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Identification of shaft line alignment with insufficient data availability

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ABSTRACT

The paper presents a method of identification parameters of shaft line alignment in case of the lack of producers' data. Proper shaft line alignment is often a problem for repair shipyards, for aged ships without sufficient documentation. Author proposed combined experimental-analytical method for identified some existing parameters and checking (and eventually correcting) power transmission system's foundation. Specialised software has been developed for shaft line alignment calculations with influence coefficients. An example analysis has been performed for cargo ships with medium-speed main engine and second one with slow-speed propulsion system. Multivariant computations supported by measurements of the ships' shaft line have been carried out.

Key words: shaft line alignment, bearings reaction, crankshaft external forces, shaft line stresses, aged ships

INTRODUCTION

Propulsion system's foundation might be changed dangerously during ship hull repairing (especially welding works) even if there is no work with power transmission system. What is more, improvement of the shaft line - crankshaft alignment is difficult because very often aged ships haven't available documentations. Repair shipyard does not know if foundation parameters of propulsion system are acceptable or not. Some of them (like shafts' diameters, intermediate bearings' reactions) are easy to measured but the others are practically inaccessible (shaft line deformation, shaft line – crankshaft interaction, stern tube and main engine bearings' reactions, stresses). The analysis become much more difficult if our software take into account isolated power transmission system from ship hull (Fig. 1) without boundary conditions (e.g. without hull displacements and stiffness) [9]. Usually, similar parameters of shaft line alignment before and after repair is a shipyard's target.

There is no, well known, cheap methods for inspection and eventually improvement of propulsion system foundation after ship hull repairing [13]. Abnormalities of the propulsion system's working parameters are often detected after ship's repairing, during sea trial or even after certain period of ship's voyage. Then, the failure repairing is very costly. Sometimes, tube of stern bearing or engine's main bearing must be replaced and the proper shaft line alignment must be performed.

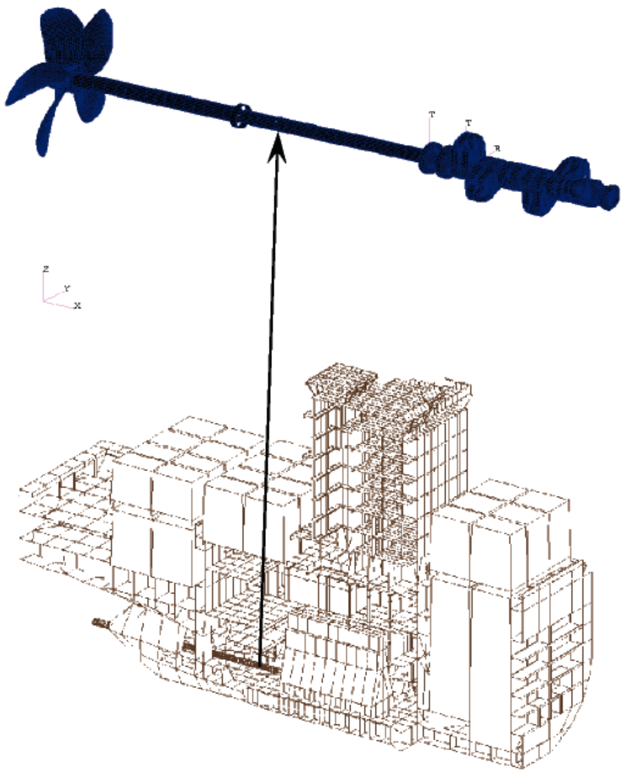

Fig. 1. Typical model of the power transmission system isolated from ship hull

Author proposed a method of shaft line alignment identification based on easy to measured parameters and numerical analysis. Elaborated specialised software can calculate influence coefficients for each bearing. Shaft line alignment identification should be performed before and after repairing process. Analysis shows if correction is necessary (if shaft line alignment parameters have been changed significantly during repairing). If yes, analysis, based on influence coefficients, give us advice how easily improve propulsion system's foundation.

IDENTIFICATIONS' METHOD

Just before starting hull repairing some typical measurements [1, 6, 7] should be performed. First of all, the jack-up test should be realized for intermediate bearings' reaction identification. Also identification of shafts' diameters is necessary. In the same time, the base of location of bearings body and shaft line position should be done.

Position changes of the shaft line can be controlled (Fig. 2) by bending stresses measurement (e.g. by strain gauge technique) [2, 3]. Bending stresses should be recorded during full rotation of the shaft (with usage of turning gear) just before and after ship repair process. Changes of the stress level in the horizontal and vertical plane may be simulated by numerical analysis and then changes of the shaft line alignment may be identified.

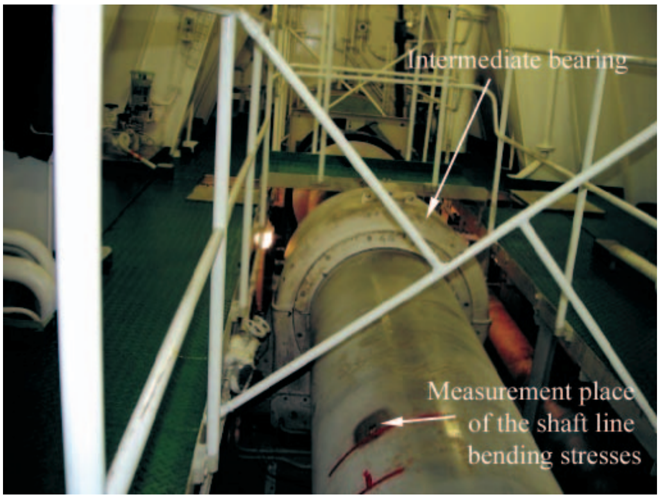

Fig. 2. Bending stress measurement of the shaft line

The relative position of bearing body might be based on measuring stress level [8] on foundation pads (Fig. 3) or on the other sensitive element of the bearing foundation (Fig. 4). Stress level should be recorded during jack-up test, before ship repair process. The simultaneous measurements can be treated as calibration process. After measurements the dependence between bearing reaction and stress level of the foundation pads (or foundation knee) is recognised. The same measurements (even without jack-up test) performed after ship repairing, give us changes of the bearing reaction which are induced during overhaul.

