Alignment Optimization of 3D Model of Propulsion Shaft System

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Abstract. Three dimensions models of propulsion shafts are presented in this work. A shaft alignment optimization is computed for a crankshaft, intermediate shaft and propeller shaft. “Design Study” sensors are used to report the best solutions of bearing reactions according to the vertical displacement. Shear forces and bending moments are listed for the flanges. The finite element analysis investigated a slope and deflection of the propulsion shaft system. Pictures of stress and displacement of the shafts, bolts and flanges are pointed in the paper. Stress concentrations and a factor of safety is calculated in the 3D dimension.

1. Introduction

Nowadays, the shipbuilding tendency is followed by increasing the vessel cargo capacity, which is associated to the rise of main drive power. The drive shafts then become increasingly sensitive to the disturbances affecting to the bearing’s vertical displacement. However, the shaft alignment procedures remain an important problem requiring accurate analyzes [1, 2]. The positive values of supporting reactions in the sliding bearings is the main criteria of shaft alignment. A software method is used to optimize the elastic shafts line [3] by monitoring and compliance of the shaft alignment criteria.

This paper examines the loading of propulsion shaft system of a bulk carrier 21100 DWT. An assemble model is created of the shafts and a methodology of alignment optimization is developed. In figure 1 is presented:

- position 1 – AFT Stern Tube Bearing;
- position 2 – FWD Stern Tube Bearing;
- position 3 – Flanges of propeller and intermediate shaft;
- position 4 – Intermediate bearing;
- position 5 – Flanges of intermediate shaft and crankshaft;
- position 6 to 11 – crankshaft bearings;
- Ø440 – basic diameter of propeller shaft;
- Ø370 – basic diameter of intermediate shaft.

The correct static alignment of shafts is developed from practice to get the smooth dynamic operations of system [4, 5]. This leads to the reduction of excessive vibration of line, as well as the transmission of gearbox noise.
The basic criteria, requirements and restrictions for shaft alignment are usually determined by classification societies, shipbuilders, designers and other control authorities [6]. Depending on which parameter is applicable, are considered:

- location of the permanent bearings, temporary bearings and location of the reaction measurement lifting points;
- propeller and intermediate shaft bearings reaction forces;
- crankshaft and transmission bearings reaction forces;
- shafts, bearings, clutches and flange mounting bolts load;
- slope and deflection of the propeller shaft, intermediate shaft and crankshaft of engine;
- propeller shaft slope accorded to the reference line of shaft;
- radial, axial and angular shaft flanges positions;
- engine base deflection and its bending;
- vessel hull deformation.

The shaft alignment is satisfactory if the above mentioned parameters can be controlled within certain limits for all operating conditions of the vessel (fully loaded or unloaded vessel, lowered or into open water, temperature changes affecting shafts, propulsion on maximum power). The shaft alignment procedure begins once the conditions are met:

- vessel's construction temperature is stabled (usually the alignment is done in the early morning);
- massive parts such as superstructure, main engine, etc. are installed;
- all elements of the hull construction and equipment are presented;
- stern blocks are fully welded;
- leak tests are completed.

It is preferable for the shaft alignment procedures to start in a dry dock (bearing positioning, slope, etc.) and to provide a sufficient information for the production personnel. The alignment procedures are extended and require many software operations, mathematical calculations and theoretical analyzes. In this regard, the present paper is focused on the study and optimization of some parameters described above. The extreme cases that can lead to damage and failure of the propulsion system of vessel are analyzed.

Figure 1. Shaft alignment scheme
The goal is to monitor and/or optimize by a software the following criteria [7]:

- vertical displacement of the FWD stern tube bearing and the intermediate bearing;
- crankshaft, intermediate shaft and propeller shaft criteria:
  - reaction forces and bending moments of bearings,
  - slope and deflection of shaft,
  - stress and displacement of shaft;
- radial, axial and angular shaft flanges positions;
- factor of safety.

2. 3D models of crankshaft, intermediate shaft and propeller shaft based on the technical documentation of a bulk carrier 21100 DWT

A crankshaft 3D model (figure 2) is presented as a shaft with variable cross section [8].

