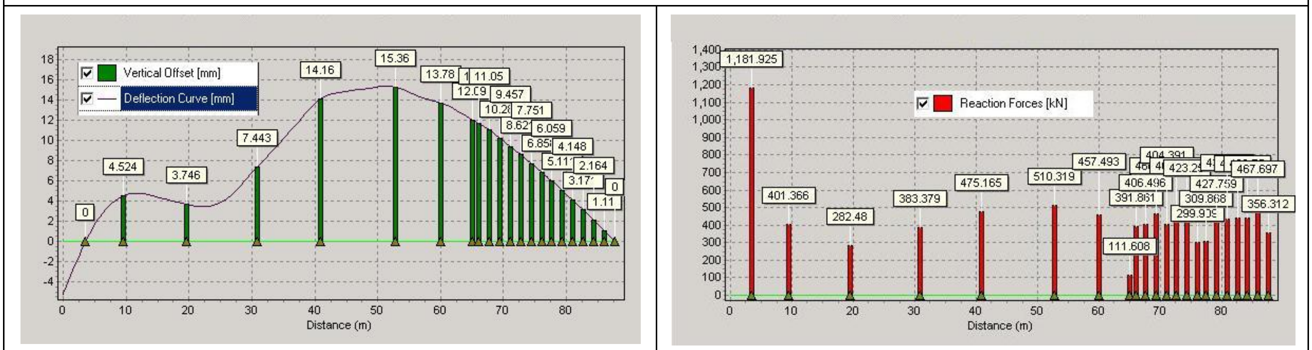
FIGURE 9
Containership – Diesel Engine Bearing Reactions as a Function of Hull Deflections and Bedplate Sag

Ballast	*Laden*
	

Conducting the analysis with hull deflection as obtained above, the following results are obtained:

FIGURE 10
Still-water Hull Deflections – Ballast

Ballast

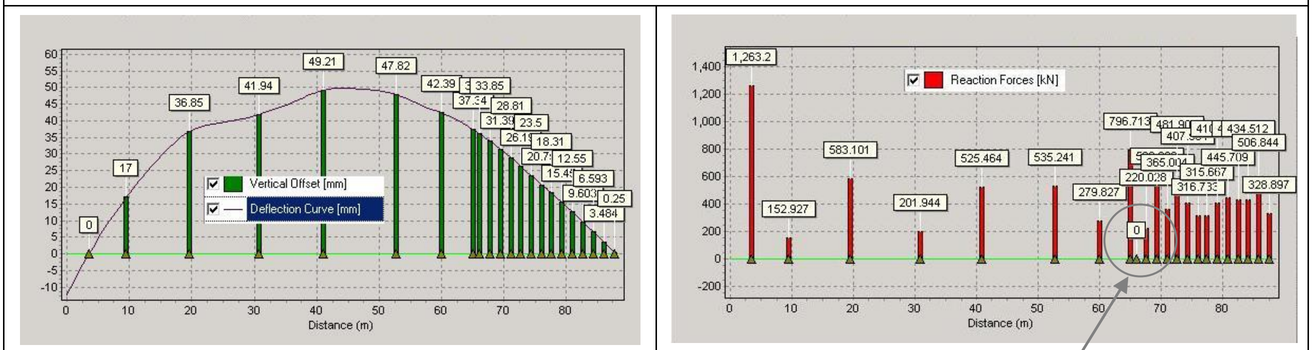


Bearing offset: Still water hull deflections – Ballast

Bearing reactions: Still water hull deflections – Ballast

FIGURE 11
Still-water Hull Deflections – Laden

Laden



Bearing offset: Still water hull deflections - Laden

Bearing Reactions: Still water hull deflections - Laden

Section 6, Figure 10 indicates that hull deflections may result in the second M/E bearing unloading. The statement made is conditional as the analytical results may often deviate from the actual condition due to:

- Approximations made in system modeling (e.g., crankshaft equivalent model),
- Errors in calculated hull deflections (FEA modeling)
- Differences in conditions between as-is alignment and design proposed alignment.

However, if analysis is conducted following good engineering practices with good error management, the designer shall be able to conclude whether the results are plausible, and if needed, suggest the bearing reaction verification (jack-up measurement within the engine)

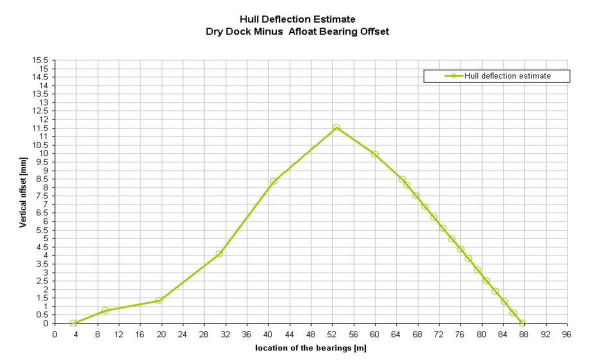
Hull deflection data is needed during the design stage of the alignment process in order to prescribe bearing offsets which will result in acceptable bearing reactions for ballast, laden and all operating conditions in between. At that time, the vessel is not yet under construction and the only option is to rely on the ship hull deflection data (which is seldom available) or measurements conducted on similar vessels.

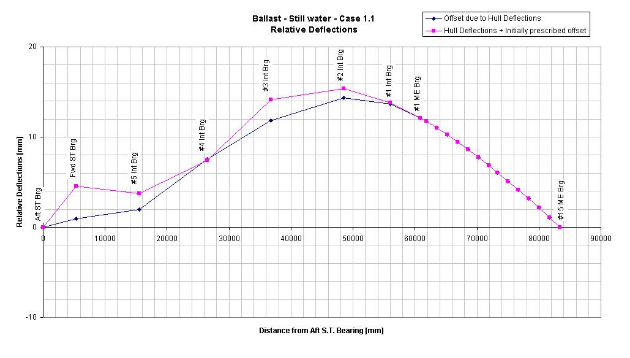
4.2 Example - Hull Girder Deflection Measurements

The example used here to show how the hull deflection measurements may be conducted is the same container vessel on which the analytical investigation of the hull deflections was conducted.

Strain gauges were placed at nine locations along the line shaft, and the bending moments were measured. At the same time, engine crankshaft deflections, M/E bearing reactions, line shaft bearing reactions and forward stern tube bearing reactions were measured. The reverse analyses were then conducted to obtain bearing offset from the above measured parameters.

