PARAMETRIC OPTIMIZATION AND CALCULATION OF VIBRATIONS INTRODUCED BY PROPULSION INSTALLATION

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Abstract. Nonlinear vibration issues are of great importance in physics, mechanical structures and other engineering research. Vibration response, stability, and frequencies are the main components of a system's vibration check. Therefore, investigating the effect of different parameters in these sections can be an important step in the design process. In recent years, much research has been done on nonlinear vibrations, and analytical and numerical methods have been used to solve complex nonlinear equations. Equipment and the use of marine structure laboratories for the practical study of the dynamic behavior of vessels require large expenditures, so in order to advance computer science, several software's have been developed and used to model and perform dynamic analysis. In this paper, the mass of the shaft, the motor assembly and the impeller are each examined as a centralized mass and are modelled by ANSYS software. Then, by extracting vibrational equations along the shaft axis and multi-objective optimization with response surface method (RSM), the comparison of the results of this method with the work of other researchers shows that this method has a good accuracy.

Keywords: Nonlinear Vibration, Ansys, RSM Method, Optimization, Shaft.

1. Introduction

Major advances in the world economy over the past two decades have had a profound impact on the marine construction industry. Therefore, the slightest vibration limit can be dangerous. Reduce vibration levels to ensure the health of the crew, mechanical, electronic systems and ship's steel structures. There are many vibrational factors in a ship, the most important of which are diesel propulsion, propellers, generators,
propellers, and etc. A ship as a complex structure has two types of natural frequencies, one is the natural frequency of the whole structure and the other is the natural frequency. The diesel propulsion system stimulates the entire structure, while the devices can stimulate and intensify the surrounding elements and are unable to stimulate the entire steel structure. There are two completely separate steps, one is the vibration of the ship's engine itself and the solutions involved in repelling it, and the other is the reaction that the steel structure gives to the engine's stimulation, and this is related to the condition of the ship structures themselves. Securing the floating structure from a vibrational point of view is a discussion that begins after minimizing the excitation caused by the engine and securing the body. Ship hydrodynamics involves several topics, one of which is the dynamics of ship in the sea. The sea is an environment in which there are always waves, so ships movements are investigated in the presence of waves, which is called the science of Seakeeping or Dynamics of Marine Vehicles. Designers have always considered prediction of ship movements for ship operational planning and proper use of ship [1].

2. Method (Design and Analysis)

2.1 Analysis of Sources of Excitation

The ships are equipped with the most modern equipment and represent the most complex transport system by sea. Equipped with a large number of equipment and force installations can lead to undesirable phenomena induced by the vibrations of different equipment or their overlap. On-board vibrations negatively influence the strength of various metal constructions, the proper functioning of systems and equipment, the comfort of the crew and passengers. Sources of noise and vibration on board sea and military ships can be divided into two main groups:

- main sources which cause the occurrence of noise and vibrating movements by direct action on the hull, consisting of main engines, auxiliary engines, thrusters, the action of the marine environment on the hull;
- secondary sources that receive movement from the main sources and which in turn become sources of noise and vibration, consisting of the various structural elements of the ship's body (bulkheads, panels, girders, beams, etc.), tree lines, installations with tubing.

The operation of propulsion engines and turbines, diesel generators and related auxiliary installations, makes an important contribution to determining the level of noise and vibration on board the ship. The installed power and the level of induced vibrations can only be compared to similar equipment. Manufacturing technologies, tolerances used,
The materials used and design of propulsion installations are important factors in determining the level of vibration induced in the hull. Rolling bearings are important components of rotary machines and must be kept in good condition and replaced whenever the situation so requires. A defect of the ball, inner or outer tread causes the rolling bearing to produce additional vibrations at a frequency equal to the frequency of its defect. Diagnosing rolling bearings by measuring the vibrations produced is important and can reduce the time and cost of maintaining a propulsion installation. Measurements show that, in general, equipment whose maintenance has been careless and whose wear is advanced, the level of vibrations produced in operation is 3-4 times higher than at installation stage. Installations related to main and auxiliary engines also contribute to the increase of noise and vibration on board by the operation of the drive pumps and by the flow of working fluids through the tubing. The metal body of the ship shall be subjected to vibration, in particular from the propulsion system (fig. 5.1): the operation of the propulsion engines or turbines, the operation of the propellers and shaft lines attached to the propulsion system specific to each vessel. An important source of noise and vibration is the action of the sea on the hull of the ship. The spectrum of waves can provide a multitude of frequencies and amplitudes that will directly influence the body of the ship. Changes in the rearing, yield of the propulsion system will indirectly influence the vibrations induced in the hull (fig.1) [2,3].

