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CALCULATION RELIABILITY OF NATURAL VIBRATIONS OF SHIP HULL AND SUPERSTRUCTURE

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Abstract

The ship hull vibration has a great impact on the performance, safety of the devices, structures, and the sailor's comfort when working on the ship. With increases in ship sizes and speeds, shipboard vibration becomes a significant concern in the design and construction of ships. Therefore, designing a ship without any excessive vibration is an important issue and should be studied through analysis right in the design phase. To ensure minimum vibration in a proposed new design; avoid damage to structures, machinery or equipment (mechanically suitable); meeting the requirements of the crew's living environment and working conditions. The ship's natural vibrations are determined to right from the design stage, which will help ship designers and structures avoid dangerous resonance areas. In this study, a three-dimensional finite element model representing the entire ship hull, including the deckhouse and machinery propulsion system, has been developed using numerical modelling implemented in Patran-Nastran software for local and global vibration analyses of the container ship 2000 TEU. Vibration analyses have been conducted under two conditions: free–free (dry) and in-water (wet). The wet analysis has been implemented using Mfluid elements in Nastran software. Because of the global ship free vibration analysis, global natural frequencies and mode shapes have been determined. Combined with the frequency of the main engine and the propeller, the resonant regions with higher frequencies are determined by the resonant graph of the hull. The application of the finite element method for ship vibration analysis shows the optimal of numerical modelling method compared to other traditional methods. This will help other technical problems to be solved with the support of the finite element method.

Keywords: *Finite element method, Ship hull vibrations, Modal Analysis, Patran-Nastran software*

1. Introduction

The ship hull vibration has a great impact on the performance, safety of the devices, structures, and the sailor's comfort when working on the ship. With increases in ship sizes and speeds, shipboard vibration becomes a significant concern in the design and construction of ships. Therefore, designing a ship without any excessive vibration is an important issue and should be studied through analysis right in the design phase. To ensure minimum vibration in a proposed new design; avoid damage to structures, machinery or equipment (mechanically suitable), meeting the requirements of the crew's living environment and working conditions.

The basic elements of a hull vibration system include basic mass elastic properties as well as damping and exciting forces. In order to control or limit the vibration response, it is necessary to modify the mass elastic properties by increasing damping, reducing excitation forces or changing the excitation frequency. Increasing damping may be useful in solutions to local structural vibration problems and in some machine and equipment problems but not as a practical solution to reduce hull vibration.

It is very important to determine the vibration of the hull girder in the design phase, in order to evaluate as well as make adjustments right in the design phase. Previously, the analysis of these vibrations was mainly based on empirical formulas. The global vibration of a ship, including the natural frequency and mode of the complete hull structure, is analysed by strip theory in which the natural frequency of the entire ship is calculated from beam theory and estimated weight and moment distribution at each hull. A method of such an approach is given by Todd [8]. While the formulas recommended by DNV [3], Japanese shipbuilding design handbook [9] and the shipping industry standard of the People's Republic of China [11], Yumei et al. [10] are used to calculate the natural frequencies of the first three orders vertical vibration. Today, due to the rapid development of computer technology and the increasing speed and capacity of modern computers, hull vibrations are analysed by the finite element method (FEM). Finite element analysis is universally recognized as the most important technological breakthrough in the field of structural engineering analysis. For analysing a complicated structure such as a ship hull, the finite element method is the only tool that yields satisfactory results. FEM is increasingly used in analysing and designing complex ship structures [1, 2, 4]. The three-dimensional finite element method is a common procedure to obtain the main vibration characteristics of ships. Therefore, the resonant frequency can be obtained and through forced vibration analysis, the maximum values of displacement, velocity, or acceleration can be tested by the ISO-standards for vibration value allows the shipbuilding association of the world.

In this study, calculating and analysing the free vibration of hull girders is carried out for medium size container ship of 2000 TEU. The global ship hull free vibration problems have been studied under two conditions, which are free–free (dry) and in-water (wet) using finite element analysis. Calculations and analyses are performed based on the finite element method implemented on popular commercial software platform Patran-Nastran. Calculated results by the finite element method are compared with calculated results based on empirical formulas. Since then, the superiority of the finite element method in calculating the vibration of ship hull has been evaluated.

2. Natural vibration analysis of the ship hull by finite element method

Global vibrations are vibrations of the ship's entire hull in the frequency range from about 0.5 to 20 Hz. Typical large substructures, such as the aft part of the ship, the deckhouse, and the double-bottom, are coupled in a way that they cannot be considered isolated. The global coordinate system of the model is the right hand Cartesian coordinate system: X-direction goes along ship's length pointing to bow; Y-direction goes along ship's breadth pointing to Portside; Z-direction goes along ship's depth pointing to the deck. Structural model and applied loads are in the International System of Units (N, mm, s).

