Torsional vibration characteristics of power transmission system

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Abstract. Torsional vibration is a frequent perturb for heavy rotating and high speed machinery. Development of large torsional vibrations produce torsional stresses which leads to increase in bearing loads and results in generation of cracks in the high stress areas of the transmission system and propeller. So, it is important to model and analyze the torsional characteristics of Power transmission system. The information obtained regarding torsion vibration characteristics will be useful to study the system dynamics and prevent premature failure caused due to resonance at critical speeds. In this paper, torsional vibration analysis is carried out for a marine power transmission system. The propulsion system is modeled as a flexible shaft with multiple inertias as lumped masses and shaft sections with torsional stiffness. Holzer method is employed to calculate the torsional resonant frequencies and their corresponding mode shapes. An algorithm for Holzer method is designed and programmed using MATLAB software.

Keywords. Holzer method, Torsional vibration, Natural frequencies, Mode shapes, Critical speeds, Marine diesel engine shafting system.

1. Introduction

The torsional vibration analysis of marine power transmission is a challenging subject and it has been investigated since 1950’s. Two distinct types of system vibrations that exist in marine diesel engines are: (i) Machinery Vibration caused due to relative motion of moving parts at certain frequency and (ii) Hull vibration caused due to excitation of Hull structure. Torsional vibrations are an example of machinery vibrations and are caused by the superposition of angular oscillations along the whole propulsion shaft system including propeller shaft, engine crankshaft, engine, gearbox, flexible coupling and along the intermediate shafts. Pulsing torque at the ends of crank usually creates twisting along the shafts, which results in torsional vibration at high frequencies. Torsional vibration has a large capacity to destructive action...
when compared to other forms of vibration due to its insidious nature without displaying any external symptoms. In addition torsional critical zones invariably occur at lower speed ranges than those corresponding to flexural modes, since the moduli of rigidity of structural materials are less than one half the moduli of elasticity. Torsional vibration will lead to huge external cycle of torsional stresses which leads to extensive fatigue along the shaft region.

Transmission system in a ship is made of propeller, shafts and bearings; they are coupled together as a whole to transmit torque from engine to the propeller and get thrust from propeller which is passed on to the hull. This is a type of system with large number of concentrated masses along the multiple segment axis interconnected together and placed in a straight line. The end of the power transmission system which is connected to the main engine is affected by the torque from the main engine and the other end of the system which is connected to the propeller will be affected by its own torque resistance. In marine power transmission system there exists interaction influence among gear transmission system, gearbox, foundation and gearboxes are coupled with each other through foundation and shaft, such systems can be studied using the approach of lumped-parameter methods. Holzer method is a lumped-parameter method for the analysis of torsional vibrations of shafting systems. A lumped mass system is one in which the shaft is mass less and equivalent masses are lumped at certain points on the shaft. The segments of shaft between the lumped masses are assumed to be mass less and are of uniform stiffness.

Niu et. al. [2] in their work state that torsional vibration in a ship propulsion system is mainly caused by sporadic fuel injection of diesel, non-uniform propeller rotation causing non uniform excitation in shafting, error in the meshing impact of gear system, due to failure in the centering installation of ship propulsion components, imprecision in processing and its own imbalance. Hyung Suk et. al[4] concluded that fatigue failure in the shaft system is the main cause of torsional vibration and to avoid the fatigue failure the coupling stiffness should be reduced to a rate of 70% of catalogue value. There are many methods to analyze torsional vibrations in a system like Extended Transfer matrix method, Finite element method, Power flow theory, Multi body dynamic coupling theory and Holzer method. Weizhong et. al.[3] has analyzed a 110000T Tankers ship propulsion shafting using both ADAMS (Multi body dynamics software) and Finite element analysis. He concluded that the difference in maximum amplitude at different orders is due to the consistency maintained between rotational frequency of drive shafts and natural frequency of shaft lines.

Yuan Mao Huang [5] analyzed the torsional vibration of the system using extended transfer matrix and suggested some disadvantages of this method. For an undamped system the residual torque converges quickly and a initial eigen value is required to find the other eigen values of the system. Extended transfer matrix method leads to a quadratic convergence of natural frequency around the range of true natural frequency. This leads to a greater range of error in the assumed trial natural frequencies [6]. Recently many methods have been developed to detect the failures caused by torsional vibration in crank shafts and propeller shafts. Charles et. al. [7] have used instantaneous angular speed waveforms (IAS) and their Fast Fourier transforms (FFT) to analyze the signature of torsional vibration. A magnetostrictive patch sensor system (small magnets tightly bound along the shaft)was designed and replaced the strain gauge system with telemetry units in a LPG carrier ships main propulsion system for the measurement of torsional vibration[8].They concluded that the use of magnetostrictive sensors is highly effective than the presently used strain gauge system.
2. Modeling Method