Whole (before and after repairing process) measurements investigation gives us necessary data for shaft line alignment's changes identification. The next step during expertises must be an assessment if identified changes are acceptable or not. The following limitations should be checked: loadings of the stern tube bearing, intermediate bearings and main bearings of the engine; stresses of the shaft line; interaction between shaft line and crankshaft. The shaft line alignment correction should be proposed if some limits are exceeded. Correction should be practicable and cheap. Generally, it should be restricted to displacements of the intermediate bearings in horizontal and vertical plane. Author made a specialised computer program which can be useful for all this tasks (identification, assessment and correction) with limited (without design documentation) data availability.

Fig. 3. Stress measurement of bearing's foundation pads

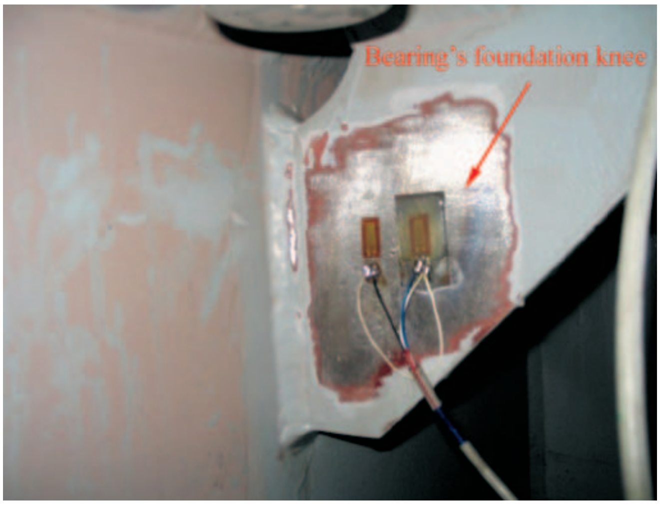

Fig. 4. Stress measurement of bearing's foundation knee

SOFTWARE DESCRIPTION

Assessment of the shaft line alignment for aged ships requires specialised software. The data for the software might be based on the measurements before and after ship's repairing in case of insufficient design data availability. During ship hull repairing (especially during welding works) power transmission system's axis might be unacceptable displaced even if there is no work with propulsion system. Assessment of the shaft line alignment before ship repairing process as well as determination of propulsion system's sensitivity on stable hull deformation is very important from technical and economical point of view. Author performed specialised software for bearing reactions' identification and shaft line alignment's influence coefficients determination.

Identification of shaft line alignment with knowledge only of bearings' reaction and shafts' geometry is reverse mathematical problem [4]. This problem is often ambiguous with multi solutions. For that reason equation no. 1 [5, 14] is solved during iteration process.

$$([K] - [K_G]) \cdot \{x\} = \{F\} \qquad (1)$$

where:

- K – global stiffness matrix,
- K_G – geometric stiffness matrix,
- x – displacement vector,
- F – generalised force vector.

Matrix equation no 1 is a system of algebraic equations with constant coefficients. Modified Gauss algorithm is used for solving the equations. The shaft line is modeled by 2-node (with 6 degree of freedom for each node) linear beam elements with nonlinear boundary conditions. The beams can be cylindrical or conical and drilled or not. Bearings might be modeled by point wise or continuous support with taking into account bearing's clearance and stiffness. Stiffness of the continuous bearing (e.g. stern tube bearing) is modeled by polynomial of 10 order. In the program there are procedures for field solution's searching. Finding out variants fulfilling measured values is a target of the algorithm. All variables are declared in the program as dynamic one so there are no limitations for number of elements and bearings. An example of multi bearings shaft line is presented on Fig. 5.

ANALYSIS EXAMPLE FOR THE CONTAINER SHIP

As a first step, the analysis has been performed for the container ship with typical propulsion system – constant pitch propeller driven directly by slow speed main engine. An example analysis has been made for container ship 4500 TEU. The hull stiffness characteristics on the base of FEM ship model analyses [10] like presented on Fig. 6. This kind of the model contains about 50 000 ÷ 150 000 degrees of freedom.

The methods of the characteristics determination of ship hull and main engine have been presented in the other author's articles [11, 12]. The examples of ship hull with propulsion system dynamic characteristics are presented on Fig. 7-8.