The calculation is based on the 2000 TEU container ship. The finite element model used in 2000 TEU container ship's vibration calculation is built entirely in accordance with the relevant design drawings, and the processing and analysis operations are completed by commercial finite element analysis software MSC/PATRAN and NASTRAN.

All plate structures, such as shell, transverse bulkhead, inner bottom, web frame, and longitudinal bulkheads etc. are modelled by CQUAD4 and CTRIA3 shell elements. All girders and stiffeners are modelled by eccentric beam with appropriate combination. Small structures with hole are adjusted when finally balancing the quality of the whole ship structure and large structures with holes are modelled according to their actual shape as possible.

In the process of establishing the finite element model, the hull weight and position of the centre are controlled by adjusting the material density of some elements and adding the weight structure points. The cargo weight model in different load conditions is modelled by rectangular blocks with the corresponding mass. The water additional weight of the hull is calculated according to the experimental equation. The corresponding vertical and horizontal additional quantities are calculated in each load condition. The added water mass is added to the underwater shell as a concentrated mass point.

A more detailed finite-element analysis, in which the entire hull is represented, may be developed by the NASTRAN computer program [5-7]. Computation of the natural frequencies and mode shapes is to be performed by solving an eigenvalue problem. The natural frequencies (eigenvalues) and corresponding mode shapes (eigenvectors) of the three-dimensional finite element model can be obtained by solving the equation of motion with damping and forces are zero:

$$[K]\{\theta\} = \omega^2[M]\{\theta\}, \tag{1}$$

where

$[K]$ – symmetrical stiffness matrix,
$[M]$ – diagonal mass matrix,
$\{\theta\}$ – column mode shape matrix,
Ω – natural frequency.

The main properties of the selected ship are listed in Tab. 1.

Tab. 1. The properties of the modelled ship

No.	Property	Value
1	Type of ship	Container ship
2	Length overall	182.85 m
3	Length between perpendiculars	171 m
4	Breadth	28 m
5	Depth	16.1 m
6	Draught	11 m
7	Deadweight	27244 tons
8	Main Engine	MAN B7W 8S70MC-C
9	Engine power	24840 kW
10	Ship speed	19.5 kn
11	Engine RPM	91 rpm
12	Propeller	Rolls Royce CPP
13	Diameter	7600 mm
14	Number of blades	5
15	Propeller RPM	91 rpm

Ship hull structures are complex and may be analysed after idealization of the structure. Several simplifying assumptions are made in the finite element idealization of the hull structure. A three-dimensional model representing the entire ship hull, including the deckhouse and the machinery propulsion system, needs to be developed for the vibration analysis. The 3-dimensional (3D) model of container ship capacity 2000TEU in Patran software is presented in Fig. 1.

The 2000 TEU container ship was modelled and displayed the results in Patran software and analysed in Nastran software. The wet 3-dimensional (3D) model in loading condition with water of 2000 TEU container ship has 25291 elements, 7773 nodes and 44166 degrees of freedom. The added water mass is considered through a virtual mass method using a boundary element method such as the “MFLUID” card of MSC NASTRAN. The dry 3-dimensional (3D) model in loading condition without water of 2000 TEU container ship has 25291 elements, 7767 nodes and 44166 degrees of freedom. As you see, in both wet and dry analyses, the number of elements and the number of degree of freedom nodes are the same. Numerical software can be analysed for ships of different sizes and capacities. The natural frequency is calculated for the ship in loading condition with and without water. The wet mode shapes of the container ship capacity 2000TEU are illustrated as shown in Fig. 2.