The obtained results are shown below and compared with the analytically obtained hull deflections:

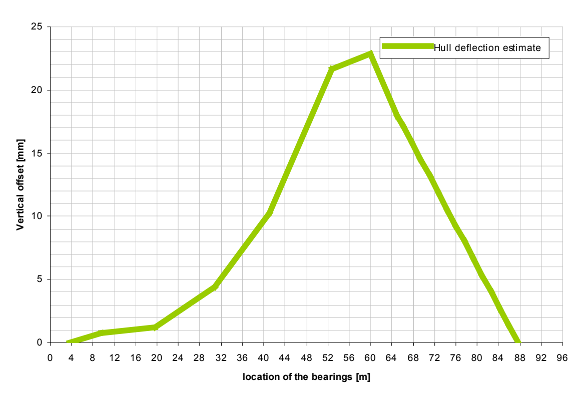




Measurement:
Hull deflection change from dry dock to ballast condition

Calculated:
Hull deflection – ballast condition

A very good agreement in analytically predicting intensity and the shape of the deflection curve of the vessel in ballast condition is obtained.



Measurement:
Hull deflection change from dry dock to laden condition

Calculated:
Hull deflection – laden condition

Laden condition prediction is in less compliance with measurement. The reason is the difference in actual load distribution from the one that was analytically predicted.

5 Hull Deflection Application

The beforehand knowledge of hull deflections or ability to predict the deflections with sufficient accuracy would allow prescribed displacements of the bearings to be selected, which will result in a robust alignment and satisfactory bearing conditions under a whole spectrum of the vessel's operating conditions. This is where hull deflection investigation has its full application.

It is important to select an appropriate set of prescribed displacements to ensure a satisfactory bearing loading condition under all operating conditions. By ensuring a robust static alignment, trouble-free dynamic operation of the shafting, i.e., lateral vibration, may certainly be expected. Whirling may be expected to result in an acceptable response, and the operating condition of the bearings (in particular, tail shaft bearing) may have a prolonged life if a larger contact is ensured and the oil film develops sooner.

The ABS optimization program is based on the genetic algorithm method where a solution is sought by a parallel search throughout the solution space bounded by two "extreme" deflection curves (e.g., estimated hull deflections). Within the defined solution space, the desired number of acceptable solutions that comply with the basic alignment requirements is extracted. It is then up to the designers to select the solution which provides the most robust design.

SECTION 7 Alignment Optimization

1 General

The shaft alignment problem is stochastic with an infinite number of bearing offsets satisfying the requirements.

The goal of the shaft alignment optimization is to provide a set of acceptable solutions which all satisfy imposed constraints, alignment parameters and criteria. Multiple solutions are necessary as it is often an imperative to have the engineering evaluation as the final decisive factor in selecting the desired alignment. Providing multiple solutions is an inherited characteristic of GA, and it is a relatively simple task for a genetic algorithm.

The Genetic Algorithm (GA) optimization procedure is used in ABS as an appropriate tool to search for the optimal set of solutions. GA's ability to conduct a parallel search throughout the solution space is its biggest advantage as opposed to other search tools. The parallel search provides software capable of simultaneously providing multiple sets of bearing offsets which satisfy the bearing loading requirements. The GA program optimizes among several constraint functions (as defined by hull girder deflections). Constraints which bind the solution space are defined by hull deflection curvatures, which normally represent the still water ballast and laden vessel conditions. Sometimes, when maximum hogging and maximum sagging wave deflections are analytically estimated, it may be advisable to investigate how the extreme hull deflections influence the alignment (these conditions are not directly applicable as they represent dynamic operating conditions).

The complexity and speed of optimization will depend on a number of variables which are considered in the optimization process. The parameters and alignment criteria which should be considered normally imply compliance with the regulatory requirements, i.e.:

- Thermal expansion
- Diesel engine bedplate-prescribed sagging
- Bearing wear down
- Bearing elasticity is not considered due to its complexity (dependent on the contact area/ misalignment slope between the shaft and the bearing)

Additional requirements also need to be satisfied, e.g., the main engine flange allowable moment and shear force are to be in accordance with the engine designer recommendations.

2 Optimization Example

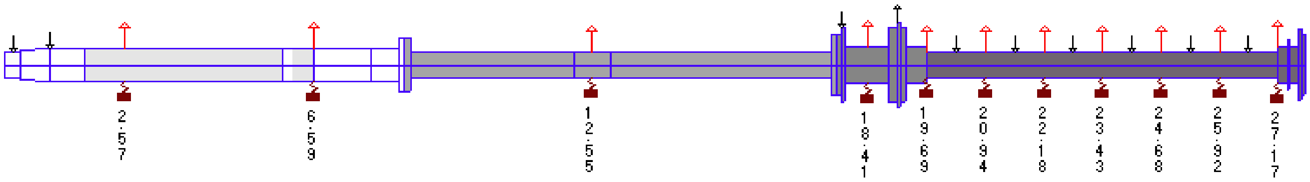
The example used to evaluate the optimization program performance is a typical VLCC arrangement with a single propulsion system, relatively short shafting and the low speed diesel engine as a main drive.

The particular problems that this kind of vessel may experience are:

- After stern tube bearing damage due to the excessive misalignment between the bearing and the shaft
- Main engine bearings (the aftmost three engine bearings are particularly at risk of being damaged due to improper alignment)

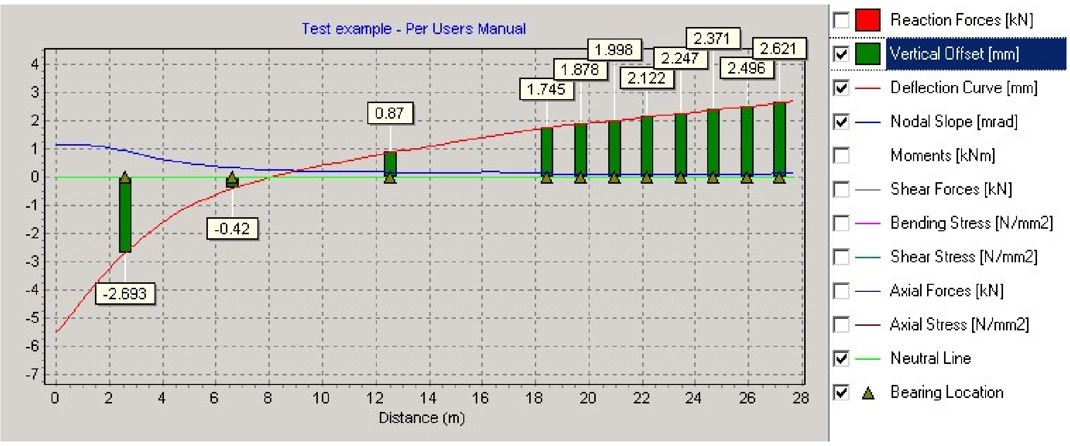
Section 7, Figure 1 represents a discrete model of the propulsion shafting and diesel engine for the purpose of shaft alignment analysis.