![Figure 2. Crankshaft 3D model](image)

A 3D model of intermediate shaft is pictured in figure 3 [9].

![Figure 3. 3D model of intermediate shaft](image)

A 3D model of propeller shaft is shown in figure 4 [9].

![Figure 4. 3D model of propeller shaft](image)
The 3D models of shafts are assembled into one model and links between them are created to meet the real conditions for joining the shafts figure 5.

**Figure 5. Assemble 3D model of shafts**

Following changes are made before the simulation of shafts alignment and load:

- bolts are located on the flanges of shafts;
- auxiliary circles and lines are added for visualizing the working surfaces of intermediate bearing (at the alignment stage of shaft, points limiting surfaces are used as an indicator of angular rotation of the elastic line of shaft);
- auxiliary circles and lines are added for visualizing the working surfaces of AFT stern tube bearing and FWD stern tube bearing;
- auxiliary circles and lines are added for visualizing the acting points of propeller mass (91 kN), turning wheel mass (14.1 kN), chain wheel mass (27.1 kN) and moving masses (51.25 kN per point), see figure 1;
- auxiliary lines are added for visualizing the points at which movements of flanges are monitored.

### 3. Configure simulation mode

In the static simulation of shafts, the following settings must be made:

- material properties:
  - Young’s modulus – \( E = 2 \times 10^{11} \text{ Pa} \),
  - Poisson’s ratio – \( \nu = 0.3 \),
  - shear modulus – \( G = 8 \times 10^{10} \text{ Pa} \),
  - density – \( \rho = 7850 \text{ kg/m}^3 \),
  - yield strength – \( R_{\text{yH}} = 3.4 \times 10^8 \text{ Pa} \);
- restraints (figure 6):
  - fixing displacement by axis \( Z \) (illustrated in red color),
  - fixing displacement by axis \( Y \) (illustrated in orange color and characterizing the positions of crankshaft bearings, intermediate bearing, AFT and FWD stern tube bearings),
• fixing displacement by axis $X$ (illustrated in green color);

Figure 6. Boundary conditions of shafts

• external loads (figure 7):
  
  o gravity – position 1,
  o propeller mass $F_{v1} = 91036.8\ N$ – position 2,
  o moving masses $F_m = 47100\ N$ – position 3,
  o chain wheel mass $F_{v2} = 27100\ N$ – position 4,
  o turning wheel mass $F_g = 14100\ N$ – position 5;

• mesh of finite elements:
  o for crankshaft element size are $S_{\text{min}} = 20\ mm$ and $S_{\text{max}} = 58\ mm$ (figure 8),

Figure 7. External loads of shafts

Figure 8. FEM mesh of crankshaft
for intermediate shaft element size are $S_{\text{min}} = 20 \, \text{mm}$ and $S_{\text{max}} = 45 \, \text{mm}$ (figure 9).

Figure 9. FEM mesh of intermediate shaft

for propeller shaft element size are $S_{\text{min}} = 20 \, \text{mm}$ and $S_{\text{max}} = 62 \, \text{mm}$ (figure 10).

Figure 10. FEM mesh of propeller shaft

4. Software shaft alignment of bulk carrier propulsion system

For most vessels, a vertical displacement of shaft’s bearings by 10% of a millimeter can lead to significant changes in the support reactions. Therefore, the process of shaft alignment takes a long time in order to determine satisfactory set of parameters that meet all criteria for the shaft alignment. The main parameter to be defined is the vertical location of FWD stern tube bearing and intermediate bearing. In addition, it must be verified that the alignment is feasible for the specific shaft geometry, material properties, installation restrictions and other requirements related to the drive shaft and the impact of surrounding systems [10].

The shaft alignment problem is different and has an infinite number of bearing vertical displacements satisfying the alignment requirements. For a optimization purpose is provided a set of acceptable solutions meeting the constraints imposed, the alignment parameters and the relevant criteria [6]. Numerous solutions are needed to engineers choose of desired alignment.

Three parameters sets are introduced for the shaft alignment optimization application: variables, constraints, and goals. Report date sensors are created for limitations and purposes of the optimization.