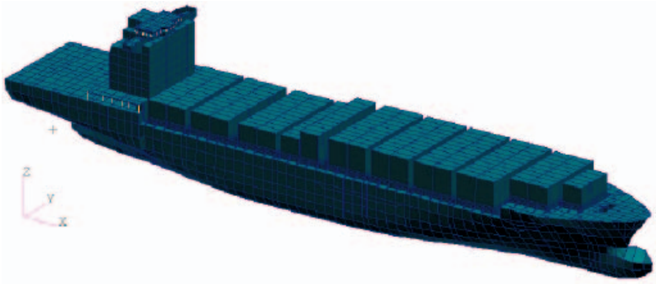

Fig. 6. *FEM model of container ship*

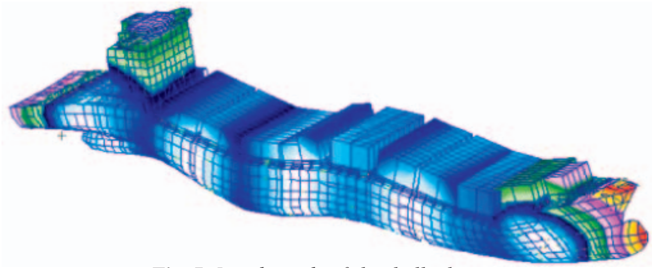

Fig. 7. *5-node mode of ship hull vibration*

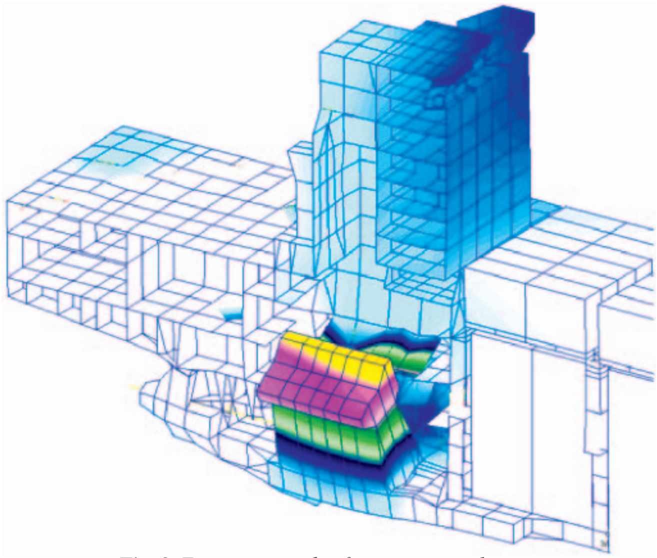

Fig. 8. *Transverse mode of main engine vibration*

Analysis is performed on the basis of standard shipyard's shaft line alignment. This alignment is correct but their parameters might be better. The aim of the calculations is showing software possibilities. Standard shaft line reactions are presented on Fig. 9.

