Vibration Characteristics Analysis and Optimization of Trawler Propulsion Shafting System

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Abstract. The propulsion shafting system enables power delivery from the main engine to the propeller and plays a vital role in promoting the motion of the ship. The increase in demand for trawlers in coastal areas has led to the increase in the need for an improvement in its performance. Therefore, while trawling at sea, vibration characteristics are essential in analyzing for the safe and efficient functioning of the propulsion shafting of trawler ship. The primary objective of this paper is to model, analyze and reduce the vibration characteristics of trawler propulsion shafting. A computational model has been modeled and analyzed by Modal Analysis using Finite Element Method, focusing on the Lateral Vibrations. The natural frequencies, mode shapes, and the maximum deformation with affected zones of trawler propulsion shafting are evaluated. The attempt has been made to reduce the vibration characteristics of trawler propulsion shafting by the optimization process considering the design parameters whereby, it comes in the acceptable range for normal operation. The results of analysis and optimization have been computed and discussed.

1. Introduction

Propulsion shafting system playing an important role is considered to be the major component to transfer the power from the main engine to propeller blades to drive the ship [1], [2]. It suffers all kinds of exciting forces during operation. Each point in the propulsion shafting generates a response in all the directions of disturbing force. The vibration aspects include torsional, longitudinal, lateral and the mutual coupling vibrations which affect adversely on the performance of propulsion shafting [3], [4]. It alters its dynamic as well as static response parameters [5]. Lateral vibration has a significant impact on the propulsion shafting which becomes the source of bending and whirling of the shaft causing an imbalance of the operational rotating part and the periodic motion of varying bending deformation due to the non-uniform flow where a propeller is operating in [6].

Researchers have paid much attention to the vibration analysis of propulsion shafting. Vibrations can be initiated by a propeller which is considered by Wang et al. [7] that can produce periodically varying exciting forces and can be transferred to the hull by the propulsion shafting system and fluids, significantly increasing the underwater noise and vibration of the hull. Jalali et al. [8] presented the model identification and ship propulsion shaft lines. The Finite element modeling and experimental modal parameters by updating propulsion shaft lines are considered in a ship structure such as natural frequencies and mode shapes. The corrected Finite Element models were used for the prediction of the dynamic response of the shaft lines. Due to the complexity of the system, the calculation of free and forced vibrations on the whole ship is a challenging issue by which vibration characteristics are governed at the local and global level. Yucel et al. [9] presented the free and forced vibration analyses of ship structures using the Finite Element method. Their research revealed that the undesired effects of the ship might result in the failure of local structural members or the malfunctioning of machinery and its component. Thus, excessive ship vibration has to be avoided.
The operating condition of propulsion shafting is different with respect to the kind of the ship. Generally, the focus of researchers is the commercial ships having larger sizes. By considering the study of large size ships, Tian et al. [10] investigated the dynamic interactions between the propulsion shafting system and ship hull in large scale ships. A simplified hull-propulsion system mathematical model was presented to investigate the dynamic interactions between the ship propulsion and hull deformations. As the trawl nets dragged behind the Trawler ship, it causes instability and oscillations in the propulsion shafting system which leads to the cause of vibration. Therefore, in enhancing the growing need of Trawler ship performance, the vibration characteristics need to be looked at.

Vibration analyses using Finite Element Method (FEM) have become a standard practice during various phases of structure design. As a result, subsequent potential issues are being analyzed and remedied before construction begins. In FEM, the selection of material, element type, mesh size, connections and boundary conditions should be well defined which are the influencing factors in acquiring accurate results [11]. It is essential to know the natural frequencies at which the excitation is likely to occur, mode shapes, and maximum deformation to figure out the dangerous and affected zones to prevent the failure of the structure. Therefore, the current study is aimed at adding to knowledge the modeling, analysis, and vibration reduction through engineering optimization, for the safe and efficient functioning of the propulsion shafting of Trawler ship.

2. CAD Modelling

2.1. Material Properties

The material used to model the Trawler propulsion shafting is Structural Steel. The material properties are listed in Table 1.

| Sr. No. | Property (Symbol)    | Value (Unit)    |
|---------|----------------------|-----------------|
| 1.      | Density ($\rho$)     | 7850 kg / m$^3$|
| 2.      | Young’s Modulus (E)  | $2e+11$ Pa      |
| 3.      | Poison Ratio (v)     | 0.3             |

2.2. Model with Dimensions

Propulsion shafting of 35.5m Trawler ship is modeled and assembled in SolidWorks. The CAD model depicted in Figure 1, was built according to exact dimensions of shaft and propeller shown in Table 2 and 3 respectively.