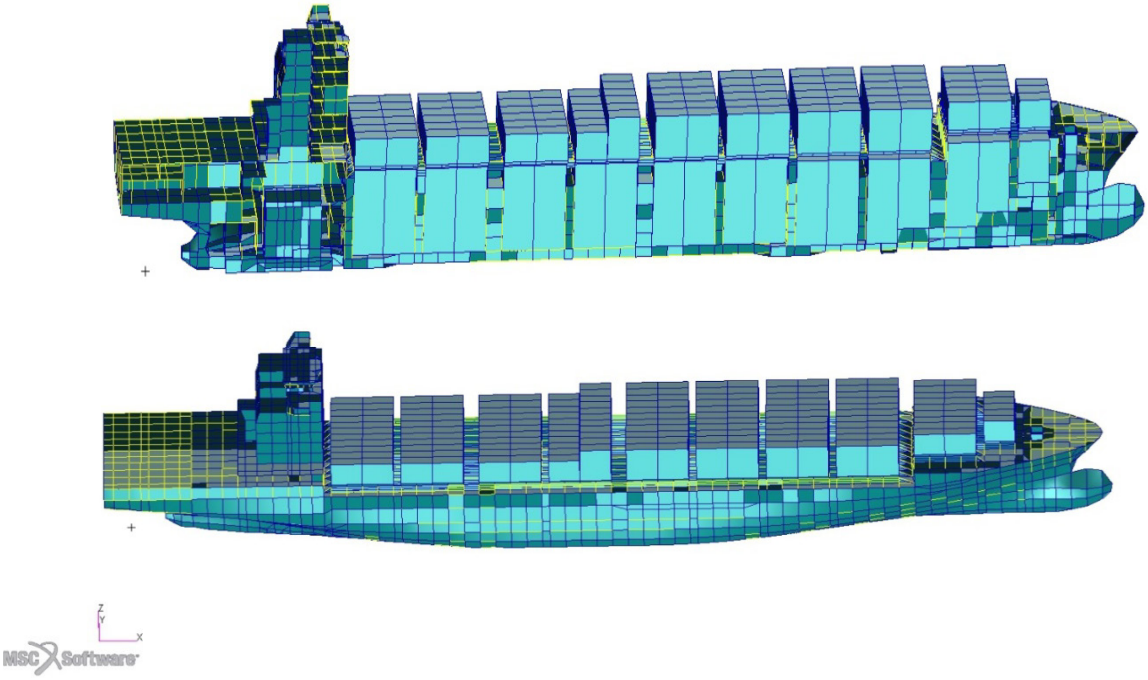
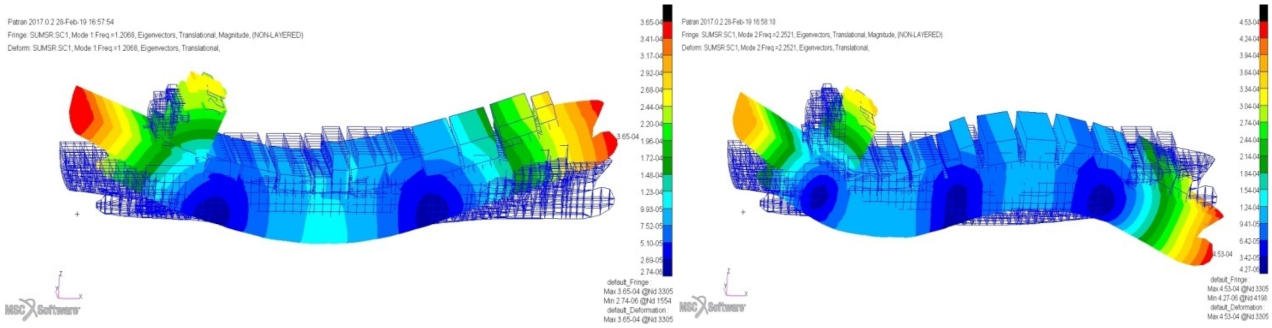
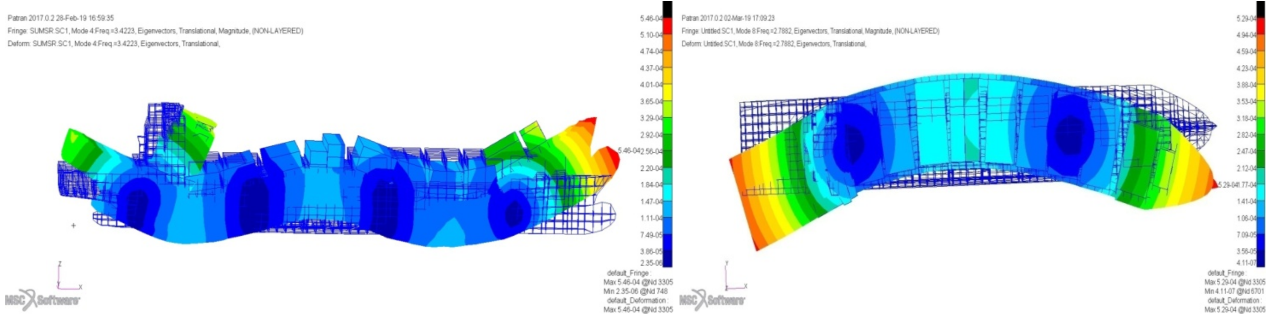


Fig. 1. Model of three-dimensional finite element of container ship capacity of 2000TEU