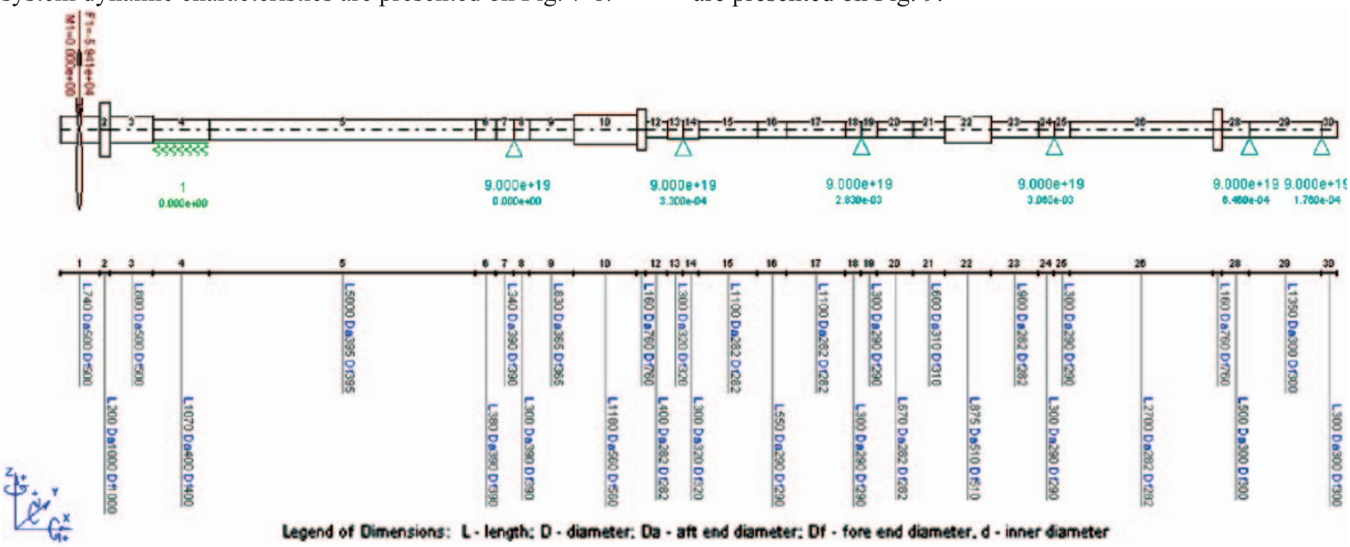

Fig. 5. *Shaft line model of two shaft's universal supply ship*

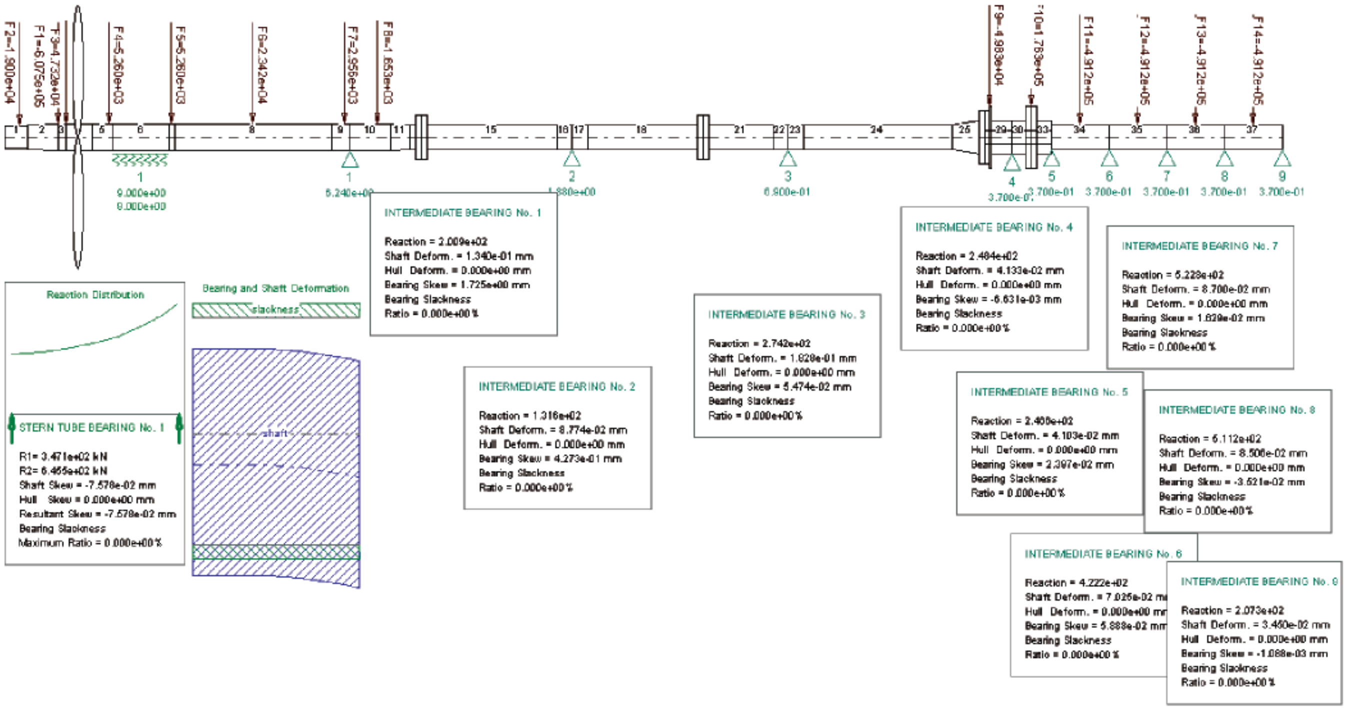

Fig. 9. Container's shaft line reactions determined by the software for standard alignment

The standard shaft line alignment might be improved by equalization of the aft stern tube bearing's reaction and by reduction of the aft engine's main bearing. Loading enlargement of the fore stern tube bearing (and aft stern tube bearing's loading equalization) is a consequence of reaction reduction of the aft intermediate bearing (to 100 kN, ~24%). Resultant skew of the propeller shaft in the bearing tube is then decreased of about 8%. Loading reduction of the main bearings (of about 9%) is an effect of reaction increasing (to 300 kN) of fore intermediate bearing. The algorithm find out automatically new (for given intermediate bearings' reactions) shaft line alignment. The modified parameters of the new shaft line alignment are presented on Fig. 10÷12.

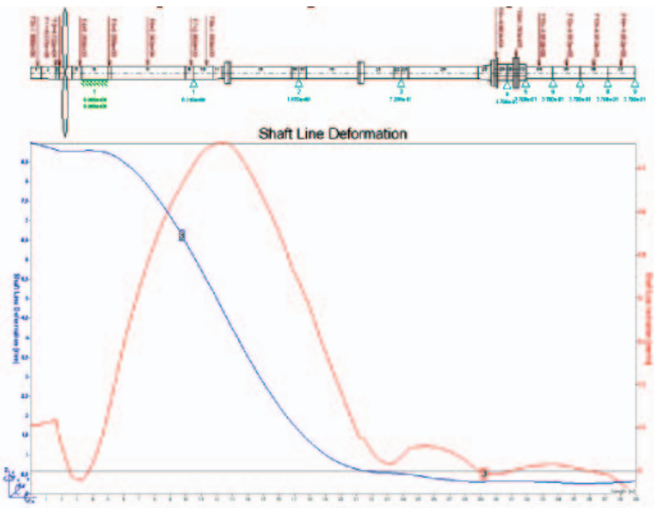

Fig. 10. Modified shaft line deformation

Influence coefficients are also determined by the program. The coefficients are useful for designers because they show the relative changing of the shaft line parameters (shaft line deformation, reactions, bending moments, shear forces, stresses) if chosen bearing is moved vertically or longitudinally. An example of influence coefficients for vertical movement of aft intermediate bearing are presented on Fig. 13 ÷ 15. Influence coefficients of the bearings reaction under the influence of bearings' longitudinal and vertical movements are also determined.