Figure 1. CAD model of shaft and propeller assembly
Table 2. Dimensions of Shaft

| Sr. No. | Parameter (Symbol)                  | Value (Unit) |
|---------|------------------------------------|--------------|
| 1.      | Length ($L_s$)                      | 4310 mm      |
| 2.      | Mean Diameter ($D_s$)               | 148 mm       |

Table 3. Dimensions of Propeller

| Sr. No. | Parameter (Symbol)                  | Value (Unit) |
|---------|------------------------------------|--------------|
| 1.      | Number of blades ($Z$)              | 4            |
| 2.      | Diameter of propeller ($D$)         | 1450 mm      |
| 3.      | Length of propeller hub ($L_k$)     | 315 mm       |
| 4.      | Mean Thickness of blade ($t_{0.5R}=t_p$) | 34.8 mm |
| 5.      | Diameter of propeller hub ($d$)     | 261 mm       |
| 6.      | Maximum width of blade ($b_{max}$)  | 327.70 mm    |

3. Vibration Analysis of Trawler Propulsion Shafting

Trawler propulsion shafting was analyzed in ANSYS Workbench v16.0, and the analysis process is explained briefly.

3.1. Boundary Conditions

The boundary conditions are essential in defining the working condition of shafting operation. Here, one end of the shaft is attached with propeller and the other with the engine. The two sliding bearings are connected at the specific positions. The model with boundary conditions is depicted in Figure 2.

![Figure 2. Model with boundary conditions](image)

3.2. Modal Analysis

Modal analysis is one of the essential tools in ANSYS Workbench to find the vibration characteristics of structures, i.e., Natural frequency, Mode shape and Maximum deformation [12]. In this section, the natural frequencies with their respective mode shapes and the maximum deformation with affected zones of Trawler propulsion shafting are presented and analyzed.

According to the theory of classical mechanics, a simple machine may be represented by the general equation of motion as having Mass, Damping, and Stiffness:

$$ [M] \ddot{X}(t) + [C] \dot{X}(t) + [K] X(t) = F(t) $$  \hspace{1cm} (1)

Where: $[M] \ddot{X}(t)$ is the Mass-Inertia, $[C] \dot{X}(t)$ is the Damping-Velocity, $[K] X(t)$ is the Stiffness-Displacement, and $F(t)$ is the Force Vector.
When a structural system is set in motion due to inherent forces and allowed to vibrate freely, the state of free vibration occurs. In this state, the system vibrates at its natural frequency.

In the modal analysis, the Force vector \( F(t) \) is set to zero which acts as free vibrations. Usually, the Damping matrix \( [C] \) is ignored.

\[
[M]\ddot{X}(t) + [K]X(t) = 0
\]  

(2)

Here, the first six mode shapes are illustrated in Figure 3, evaluating the modal parameters.

![Mode 1](image1)
(a) Mode 1

![Mode 2](image2)
(b) Mode 2

![Mode 3](image3)
(c) Mode 3

![Mode 4](image4)
(d) Mode 4

![Mode 5](image5)
(e) Mode 5

![Mode 6](image6)
(f) Mode 6

Figure 3. First 6 order mode shapes

### 3.3. Analysis Results and Discussions

The maximum deformation and natural frequency values obtained from the modal analysis are listed in Table 4.

| Mode | Maximum Deformation (m) | Natural Frequency (Hz) |
|------|------------------------|------------------------|
| 1.   | 6.6474e-002            | 15.941                 |
| 2.   | 5.0557e-002            | 17.999                 |
| 3.   | 5.056e-002             | 18.021                 |
| 4.   | 0.1001                 | 76.064                 |
| 5.   | 0.1014                 | 76.353                 |
| 6.   | 7.9051e-002            | 81.842                 |
The vibration characteristics of Trawler propulsion shafting can be analyzed from the illustration of mode shapes. Mode 1 is representing torsional whereas Mode 6 is representing longitudinal vibration. All the other modes from Mode 2 to Mode 5 are representing lateral vibrations (bending modes). The analyses of Trawler propulsion shafting made to notice that the shaft line is in a safe condition with having minor deformation, but the maximum deformation is occurring on the propeller. The cause of the maximum deformation on the propeller is because it is attached at the free end and the system is acting as a cantilever beam. It can also be seen that Mode 4 and Mode 5 are in maximum deformation among all the other modes, which can be the severe cause of vibration and must be avoided.

4. Optimization Scheme
Optimization is the process of maximizing or minimizing the desired objective function while satisfying the prevailing constraints [13]. Optimization can be applied to evaluate any engineering problem.

From the analysis of Trawler propulsion shafting, considerable deformation at the propeller as well as a minor deformation at the part of shaft line in between the bearing shells is found which indicates that these are the affected zones. Optimization is aimed at minimizing the deformation of affected zones which leads the system to the reduction in vibrations. Two Optimization schemes are adopted by using ANSYS Workbench v16.0 to reduce the vibration of these zones.

4.1. Goal Driven Optimization
Goal Driven Optimization (GDO) is a multi-objective technique in which the best possible designs are obtained from a sample set given the purposes as set for parameter [14]. The distance between the bearing shells has been changed by changing the position of tail shaft aft bearing, but the forward bearing remains at the same location.