FIGURE 1
Discrete Model of the Shafting



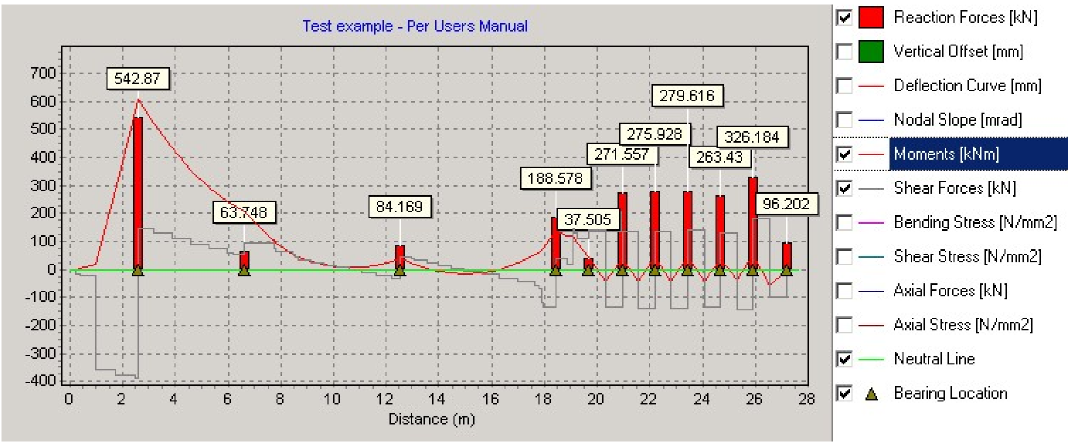
The above system (Section 7, Figure 1) was originally designed with the following bearing offsets (Section 7, Figure 2) and bearing reactions (Section 7, Figure 3):

FIGURE 2
Bearing Offset; Shaft Deflection Curve; Nodal Slopes



☐ 🟥 Reaction Forces [kN]
☑ 🟩 Vertical Offset [mm]
☑ — Deflection Curve [mm]
☑ — Nodal Slope [mrad]
☐ Moments [kNm]
☐ — Shear Forces [kN]
☐ — Bending Stress [N/mm2]
☐ — Shear Stress [N/mm2]
☐ — Axial Forces [kN]
☐ — Axial Stress [N/mm2]
☑ — Neutral Line
☑ ▲ Bearing Location

FIGURE 3
Bearing Reactions; Bending Moment; Shear Forces



☑ 🟥 Reaction Forces [kN]
☐ 🟩 Vertical Offset [mm]
☐ — Deflection Curve [mm]
☐ — Nodal Slope [mrad]
☑ — Moments [kNm]
☑ — Shear Forces [kN]
☐ — Bending Stress [N/mm2]
☐ — Shear Stress [N/mm2]
☐ — Axial Forces [kN]
☐ — Axial Stress [N/mm2]
☑ — Neutral Line
☑ ▲ Bearing Location

The above results look satisfactory for the particular case evaluated. However, if hull deflections are applied to the same system, the results of the analyses for two extreme cases of hull girder deflections (Section 7, Table 1) are not satisfactory.

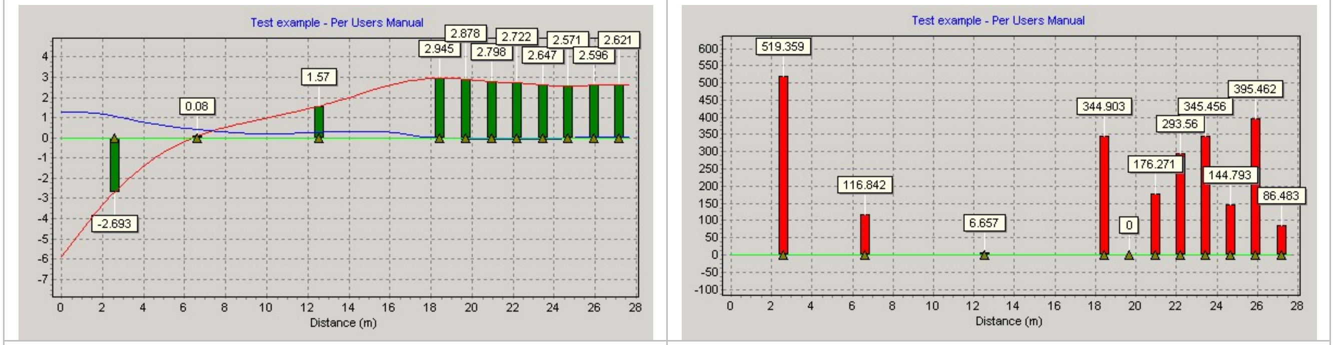
(Hull deflections are the rough estimate of possible hull girder deflections applied for evaluation purposes only.)