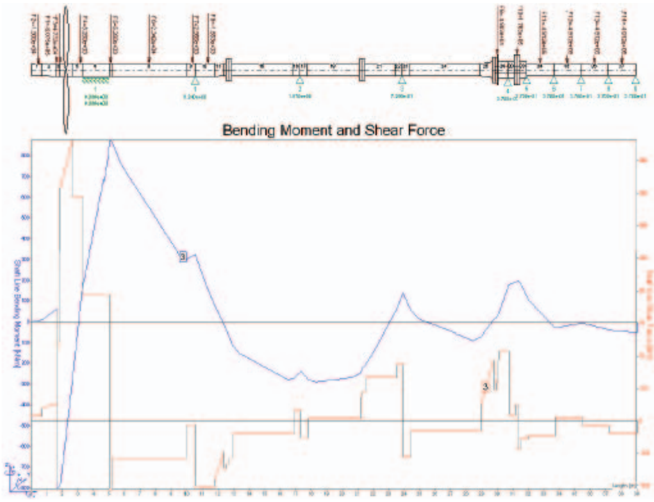

Fig. 11. Modified shaft line bending moments and shear forces

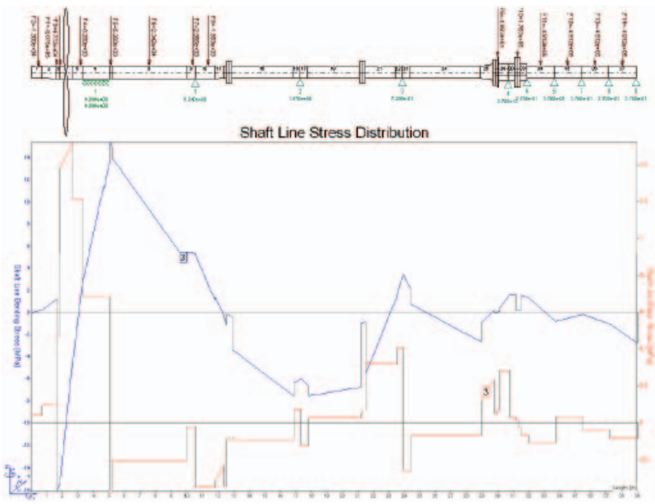

Fig. 12. Modified shaft line stresses distribution

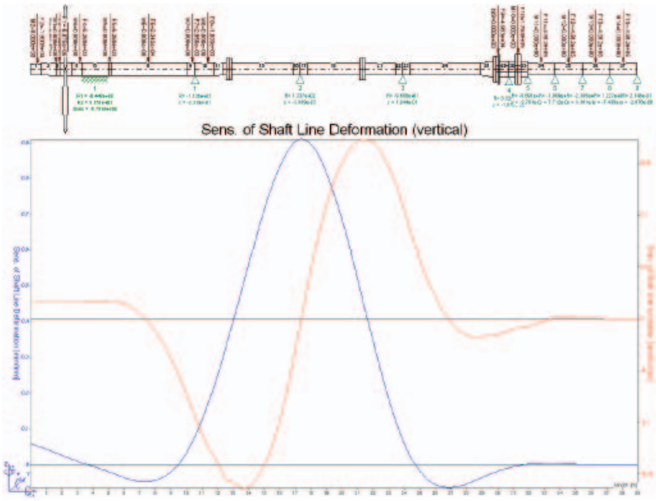

Fig. 13. Influence coefficients of shaft line deformation under the influence of vertical movement of aft intermediate bearing

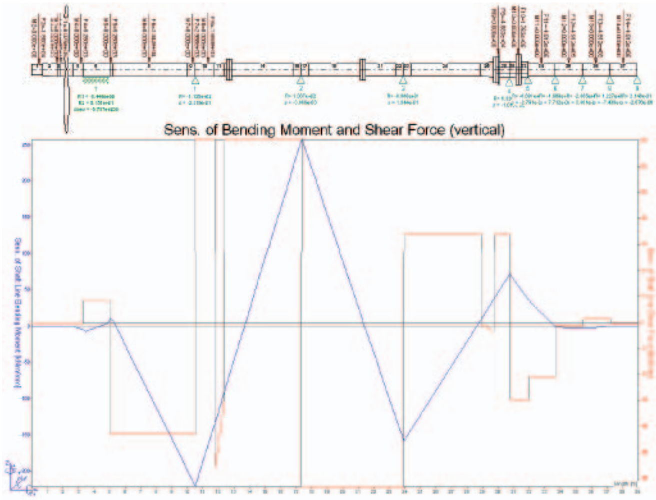

Fig. 14. Influence coefficients of bending moments and shear forces under the influence of vertical movement of aft intermediate bearing

The analysed shaft line is relatively stiff – it is short with big diameter and the propulsion system is equipped in many lateral bearings. For that reason, displacement of one bearing have an influence on only one shaft segment limited by adjacent bearings. Longitudinal movement of the intermediate bearings has hardly perceptible influence on the analysed shaft line alignment parameters.

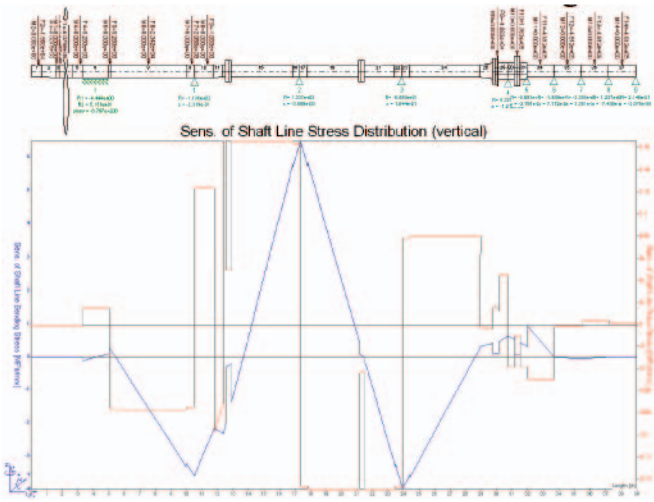

Fig. 15. Influence coefficients of shaft line stresses under the influence of vertical movement of aft intermediate bearing

IDENTIFICATION OF THE MIDDLE-SPEED PROPULSION SYSTEM

Identification has been performed for aged ship destined for heavy repair process. It is universal supply ship with double-shaft, middle-speed propulsion system (with gear box). The shaft line is more flexible then previous one: ϕ282 is a diameter of intermediate shaft and ϕ400 is a diameter of propeller shaft. In the ship's documentation, only design bearings' reactions are available. Real reactions are known after measurements. Design and real shaft line alignment have been identified by the discussed software. Identified shaft line reactions are presented on Fig. 16 and 17. Significant difference between design and real reactions are observed. The most important differences (which needed improvements) are as follows: unloaded aft edge and overloaded fore part of stern tube bearing and insufficiently loading of stern intermediate bearing. Shaft line alignment should be improved.