The power transmission system of a 6 cylinder slow speed marine diesel engine is studied in this paper. It consists of a crank shaft, propeller shaft, propeller and the intermediate shaft. In proportion with keeping the vibration characteristics unchanged, the above stated system is simplified to a lumped parameter model with 12 inertias and 11 elastic shafts as shown in Figure 1. The input parameters of the lumped system are shown in Table 1. The torsional vibration characteristics of the lumped parameter model will be equal to that of a real system. In the simplified model, the crank shaft is modeled by first nine elements; shaft line is represented by tenth and eleventh element and the propeller by twelfth element. These types of slow speed marine diesel engine usually have a short shaft line. To carry out natural frequency calculation, an algorithm based on Holzer method is developed (Figure 2) and is programmed using MATLAB. The generalized Holzer equation is given by Equation (1). The inertia and stiffness of the elements are given as input to the Holzer algorithm and the natural frequencies and mode shapes are obtained.

\[
\theta_i = \frac{\theta_{i-1} - (\sum T_i \theta_i \omega^2)}{(k_i - 1)}
\]  

(1)
2.1 Procedural Flow chart

![Flow chart diagram]

Figure 2. Simplified Lumped Parameter Model of Power Transmission System

3. Experimental Results

The natural frequencies of the shafting system are found out using Holzer method. Natural frequencies are calculated by plotting Sum of inertial torque (A(sum)) vs Natural frequency (\(\omega\)) (rad/sec). The natural frequency occurs when there is a change in sign of sum of inertial torque. Fig. 3 to Fig. 12 represents the graph between Sum of inertial torque vs Natural frequency. Table 2 lists all the natural frequencies of the system. Table 2 compares the values of natural frequencies obtained between Holzer method compared with the example of 2600 TEU container ships power transmission system [1]. This type of ship has a two stroke, slow speed, 7 cylinder main engine of type: MAN B&W7 S70 MC-C. The propulsion system contains a five blade propeller of 7.42 min diameter and intermediate shafts with diameter 595mm. The propeller shaft of diameter 675mm. The overcritical propulsion unit has a polar moment of inertia of 107200 kgm². Torsional vibration analysis of above specified system is done by an independent box office and analysed by a specialised design team. The Natural frequency values used are universally accepted by big shipyards and all main classification societies.
Table 1. Natural Frequency of Shafting Torsional Vibration

| Vibration | $\omega_1$ | $\omega_2$ | $\omega_3$ | $\omega_4$ | $\omega_5$ | $\omega_6$ |
|-----------|------------|------------|------------|------------|------------|------------|
| Frequency (rad / sec) | 0 | 28.51 | 128.4 | 258.8 | 383.3 | 435.7 |
| Vibration | $\omega_7$ | $\omega_8$ | $\omega_9$ | $\omega_{10}$ | $\omega_{11}$ | $\omega_{12}$ |
| Frequency (rad / sec) | 503.2 | 590.5 | 656.43 | 690.57 | 772.58 | 1172 |

Figure 3. Natural Frequency $\omega_1$, $\omega_2$

Figure 4. Natural Frequency $\omega_3$

Figure 5. Natural Frequency $\omega_4$

Figure 6. Natural Frequency $\omega_5$
The curves in Figure 3 to Figure 10 represent the change in magnitude of sum of inertial torque $A(\text{sum})$. The change in magnitude of sum of inertial torque represents the natural frequencies of the system. The maximum relative error between independent design office and
Holzer method is compared in Table 2. Torsional vibration amplitude (degree) of each natural frequency is used to calculate the mode shape of the system. Mode shape is a specific pattern of vibration executed by a mechanical system at particular frequency. Mode shape is calculated for all natural frequencies. Figure 9, Figure 10 and Figure 11 represent the mode shape of first order of natural frequency, third order of natural frequency and sixth order of natural frequency respectively.

**Table 2.** Comparison Natural Frequencies between Independent box office and Holzer method

| Description               | Independent design office (Hz) | Holzer Method (Hz) | % Error |
|---------------------------|--------------------------------|--------------------|---------|
| First Natural Frequency   | 4.858                          | 4.53               | 6.75    |

4. Conclusion

All marine classification societies require standard calculations to avoid the consequence of torsional vibration problems in propeller and power transmission systems. There are many torsional vibration algorithms which depend on finite element method for vibration analysis. These algorithms are too complicated, time consuming and difficult to use for unspecialised engineers. The power transmission system of 2600 TEU container ships contain a small shaft line which directly connects the engine to a directly driven propeller. This type of arrangement is usually effective, but they are mostly prone to high vibration levels. For this type of container ships the classification societies require a simplified calculation method to calculate torsional vibration characteristics. The Holzer algorithm developed using MATLAB simplifies the work of choosing operating speed range of the system. We can conclude that Holzer method is a systematic and simple method to find natural frequencies and mode shapes for an undamped system. But, being an iterative method based on hit and trial technique it takes a long time to compute for branched systems. The Holzer algorithm developed has an advantage of producing mode shapes, which helps the classification societies to obtain revised mode shapes for any changes in specification of the power transmission system, without using tools like artificial neural networks.

5. References

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