Fig. 1 - Primary sources of excitation to the ship.
2.2 Method Rayleigh

Method Rayleigh used in the study of vibrations of propulsion installations. Using Rayleigh’s principle that for conservative systems in vibration after their own way the maximum kinetic energy is equal to the maximum potential energy \( E_{p \text{ max}} = E_{c \text{ max}} \)

Results: \( p^2 = \frac{U}{K} \) if the deformed shape of the n mode is inserted into the expressions of U and K, the pulsation of that mode is obtained. Thus, in the example considered above, the relationship becomes:

\[
p^2 = \frac{EI_y \int_0^l [Y''(x)]^2 \, dx}{\rho A \int_0^l Y^2(x) \, dx + mY^2 \left( \frac{1}{2} \right)}
\]

which:

For \( Y(x) = a_1 \phi_1(x) = a_1 \sin \frac{\pi x}{l} \):

\[
p^2 = p_1^2 = \frac{\pi^4 EI_y}{2l^3 \left( \frac{M}{2} + m \right)}\]

For \( Y(x) = a_2 \phi_2(x) = a_2 \sin \frac{2\pi x}{l} \):

\[
p^2 = p_2^2 = \frac{16\pi^4 EI_y}{Ml^3}\]

Usually, the static deformed shape of the bar is used, resulting in a fundamental pulsation of an approximate value, higher than the exact one. The calculation method requires validation of calculations made with rigorous measurements of the equipment studied. The set investigated, including the motor, shaft, propeller and bearings, can be modeled in the simplest way as shown below.
Equivalent differential set equation $I\ddot{\theta} + C\dot{\theta} + K\theta = Q$ it must be written. The free body diagram for the free vibration mode will be as follows.

\[
\begin{bmatrix}
    l_p & k_2(\theta_S - \theta_P) \\
    k_2(\theta_S - \theta_P) & k_1(\theta_e - \theta_S)
\end{bmatrix}
\begin{bmatrix}
    \ddot{\theta}_P \\
    \ddot{\theta}_P
\end{bmatrix}
\begin{bmatrix}
    l_s \\
    k_1(\theta_e - \theta_S)
\end{bmatrix}
\begin{bmatrix}
    \ddot{\theta}_S \\
    \ddot{\theta}_S
\end{bmatrix}
\begin{bmatrix}
    k_1 - k_1 \\
    0
\end{bmatrix}
\begin{bmatrix}
    k_1 + k_2 + k_3 \\
    -k_2
\end{bmatrix}
\begin{bmatrix}
    0 \\
    k_2
\end{bmatrix}
\begin{bmatrix}
    \ddot{\theta}_e \\
    \ddot{\theta}_e
\end{bmatrix}
\begin{bmatrix}
    \theta_e \\
    \theta_e
\end{bmatrix}
\begin{bmatrix}
    0 \\
    0
\end{bmatrix} = 0
\]

(4)

For free vibrations, which have the single harmonic motion (SHM), it takes the form:

\[
\begin{bmatrix}
    l_m & 0 & 0 \\
    0 & l_s & 0 \\
    0 & 0 & l_p
\end{bmatrix}
\begin{bmatrix}
    \ddot{\theta}_e \\
    \ddot{\theta}_S \\
    \ddot{\theta}_P
\end{bmatrix}
+ \begin{bmatrix}
    k_1 & -k_1 \\
    -k_1 & k_1 + k_2 + k_3 & 0 \\
    0 & -k_2 & k_2
\end{bmatrix}
\begin{bmatrix}
    \theta_e \\
    \theta_S \\
    \theta_P
\end{bmatrix} = 0
\]