The author's software determine given shaft line alignment as a first step, and searching the field of optimal solutions in

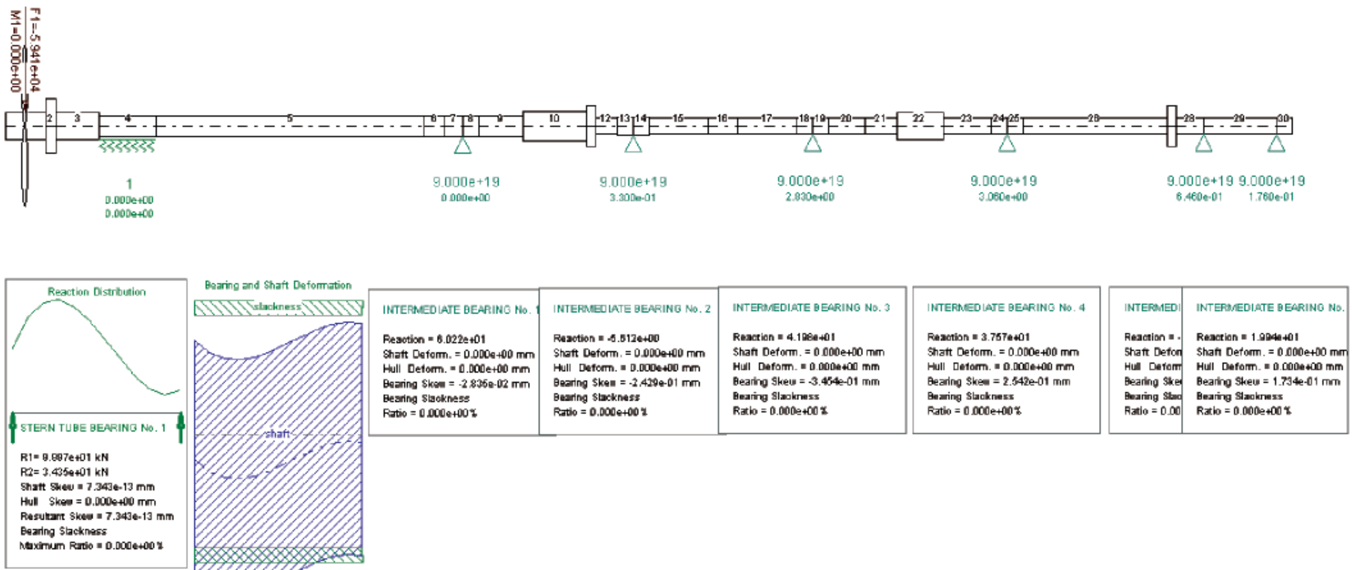

Fig. 16. Design shaft line alignment and reactions

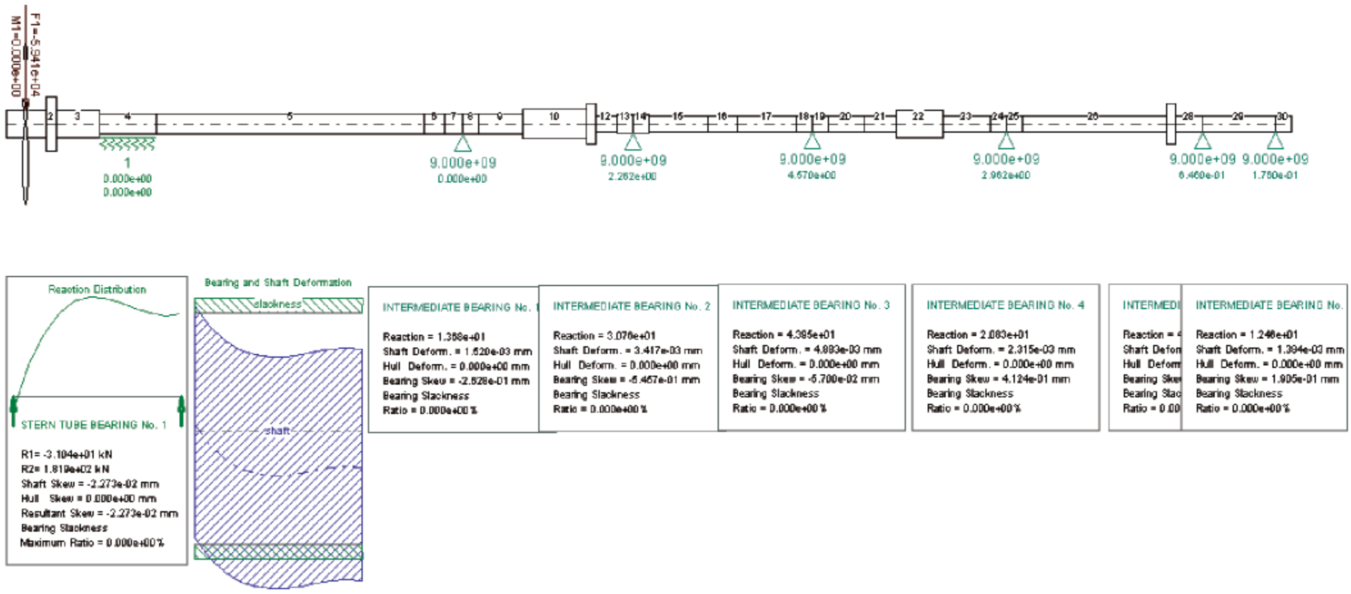

Fig. 17. *Real shaft line alignment and reactions*

the second step. In the third step the influence coefficients are determined by the program. The coefficients are useful for fast and precisely determination of proper bearings position in vertical and longitudinal plane. Determined influence coefficients are presented in Tab. 1. Denotations: **ST** – stern tube bearing, **I1** – first (starting from the stern) intermediate bearing, etc.