- variables – vertical displacement of bearing №2 and №4;
- constraints:
  - all bearing reactions have to be positive,
  - bearing reaction №1 have to be less than $232320 \, \text{N}$ [11],
  - every bearing reaction from №6 to №11 have to be greater than $9300 \, \text{N}$ and less than $186000 \, \text{N}$ [11],
  - max bending stress of the crankshaft, intermediate shaft and propeller shaft have to be less than allowable,
  - max stress of the crankshaft, intermediate shaft and propeller shaft have to be less than yield strength,
  - reporting shear stress of the crankshaft, intermediate shaft and propeller shaft,
  - reporting shear forces and bending moments of the crankshaft and propeller flange,
  - reporting displacement of the crankshaft and propeller flange,
  - reporting axis displacement of bearing №1, №2, №4, №6 and №7,
  - reporting radial displacement of bearing №1, №2 and №4,
  - reporting deflection of the intermediate and propeller shaft;
- goals – getting min factor of safety;
- sensors:
  - report sensor of the reaction forces,
  - report sensor of the max and min bending stresses of crankshaft, intermediate shaft and propeller shaft.
o report sensor of the max and min shear stresses of crankshaft, intermediate shaft and propeller shaft,
o report sensor of the maximal stresses of crankshaft, intermediate shaft and propeller shaft,
o report sensor of the max and min bending stresses of crankshaft and propeller shaft,
o report sensor of the shear forces of crankshaft and propeller flange,
o report sensor of the max and min displacements by axis Y and Z of crankshaft and propeller flange,
o report sensor of the max and min cross-section displacement of bearing №1, №2, №4, №6 and №7 by axis Y and Z,
o report sensor of the max and min deflection of intermediate and propeller shaft.

72 sensors have been created to meet the variables, constraints, goals and sensors of the optimizing shaft alignment. A part of them are shown in figure 11.

Figure 11. Constraints

5. Shaft alignment optimization results
The simulation is made of 38 displacement scenarios. The vertical displacement is set to the bearing №2 (2.1 mm ÷ 2.6 mm) and the bearing №4 (1.3 mm ÷ 1.8) for duration 37 minutes and data 10.27 GB. Data is extracted of the scenario №25 with vertical displacement 2.1 mm of bearing №2 and vertical displacement 1.7 mm of bearing №4. The slope of bearing №1 – 0.9516*10^-3 rad.

The following figures are presented to show deformation and stress in the individual shaft sections as follows:
- crankshaft displacements (figure 12);

![Figure 12. Crankshaft displacements](image)

- crankshaft stress concentrations (figure 13);

![Figure 13. Stress concentrations of crankshaft](image)

- bolt displacements and stresses (figure 14);

![Figure 14. Bolt displacement and stresses](image)
6. Conclusion
A methodology has been developed for a software alignment optimization of a propulsion shaft system. The method advantage is the deformations and stress calculation of loaded 3D shaft models, associated to bearing supports displacement. Load data is presented of the additional elements, such as bolt connections. Stress concentrators are pictured of the crankshaft.
The method can be used to simulate the loading of additional elements, such as stern tube elements, seals, caps, technological holes, thread etc., in parallel with the shaft alignment optimization. It is possible to optimize the model geometry, to monitor the working capacity criterion, to set temperature differences and many others.

Some of the *scenario №25 values* are written in table 1.

| Sensors                  | Values  | Unit  |
|--------------------------|---------|-------|
| Bearing reaction №1      | 136543  | N     |
| Bearing reaction №2      | 48631.4 | N     |
| Bearing reaction №4      | 40406.6 | N     |
| Bearing reaction №6      | 13896.3 | N     |
| Bearing reaction №7      | 35330.4 | N     |
| Bearing reaction №8      | 57771.7 | N     |
| Bearing reaction №9      | 49658.4 | N     |
| Bearing reaction №10     | 58555.7 | N     |
| Bearing reaction №11     | 18896.1 | N     |
| Crankshaft flange shear forces | 10.64  | kN    |
| Crankshaft flange bending moment | 28.223 | kNm   |
| Factor of safety         | 2.56    | -     |

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