TABLE 1
Estimated Hull Girder Deflections

	Hull Deflection Estimate [mm]	
Bearing #	*Laden*	*Ballast*
1	0	0
2	0.5	-0.05
3	0.7	-0.07
4	1.2	-0.12
5	1	-0.1
6	0.8	-0.08
7	0.6	-0.06
8	0.4	-0.04
9	0.2	-0.02
10	0.1	-0.01
11	0	0

FIGURE 4
Laden – Bearing Offset Disturbed by Hull Deflections; Bearing Reactions – Unloaded M/E Bearing #2

Laden vessel hull girder deflections from Section 7, Table 1

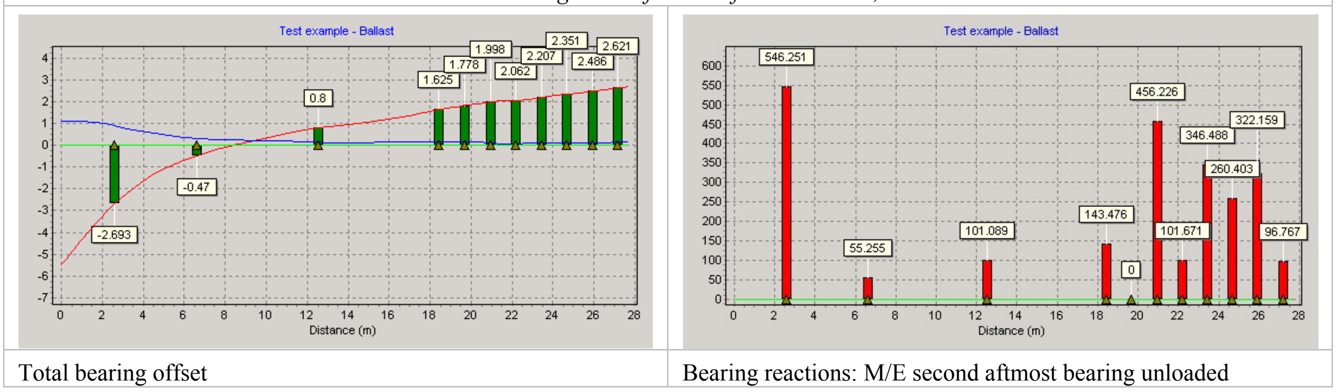


Total bearing offset

Bearing reactions: M/E second aftmost bearing unloaded, intermediate shaft bearing very lightly loaded

FIGURE 5
Ballast – Bearing Offset Disturbed by Hull Deflections; Bearing Reactions – Unloaded M/E Bearing #2

Ballast vessel hull girder deflections from Section 7, Table 1



Total bearing offset

Bearing reactions: M/E second aftmost bearing unloaded

The above analyses show that the initially prescribed offset does not satisfy the alignment requirements if hull deflections are considered, as the M/E second aftmost bearing gets unloaded (Section 7, Figure 4 for laden, and Section 7, Figure 5 for ballast condition).

The present practice in shaft alignment design does not normally include the hull deflections. Therefore, the only means of controlling the alignment condition is by measurement. However, measurements on the most sensitive segment of the system, i.e., the diesel engine bearings, are not conducted as a regular practice either. The consequence of this may be eventual damage and failure of the bearings.

In the above case, if the hull deflections were initially included, one would be able to predict the eventual problems and conduct the alignment with another set of prescribed offset at the bearings. However, without an optimization tool at hand, this process may be extremely time-consuming and difficult.

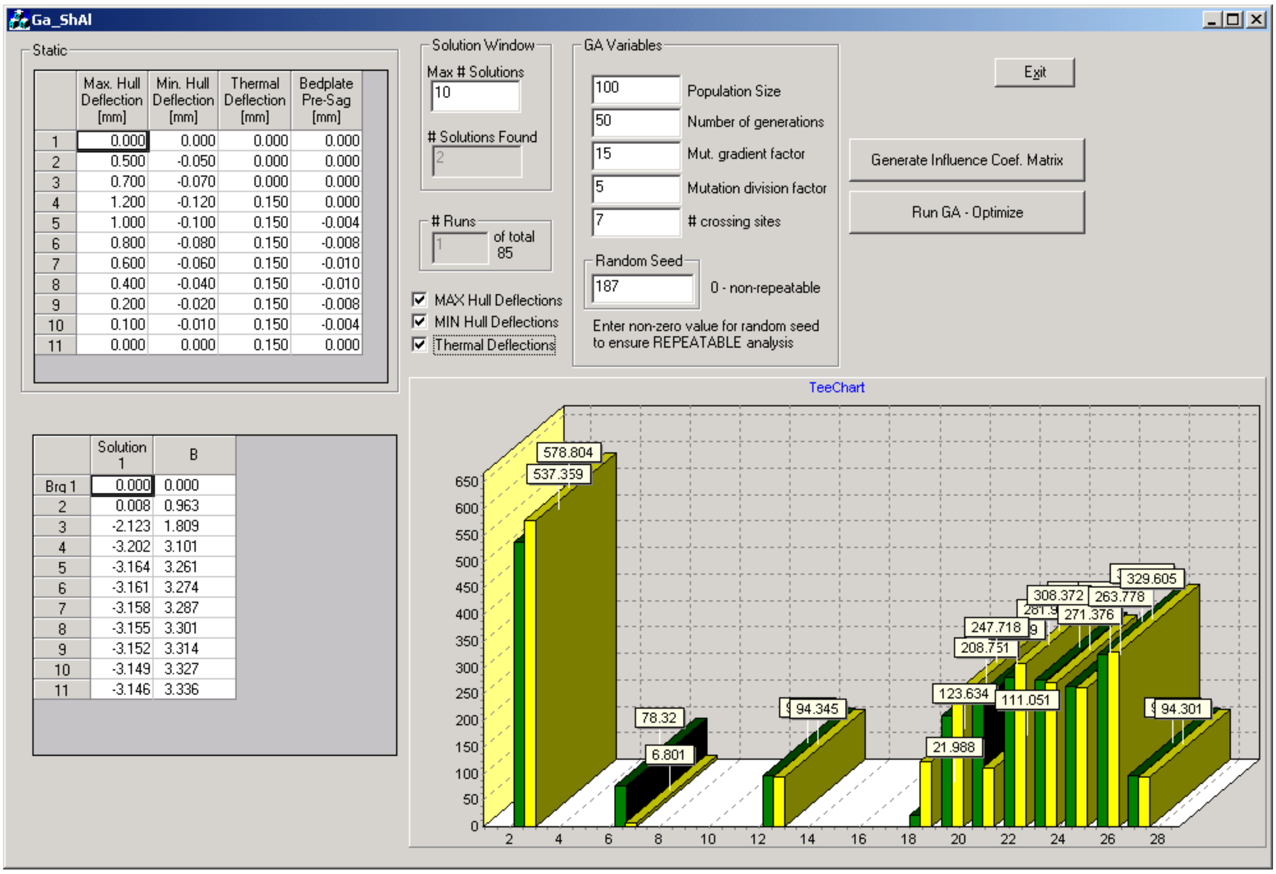
All of this indicates the necessity for optimization to be applied.