(5)

In this relation, $\omega$ the natural frequency is twisting and $I$ Moment of inertia and $k$ of the axial stiffness. By calculating the characteristic equation, the natural frequency can be obtained, the characteristic equation of the system is:

\[
-\omega^2 \left\{ \omega^4 - \left( k_1 \frac{l_e + l_s}{l_e l_s} + k_2 \frac{l_p}{l_s l_p} \right) \omega^2 + \left( \frac{k_1 k_2 (l_e + l_s + l_p)}{l_e l_s l_p} \right) \right\} = 0
\]

(6)

By solving the equation, the natural frequencies are as follows:

\[
\omega = 0
\]

(7)
\[ \omega^2 = \frac{1}{2} \left( k_1 \frac{l_e + l_s}{l_e l_s} + k_2 \frac{l_s + l_p}{l_s l_p} \right) \pm \sqrt{\frac{1}{4} \left( k_1 \frac{l_e + l_s}{l_e l_s} + k_2 \frac{l_s + l_p}{l_s l_p} \right)^2 - \left( k_1 l_e l_s l_p \right) \left( l_s \right)} \]  

(8)

The torsional stiffness of each part of the shaft are also calculated as follows:

\[ k = \frac{GJ}{l} \]  

(9)

Which G is the modulus of torsional stiffness, J is the second torque of the surface around the axis of rotation and L is the length of the axes. Frequency changes compared to shaft diameter can be seen in the figure 3.

![Fig. 3 - Frequency changes compared to shaft diameter.](image)

2.3 Measurement Methods

The measurement of vibrations produced by in-service equipment can be done with the help of diagnostics Toolbox Type 9727, available within the "Mircea cel Batran" Naval Academy. This equipment is accompanied by Pulse Labshop software specifically designed to record and analyzes the results. Diagnostics Toolbox Type 9727 equipment and has uniaxial and triaxle accelerometers that can be mounted in the analysis locations identified on board the vessel following analysis of the sources of excitation present. The records made may be analyzed using the FFT analysis to identify the frequencies and amplitudes present during the measurements [8,9].
3. General Methods of Combating Noise and Vibration

To reduce the vibrations felt at the level of the superstructure, dynamic dampers controlled by computers began to be used, at which a transducer coupled to the line of trees senses the size and phase of the vibrating motion generated by the main engine, transmits it to a unit of calculation which, by comparing with certain preset values, controls the movement of the dynamic absorber so that the vibration level falls within the prescribed limits. The scheme of principle of such a system is shown in the figure below.

![Vibration control system with dynamic absorber.](image)

Fig. 4 - Vibration control system with dynamic absorber.

To reduce the roll-over and meandering vibrations of the engine, lateral support of the frame is used with hydraulic dampers [10,11].

![Side support of the engine frame.](image)

Fig. 5 - Side support of the engine frame.
4. Result and Discussion

The software modelling of the propulsion installation in the calculations presented is done with the help of Ansys Workbench. A classic propulsion system, simplified and reported to equivalent masses as shown in Figure 6, was used in modeling. Software analysis with finite elements must go through the following steps:

- The definition of its structure, its geometric and elastic characteristics, the loads applied and the conditions of resuscitation;
- The choice of the types of finished elements in the program library for the modeling of the structure, taking into account the deformation modes or tensions arising in the elements;
- Discretion of the structure into finite elements, taking into account: geometric dimensions of the structure, elastic characteristics of the material, edge conditions, loads and movements imposed on materials;
- Verification of input data;
- Running the Ansys calculation program;
- Verification of the results obtained in the report generated by the application.

The reference drawing for the study of its own vibration modes of a propulsion installation is shown in Figure 6.