While using the Response Surface Optimization in ANSYS Workbench which is one of the categories of GDO, aft bearing is considered to be the input parameter, and the Total deformation of the first six modes considers being the output parameters. The goal set at the input is to adjust the position of aft bearing, and at the output is to minimize the total deformation of all the first six modes. The actual value of the aft bearing from propeller was 1.015m, but by using the Response Surface Optimization, ANSYS Workbench finds the best-suited candidate point which is 0.9483m, reducing the maximum deformation. The optimized maximum deformation values at the new candidate point are listed in Table 5.

| Mode | Actual Maximum Deformation (m) | Optimized Maximum Deformation (m) |
|------|--------------------------------|----------------------------------|
| 1.   | 6.6474e-002                   | 6.6375e-002                      |
| 2.   | 5.0557e-002                   | 4.9893e-002                      |
| 3.   | 5.056e-002                    | 4.9897e-002                      |
| 4.   | 0.1001                         | 9.7481e-002                      |
| 5.   | 0.1014                         | 9.8893e-002                      |
| 6.   | 7.9051e-002                   | 7.8691e-002                      |

4.2. Design Optimization
Design Optimization is the process to find the best design parameters that satisfy the project requirements [15]. The thickness of the propeller blade is increased by 1mm, and the radius of the shaft between bearing shells is increased by 2mm (diameter 4mm). The design parameters varied manually in SolidWorks to analyze the effect of variation in ANSYS Workbench. Several results obtained by altering the parameters, and finally selecting the most appropriate value. The effect of blade thickness and shaft diameter between bearings on deformation can be seen from Table 6 and 7 respectively.
Table 6. Effect of propeller blade thickness on deformation

| Mode | Actual Maximum Deformation (m) | Optimized Maximum Deformation (m) |
|------|-------------------------------|-----------------------------------|
| 1.   | 6.6474e-002                   | 6.5533e-002                       |
| 2.   | 5.0557e-002                   | 4.9143e-002                       |
| 3.   | 5.056e-002                    | 4.9134e-002                       |
| 4.   | 0.1001                        | 9.6536e-002                       |
| 5.   | 0.1014                        | 9.6623e-002                       |
| 6.   | 7.9051e-002                   | 7.2903e-002                       |

Table 7. Effect of shaft diameter between bearing shells on deformation

| Mode | Actual Maximum Deformation (m) | Optimized Maximum Deformation (m) |
|------|-------------------------------|-----------------------------------|
| 1.   | 6.6474e-002                   | 6.6442e-002                       |
| 2.   | 5.0557e-002                   | 4.9788e-002                       |
| 3.   | 5.056e-002                    | 4.9761e-002                       |
| 4.   | 0.1001                        | 9.9946e-002                       |
| 5.   | 0.1014                        | 9.8947e-002                       |
| 6.   | 7.9051e-002                   | 7.8088e-002                       |

4.3. Optimization considering parameters collectively

Effects of the parameters by variation have been analysed one by one (Table 5, 6 and 7). The values of all the parameters found after Optimization schemes applied. Modify the design of Trawler propulsion shafting, according to these values in SolidWorks and analyze the optimized maximum deformation values in ANSYS Workbench, which are listed in Table 8.

Table 8. Effect on deformation when all parameters considered collectively

| Mode | Actual Maximum Deformation (m) | Optimized Maximum Deformation (m) |
|------|-------------------------------|-----------------------------------|
| 1.   | 6.6474e-002                   | 6.5574e-002                       |
| 2.   | 5.0557e-002                   | 4.9829e-002                       |
| 3.   | 5.056e-002                    | 4.9837e-002                       |
| 4.   | 0.1001                        | 9.4285e-002                       |
| 5.   | 0.1014                        | 9.4319e-002                       |
| 6.   | 7.9051e-002                   | 7.4949e-002                       |

4.4. Optimization Results and Discussions

The comparison has been made by altering the parameters separately and then collectively. The effect on the maximum deformation of Trawler propulsion shafting in the first six modes can be seen from Figure 4.
Figure 4. Comparison Optimization data chart

It is clear from Figure 4 that by a slight change in the parameters, the deformation of all the modes reduced and Trawler propulsion shafting comes in the acceptable range for normal operation and ultimate results in the reduction of vibration.

In GDO, it generates 1000 samples and finds three best-fitted candidate points. Among them, one is verified which is used as the appropriate position of aft bearing. This method uses a simple approach based on sampling and sorting. In Design Optimization, it has come to our realization that, as long as the thickness of the blade and the shaft diameter between the bearings shells increases, the deformation decreases. But these parameters cannot be increased much because it also increases the mass of the Trawler propulsion shafting system which can affect the efficiency of the system. Notably, the slight change in feasible limit has been done to optimize the design.

5. Conclusion
The study has shown the Modeling, Analysis, and Optimization of trawler propulsion shafting system with the ultimate aim of reduction in vibrations. The computational model has been modeled with accurate dimensions and analyzed by Modal Analysis using Finite Element Method. It is essential to know the natural frequencies, mode shapes, and maximum deformation to figure out the affected zones to prevent failure.

To analyze the effect of parameters on trawler propulsion shafting, the position of the aft bearing, the thickness of propeller, and the diameter of the shaft between the bearing shells have been optimized. By Optimization of these parameters, the maximum deformation is noticeably reduced leading to the reduction of vibration characteristics.

6. References
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