3 Optimization

The above analyses suggest that a different set of initially prescribed offsets be provided in order to ensure the subject installation's satisfactory alignment under ballast and loaded vessel conditions. Optimization may help investigate the solution more simply and faster than a trial and error process conducted without support of the computer software.

GAR software is applied, taking into consideration the following data (Section 7, Figure 6):

FIGURE 6
GA Input Data and Output Showing Two of Ten Desired Solutions



Static

	Max. Hull Deflection [mm]	Min. Hull Deflection [mm]	Thermal Deflection [mm]	Bedplate Pre-Sag [mm]
1	0.000	0.000	0.000	0.000
2	0.500	-0.050	0.000	0.000
3	0.700	-0.070	0.000	0.000
4	1.200	-0.120	0.150	0.000
5	1.000	-0.100	0.150	-0.004
6	0.800	-0.080	0.150	-0.008
7	0.600	-0.060	0.150	-0.010
8	0.400	-0.040	0.150	-0.010
9	0.200	-0.020	0.150	-0.008
10	0.100	-0.010	0.150	-0.004
11	0.000	0.000	0.150	0.000

Solution Window
Max # Solutions: 10
Solutions Found: 2
Runs: 1 of total 85

☑ MAX Hull Deflections
☑ MIN Hull Deflections
☑ Thermal Deflections

GA Variables
100 Population Size
50 Number of generations
15 Mut. gradient factor
5 Mutation division factor
7 # crossing sites

Random Seed: 187 0 - non-repeatable
Enter non-zero value for random seed to ensure REPEATABLE analysis

	Solution 1	B
Brg 1	0.000	0.000
2	0.008	0.963
3	-2.123	1.809
4	-3.202	3.101
5	-3.164	3.261
6	-3.161	3.274
7	-3.158	3.287
8	-3.155	3.301
9	-3.152	3.314
10	-3.149	3.327
11	-3.146	3.336

The diversified solutions are desired because very different bearing offsets may similarly satisfy the bearing reactions. Namely, satisfactory bearing reactions may be obtained by the engine being raised above the zero offset line. At the same time, a very similar solution (bearing reaction wise) may be obtained with the main engine (M/E) being lowered below zero offset line.

The solution with M/E being lowered below the zero line will eventually result in a smaller inclination gradient between the shaft and the stern tube bearing. However, the stress in the shaft in that case will be higher.

In cases without forward stern tube bearing, the solution with M/E below zero line will result in a much more sensitive misalignment in the aft stern tube bearing, and therefore, this solution may not be found acceptable.

Solutions obtained by applying an optimization routine are tabulated in a format which provides detailed information on how a particular change in the offset condition affects the alignment. Namely, bearing reactions calculated for respective bearing offset are as follows:

- Zero offset reactions
- Reaction difference which when applied to zero-offset solution provides the desired bearing load (i.e., all positive reactions)
- Maximum hogging bearing reactions
- Maximum sagging bearing reactions
- Even keel bearing reactions
- Bearing offset – includes thermal condition and bedplate prescribed sagging:
    - Maximum hogging bearing offset
    - Maximum sagging bearing offset
    - Optimization software generated bearing offset
    - Deflection data (max. hogging, max, sagging, thermal and prescribed bedplate sag)

The “best”, i.e., the most robust solution for the particular case (Section 7, Table 2), is taken and further analyzed.

In this particular case, it is presumed that the alignment procedure is fully conducted in the dry dock. Therefore, the optimized bearing offsets are actually values which are to be applied to the bearings while the vessel is in the dry dock.

The obtained reactions may therefore be verified with a relatively high accuracy. Section 7, Table 3 shows a set of dry dock values for the first of four selected solutions.

TABLE 2
Optimal Solution

Optimization results: selected solutions from a pool of 10 satisfactory solutions

```
 Optimization with Genetic Algorithm


  Generation:    9    String: 52   FITNESS: 1.100000
             |                SUPPORT REACTIONS                     |  Total     Total      GA      Max Hull  Min Hull   Thermal    Engine
             |    Ry[0]      delRy       Ry         Ry          Ry  |  Offset    Offset   defined   Deflect.  Deflect.   Offset      Sag.
Sup. Node |                          (Max.Offs) (Min.Offs)    (dy)  |   Max.      Min.      dy
No    No  |     [kN]        [kN]       [kN]       [kN]       [kN]   |   [mm]      [mm]      [mm]      [mm]       [mm]       [mm]       [mm]
  ------------------------------------------------------------------------------------------------------------------------------------------
  1  <  7> |  601.283    -56.872    518.533    544.996    544.411|  0.000 |  0.000 |  0.000 |  0.000 |  0.000 |  0.000 |  0.000
  2  < 14> |  -41.678     87.605    106.331     46.072     45.927|  3.979 |  3.429 |  3.479 |  0.500 | -0.050 |  0.000 |  0.000
  3  < 27> |  148.734    -20.861     34.172    124.780    127.873|  6.893 |  6.123 |  6.193 |  0.700 | -0.070 |  0.000 |  0.000
  4  < 41> |  133.298   -108.513    275.984     32.933     24.785|  8.234 |  6.914 |  6.884 |  1.200 | -0.120 |  0.150 |  0.000
  5  < 46> |   64.015    208.676     81.192    267.522    272.691|  8.149 |  7.049 |  7.003 |  1.000 | -0.100 |  0.150 | -0.004
  6  < 48> |  286.255   -132.362    155.648    152.923    153.893|  7.954 |  7.074 |  7.012 |  0.800 | -0.080 |  0.150 | -0.008
  7  < 50> |  272.916     26.788    285.205    301.263    299.704|  7.762 |  7.102 |  7.022 |  0.600 | -0.060 |  0.150 | -0.010
  8  < 52> |  277.995     -5.009    345.582    265.960    272.986|  7.572 |  7.132 |  7.032 |  0.400 | -0.040 |  0.150 | -0.010
  9  < 54> |  265.291     -1.102    143.036    274.995    264.188|  7.384 |  7.164 |  7.042 |  0.200 | -0.020 |  0.150 | -0.008
 10  < 56> |  325.359      3.146    399.197    322.706    328.505|  7.298 |  7.188 |  7.052 |  0.100 | -0.010 |  0.150 | -0.004
 11  < 58> |   96.318     -1.496     84.905     95.636     94.822|  7.208 |  7.208 |  7.058 |  0.000 |  0.000 |  0.150 |  0.000
```