Tab. 1. *Vertical influence coefficients*

Bearing:	I2 [kN/mm]	I3 [kN/mm]	I4 [kN/mm]
ST	-5.85 15.41	0.69 -1.82	-0.16 0.43
I1	-32.89	9.74	-2.29
I2	40.26	-23.48	8.06
I3	-23.48	26.28	-17.12
I4	8.06	-17.12	24.50

Target of the shaft line alignment is determining proper and uniform bearings reaction, acceptable stress level and good interaction between shaft line and crankshaft or gearbox [15]. Proper shaft line alignment has been determined (based on coefficients presented in tab. 1) by following lift of the intermediate bearings: **I1** – 4.8 mm, **I2** – 6.1 mm, **I3** – 4.5 mm, **I4** – 2.0 mm. Improved bearings reaction distribution is presented on Fig. 18. Comparison of the shaft line alignment's parameters, before and after improvements, is shown on Fig. 19 ÷ 21.

Shaft line alignment after correction is characterised by smoother axis deformation and uniform bearings reaction. Intermediate bearing no. 1 is heaviest loaded by the others because of desirable loading of stern tube bearing. After correction loading of the fore edge of stern tube bearing is reduced two times, while loading of aft edge become acceptable. Before correction the aft edge of stern tube bearing was unloaded and was threaten by hammering phenomenon.