![Fig. 6 - Modelling of reference geometry for modes of vibrations.](image)

For analysis we used a specialized program in the finite element method, Ansys Workbench, available within the Naval Academy "Mircea cel Batran". The propulsion system made and used as a model for calculations shall be made of steel with properties as defined in Table 1 [4,5].
Table 1.
Material Properties

| Property                   | Value                      |
|----------------------------|----------------------------|
| Density                    | 7850 kg m^{-3}             |
| Linear dilation coefficient| 1.2e-005 C^{-1}            |
| Specific heat              | 434 J kg^{-1} C^{-1}       |
| Thermal conductivity       | 60.5 W m^{-1} C^{-1}       |
| Resistive                  | 1.7e-007 ohm m             |
| Admissible effort          | 250N/mm2                   |
| Reference temperature      | 22°C                       |
| Young mode                 | 2.e+011                    |

Next, we will present how the modal analysis is carried out for the model propulsion plant. Open the calculation program and select the Modal Analysis module. Table 2 can extract the propulsion system's own vibration values and it is recommended to avoid operating at frequencies similar to those obtained in its own vibration modes. Following the calculations, the following displacement distribution diagrams (fig. 3-5) corresponding to the frequencies in the solution present in Table 2 were obtained [6,7].

Table 2
Modal analysis solution and Vibration mode frequencies.

| Mod | Frequency [Hz] |
|-----|----------------|
| 1.  | 0.25216        |
| 2.  | 67.923         |
| 3.  | 68.726         |
| 4.  | 72.949         |
| 5.  | 142.15         |
| 6.  | 143.24         |

Fig. 7 - Chart of movements at 0.25 Hz frequency.
Following the analysis of the above diagrams, the following can be concluded:

1. The maximum displacement will be searched for the first 6 vibration modes.
2. The maximum amount of effort shall be assessed for each vibration mode.
3. The maximum value of the equivalent tension [N/mm] identified in the Ansys calculations shall be below the flow limit of 250 [N/mm].
4. All of the above leads to the final conclusion that the Ansys analysis may impose conditions and assess very close to the technical reality the phenomena associated with the propulsion installations' own vibrations.

4.1 Parametric optimization

The optimization method is used to solve the optimization problems where the salient points of this optimization method are:

- Effectiveness of this method is retained in non-convex problems.
- With the help of this method, optimum quasi-optimal responses are determined.
The second version of the NSGA algorithm was introduced due to the relatively high sensitivity that the algorithm responds to shared and fitness parameters and other parameters. Answers $i-1$ and $i-2$ the answers before and after are the answer of $i$, then the distance of the congestion of my answer is as follows:

$$d_i^1 = \frac{f_i(x_{i+1}) - f_i(x_{i-1})}{f_1^{\text{max}} - f_1^{\text{min}}}$$  \hspace{1cm} (10)$$

$$d_i^2 = \frac{f_2(x_{i-1}) - f_2(x_{i+1})}{f_2^{\text{max}} - f_2^{\text{min}}}$$  \hspace{1cm} (11)$$

$$d_i = d_i^1 + d_i^2$$  \hspace{1cm} (12)$$

To improve answers solvers can use various conditions for solution acceptance [14].
Choosing the right solution is a difficult task and must correlate relations and conditions imposed in solving engineering issues. [15].

The response surface methodology (RSM) is a collection of mathematical and statistical techniques to match the experimental data with polynomial models. [16].
5. Conclusion

The experience gained to date in the field of shipbuilding has shown that the main source of excitation of shipbuilding is the propulsion plant through its components: the main engine, the reduction gear, the shaft line and the propeller. The study of the vibration level of the propulsion system must be analysed because of two major effects:

- effects on the physical-psychic performance of the craft operating personnel, increasing the risk of damage due to human error.
- the influence of their level on the state of operation of the propulsion system, collecting global values that reveal the "health" state of the components of the installation or performing spectral analysis to locate and find the cause of the defect. Therefore, by calculating, constantly monitoring and combating the vibration level of the plant, you can minimize the repercussions of stresses and strains induced due to vibration and eventual failure of machine or its ill-effects on humans operating the machine. The comparison of the results of this method with the work of other researchers shows that this method has a good accuracy.

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