TABLE 3
Dry Dock – Bearing Reactions for Prescribed Offset

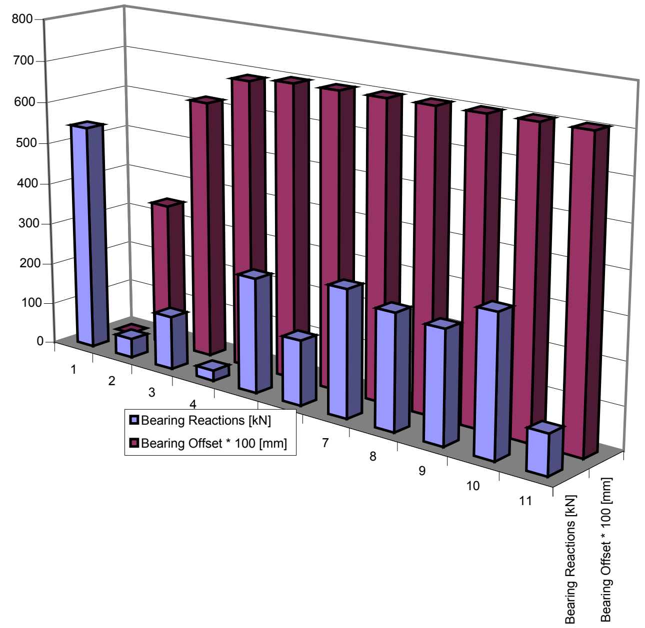
Dry dock condition offset and bearing reactions			
	Reactions	Offset	
	Ry (dy) [kN]	GA Defined Dy [mm]	
1	544.411	0	
2	45.927	3.479	
3	127.873	6.193	
4	24.785	6.884	
5	272.691	7.003	
6	153.893	7.012	
7	299.704	7.022	
8	272.986	7.032	
9	264.188	7.042	
10	328.505	7.052	
11	94.822	7.058	

TABLE 4
Ballast Vessel Hull Deflections – Bearing Reactions and Total Bearing Offset

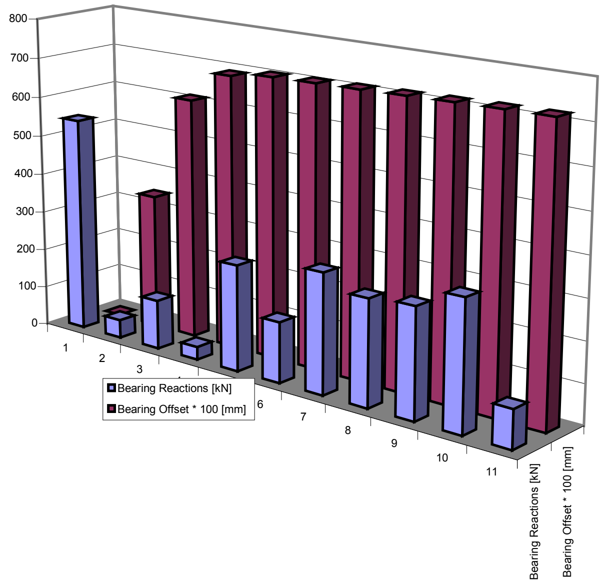
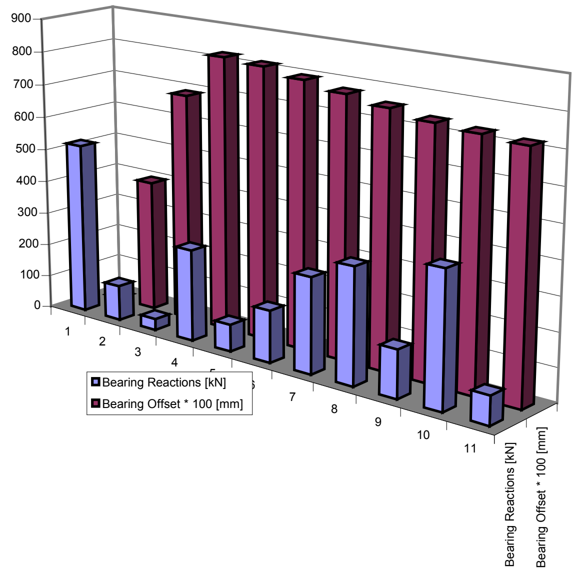
Ballast vessel offset and bearing reactions			
	Reactions	Offset	
	Ry (dy) [kN]	GA Defined Dy [mm]	
1	544.996	0	
2	46.072	3.429	
3	124.78	6.123	
4	32.933	6.914	
5	267.522	7.049	
6	152.923	7.074	
7	301.263	7.102	
8	265.96	7.132	
9	274.995	7.164	
10	322.706	7.188	
11	95.636	7.208	

TABLE 5
Laden Vessel Hull Deflections – Bearing Reactions and Total Bearing Offset

Laden vessel offset and bearing reactions		
	Reactions	Offset
	Ry (dy) [kN]	GA Defined Dy [mm]
1	518.533	0
2	106.331	3.979
3	34.172	6.893
4	275.984	8.234
5	81.192	8.149
6	155.648	7.954
7	285.205	7.762
8	345.582	7.572
9	143.036	7.384
10	399.197	7.298
11	84.905	7.208

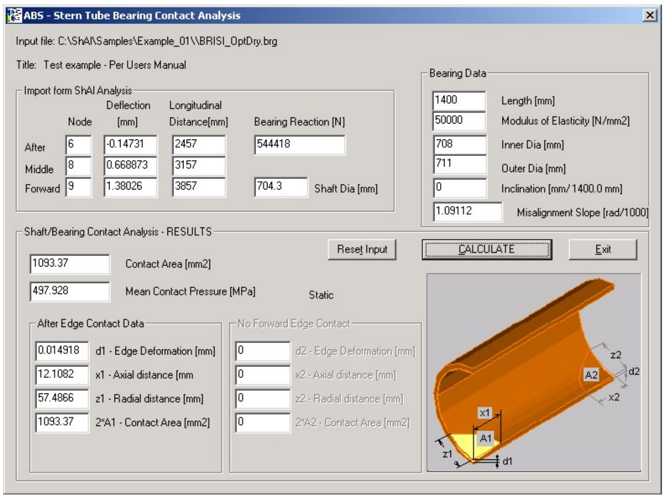


For the estimated hull deflections, the bearing reactions in all three cases, i.e., even keel (dry dock), ballast and laden, are satisfactory. The solution is robust, and if predicted hull deflections are within given limits, no unloaded bearings are to be expected.