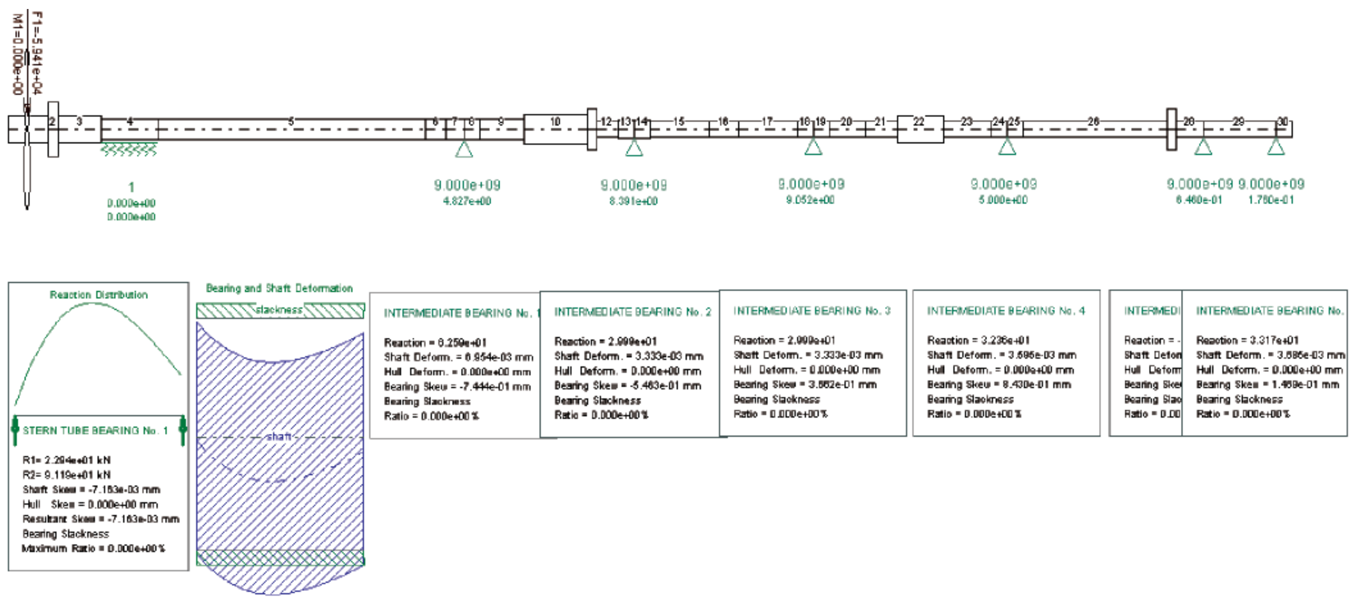

Fig. 18. *Shaft line alignment and reactions after correction*

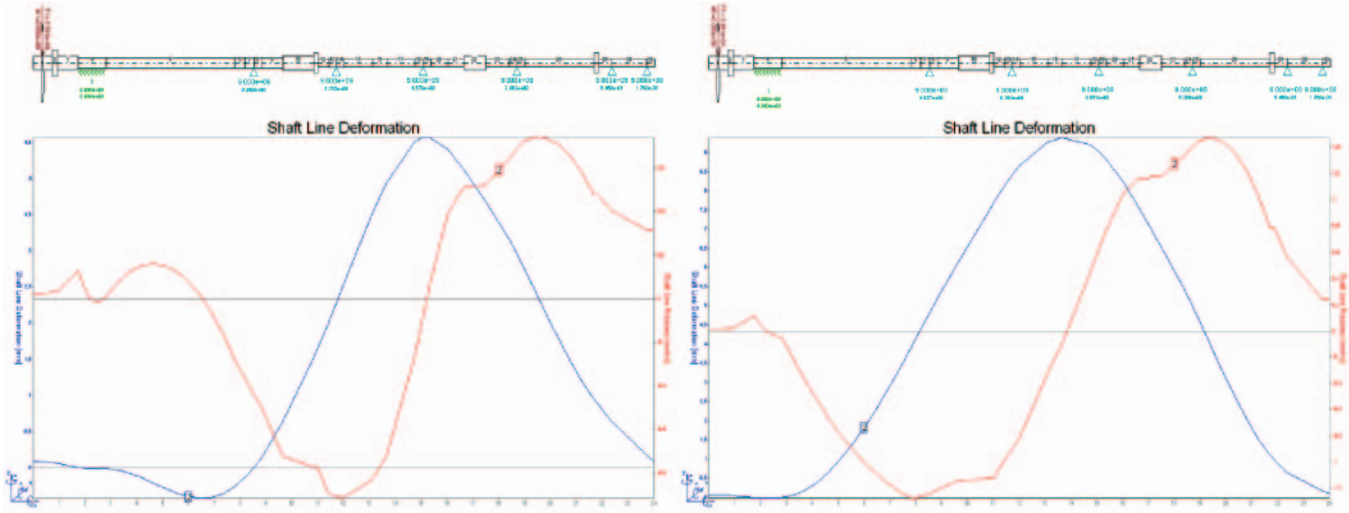

Fig. 19. Shaft line deformations before and after correction

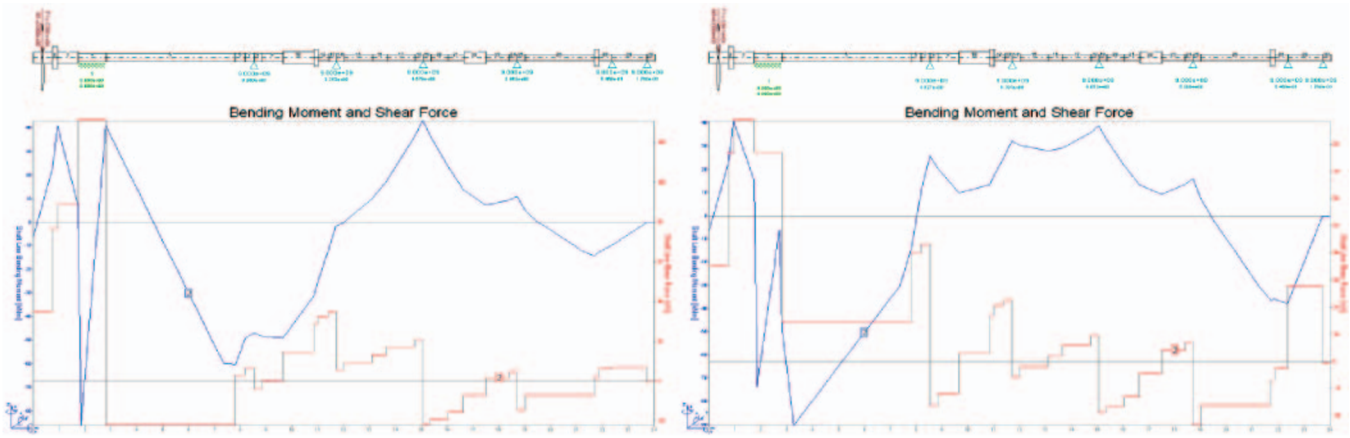

Fig. 20. Shaft line bending moments and shear forces before and after correction

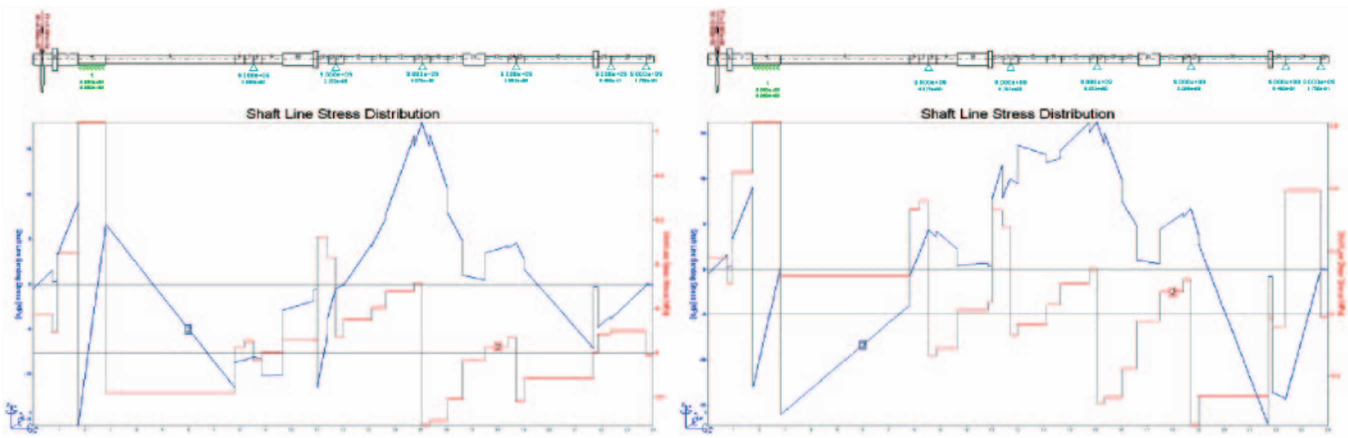

Fig. 21. Shaft line stresses distribution before and after correction

SUMMARY

Changes of shaft line alignment of aged ship with insufficient data availability have been difficult for proper realisation with standard methodology. Shipyards are looking out for well experienced workers because shaft line alignment has been performed by tests and errors method. Usually, it is very costly and the cost of the process is depended on engineer's experience. Sometimes, repair shipyards make an assumption that bearing reaction deviation ± 50% is acceptable!

In the paper author proposed a quite simple and cheap method for identification of shaft line alignment parameters in case of the lack of producers' data. It is proposed combined experimental-analytical method for identification and correcting some existing parameters of power transmission system's foundation. Specialised software has been developed and verified for shaft line alignment

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