Another important issue to be investigated is the misalignment slope between the shaft and the tail shaft bearing. The misalignment shall be reduced by slope boring if the shaft exerts excessive pressure on the bearing shell. ABS shaft alignment software is used in the bearing contact investigation.

Dry dock condition no slope boring

Contact pressure 497 MPa


ABS - Stern Tube Bearing Contact Analysis

Input file: C:\ShAl\Samples\Example_01\\BRISI_OptDry.brg

Title: Test example - Per Users Manual

Import form ShAl Analysis

	Node	Deflection [mm]	Longitudinal Distance[mm]	Bearing Reaction [N]
After	6	-0.14731	2457	544418
Middle	8	0.668873	3157	
Forward	9	1.38026	3857	704.3 Shaft Dia [mm]

Bearing Data

1400 Length [mm]
50000 Modulus of Elasticity [N/mm2]
708 Inner Dia [mm]
711 Outer Dia [mm]
0 Inclination [mm/ 1400.0 mm]
1.09112 Misalignment Slope [rad/1000]

Shaft/Bearing Contact Analysis - RESULTS

1093.37 Contact Area [mm2]
497.928 Mean Contact Pressure [MPa]
Static

After Edge Contact Data

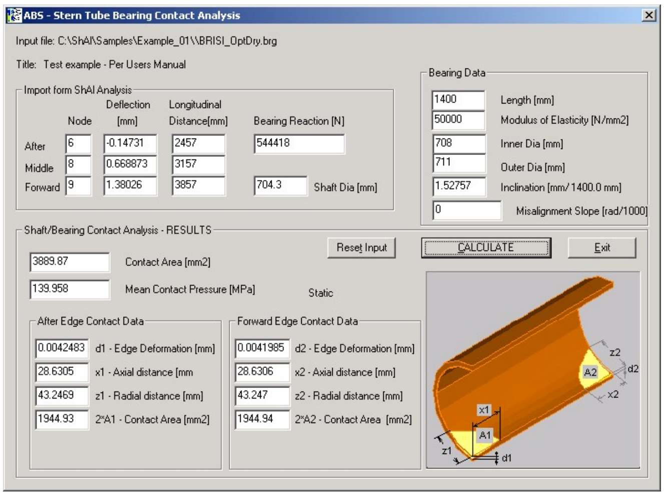
0.014918 d1 - Edge Deformation [mm]
12.1082 x1 - Axial distance [mm
57.4866 z1 - Radial distance [mm]
1093.37 2*A1 - Contact Area [mm2]

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]

Dry dock condition with slope boring

Contact pressure reduced to 139 MPa


ABS - Stern Tube Bearing Contact Analysis

Input file: C:\ShAl\Samples\Example_01\\BRISI_OptDry.brg

Title: Test example - Per Users Manual

Import form ShAl Analysis

	Node	Deflection [mm]	Longitudinal Distance[mm]	Bearing Reaction [N]
After	6	-0.14731	2457	544418
Middle	8	0.668873	3157	
Forward	9	1.38026	3857	704.3 Shaft Dia [mm]

Bearing Data

1400 Length [mm]
50000 Modulus of Elasticity [N/mm2]
708 Inner Dia [mm]
711 Outer Dia [mm]
1.52757 Inclination [mm/ 1400.0 mm]
0 Misalignment Slope [rad/1000]

Shaft/Bearing Contact Analysis - RESULTS

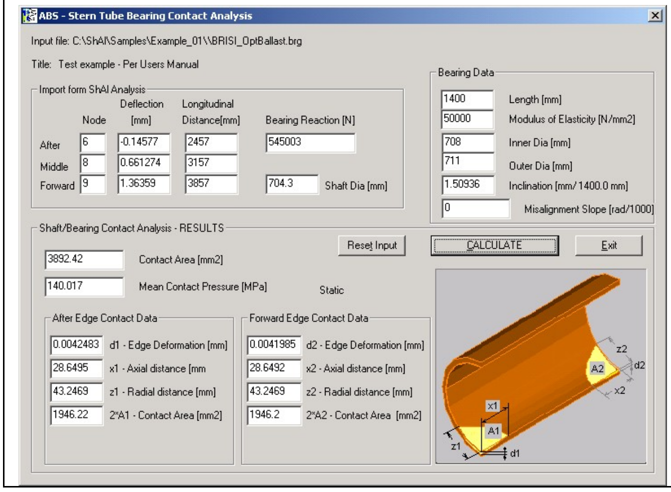
3889.87 Contact Area [mm2]
139.958 Mean Contact Pressure [MPa]
Static

After Edge Contact Data

0.0042483 d1 - Edge Deformation [mm]
28.6305 x1 - Axial distance [mm
43.2469 z1 - Radial distance [mm]
1944.93 2*A1 - Contact Area [mm2]

Forward Edge Contact Data

0.0041985 d2 - Edge Deformation [mm]
28.6306 x2 - Axial distance [mm]
43.247 z2 - Radial distance [mm]
1944.94 2*A2 - Contact Area [mm2]



ABS - Stern Tube Bearing Contact Analysis

Input file: C:\ShAl\Samples\Example_01\\BRISI_OptBallast.brg

Title: Test example - Per Users Manual

Import form ShAl Analysis

	Node	Deflection [mm]	Longitudinal Distance[mm]	Bearing Reaction [N]
After	6	-0.14577	2457	545003
Middle	8	0.661274	3157	
Forward	9	1.36359	3857	704.3 Shaft Dia [mm]

Bearing Data

1400	Length [mm]
50000	Modulus of Elasticity [N/mm2]
708	Inner Dia [mm]
711	Outer Dia [mm]
1.50936	Inclination [mm/ 1400.0 mm]
0	Misalignment Slope [rad/1000]

Shaft/Bearing Contact Analysis - RESULTS

3892.42 Contact Area [mm2]

140.017 Mean Contact Pressure [MPa]

Static

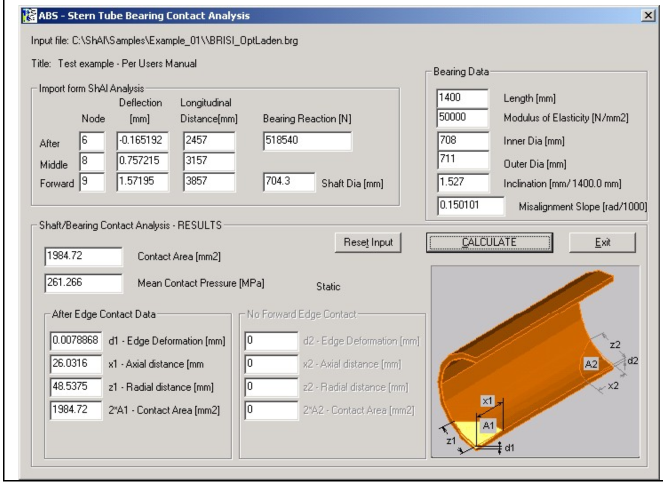
After Edge Contact Data

0.0042483	d1 - Edge Deformation [mm]
28.6495	x1 - Axial distance [mm
43.2469	z1 - Radial distance [mm]
1946.22	2*A1 - Contact Area [mm2]

Forward Edge Contact Data

0.0041985	d2 - Edge Deformation [mm]
28.6492	x2 - Axial distance [mm]
43.2469	z2 - Radial distance [mm]
1946.2	2*A2 - Contact Area [mm2]

Slope boring requirements for the dry dock condition would satisfy the ballast condition also.



ABS - Stern Tube Bearing Contact Analysis

Input file: C:\ShAl\Samples\Example_01\\BRISI_OptLaden.brg

Title: Test example - Per Users Manual

Import form ShAl Analysis

	Node	Deflection [mm]	Longitudinal Distance[mm]	Bearing Reaction [N]
After	6	-0.165192	2457	518540
Middle	8	0.757215	3157	
Forward	9	1.57195	3857	704.3 Shaft Dia [mm]

Bearing Data

1400	Length [mm]
50000	Modulus of Elasticity [N/mm2]
708	Inner Dia [mm]
711	Outer Dia [mm]
1.527	Inclination [mm/ 1400.0 mm]
0.150101	Misalignment Slope [rad/1000]

Shaft/Bearing Contact Analysis - RESULTS

1984.72 Contact Area [mm2]

261.266 Mean Contact Pressure [MPa]

Static

After Edge Contact Data

0.0078868	d1 - Edge Deformation [mm]
26.0316	x1 - Axial distance [mm
48.5375	z1 - Radial distance [mm]
1984.72	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]

Slope boring requirements for the dry dock condition would satisfy the loaded condition also. The misalignment slope is 0.15 mrad, which is below normal industry requirements for slope change.

The optimization algorithm applied here appears to determine the desired number of acceptable solutions within given constraints. The solution is found in a relatively short time. All of the benefits of conducting the shaft alignment optimization are immediately obvious from the presented example. It is noticed that the original alignment, as defined by taking the conventional approach in conducting alignment, will not result in a satisfactory static loading condition for the estimated hull deflections applied. In the conventional approach, the second aftmost main engine bearing and possibly the intermediate shaft bearing may become unloaded. Unloading of the main engine bearing confirms the very problems currently plaguing the propulsion installations. This all gives even more credibility to the proposed method, which can provide satisfactory solutions to the potentially dangerous problem.

Another problem is the accurate prediction of the hull girder deflections. The solution to the problem will obviously be very much dependent on the ability to evaluate hull deflections accurately enough to confidently evaluate the alignment. One possible way of doing so is to establish a generic data base of hull girder deflections for certain categories of vessels and to use the data base when vessels of similar design are evaluated. Data can be obtained either analytically or by measurement. ABS has already taken steps in that direction.

Relatively accurate hull deflection prediction and optimized alignment would allow alignment designers to confidently design alignment for the dry dock vessel condition. The alignment procedure could then be conducted fully in the dry dock. This would significantly increase the accuracy of the whole process, as verification of analysis by measurement would be possible with very little disturbance affecting the system.

SECTION 8 Glossary

1 Abbreviations

ABS	American Bureau of Shipping
Class	Classification society
M/E	Main engine; implies diesel engine if not stated differently
Rules	ABS *Rules for Building and Classing Steel Vessels* are implied if not stated differently
S/T	Stern tube
TDC	Top dead center – defines position of the piston in the engine cylinder.

2 Definitions

Alignment procedure: An executable part of the alignment process where alignment is performed in accordance with the requirements defined by the alignment designer.

Alignment process: Consists of the design and analysis, the alignment procedure and measurements.

Bearing offset: Bearing offset is vertical displacement of the contact face of the bearing from the optically established central line of the shafting.

Bedplate pre-sagging: Process by which the vertical deformation (catenary curve) is introduced on engine's bedplate to prevent engine alignment problems.

Bore sighting: See sighting-through.

Crankshaft deflections: Change in distance between crank webs, measured during one rotation of the crankshaft.

Bearing clearance: Radial gap between the shaft and the bearing shell.

Horizontal offset: Horizontal bearing offset is normally not desired.

Influence coefficients: Values defining relative change in bearing reactions as the offset at particular bearing changes for unit value.

Jack-up procedure: Procedure which uses hydraulic jacks to measure bearing reactions.

Lifting/lowering line gradient: Angle of the plotted jack-up line measured in mm/kN (or similar displacement vs. force units).

Misalignment angle: Angular difference between central line of the shaft and the central line of the respective bearing.

Negative offset: Bearing vertical position below the referenced (zero) line.

Prescribed displacements: Desired bearing offset prescribed by designer to obtain satisfactory alignment

Positive offset: Bearing vertical position above the referenced (zero) line

Rule of thumb: A method established, or a procedure derived entirely from practice or experience, without any basis in scientific knowledge; a roughly practical method.

Sag and gap: Procedure of verification of the alignment condition prior to shafting assembly.

Sighting through: Optical procedure by which bearings are offset to the prescribed values and slope bored/inclined (if required)

Slope boring: Procedure by which the bearing is machined so to comply with misalignment requirements.

Straight alignment shafting: Propulsion shafting supported by the bearings which are positioned so to ensure straight center line of the undeformed shafting. Straight alignment shafting is also called zero offset alignment.

Strain-gauge method: Method used to measure strain change in the shafting.

Undeformed shafting: Shafting which central line is straight. This assumes that no gravity and external forces or moments are acting on the propulsion shafting system.

Vertical offset: See bearing offset.

Zero offset alignment: See straight alignment shafting.