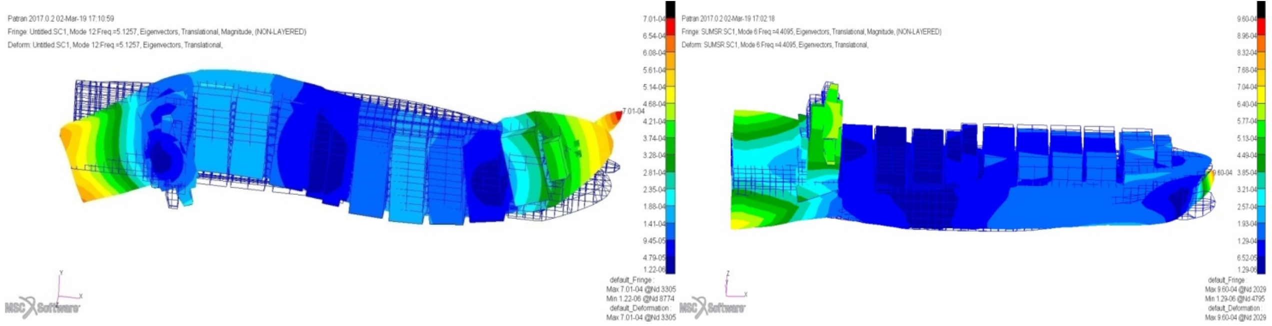
a) Mode 1. Vertical vibration 2 nodes

b) Mode 2. Vertical vibration 3 nodes



c) Mode 3. Vertical vibration 4 nodes

d) Mode 4. Horizontal vibration 2 nodes



e) Mode 5. Horizontal vibration 3 nodes

f) Mode 6. Torsional vibration

Fig. 2. Global wet mode shapes of the container ship 2000 TEU

Natural vibration frequency of 2000 TEU container ship with water and without water is illustrated in Fig. 3.

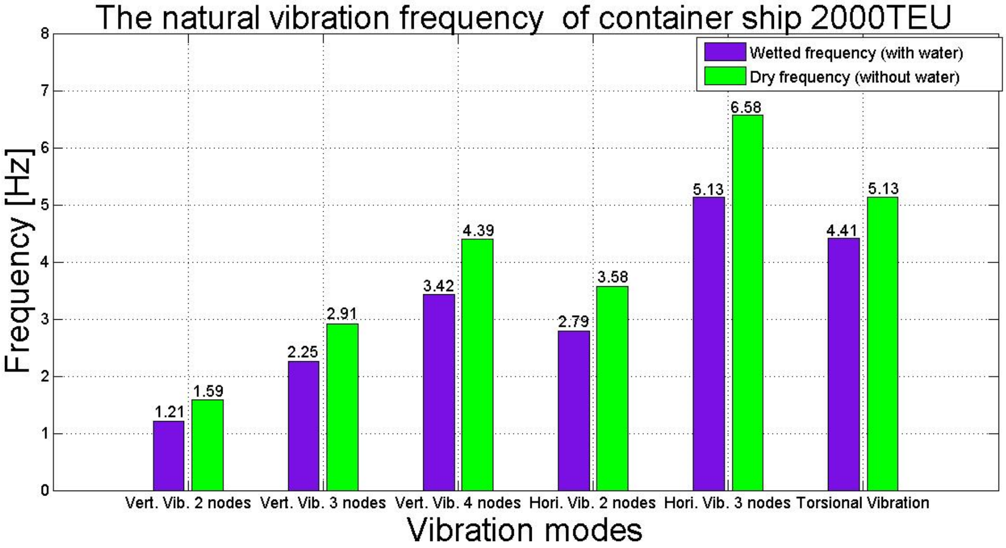


Fig. 3. The natural frequency of 2000TEU container ship with and without water

3. Empirical calculation procedures

In this study, some empirical calculations determine the natural vibration frequency of vertical bending vibrations to be carried out. Experimental formulas were developed by Yumei et al. The approximate formulas of Yumei and et al. were used to calculate the first three orders natural frequency of ship.

The approximate natural vertical vibration frequency calculation formula of ship proposed by Yumei et al. [9] as follows:

$$f_n = A_n\sqrt{\frac{I_v}{\Delta_v L^3(1+\alpha)}}, \tag{2}$$

The second approximate natural vertical vibration frequency calculation formula of ship proposed by Yumei et al. [9] as follows:

$$f_n = C_n\sqrt{\frac{BD^2}{\Delta_v L^2}}, \tag{3}$$

and:

$$\Delta_v = \Delta(1.2 + \frac{1}{3}\cdot\frac{B}{d}), \tag{4}$$

where:

L – is length, L= 182.85 m,
B – is breadth, B = 28 m,
D – is depth, D = 16.1 m,
d – the draft (m), d = 11 m,
I_v – moment of inertia of the cross section, I = 126.075 m^4,
Δ – displacement of ship (ton), Δ = 27244 tons,
Δ_v – virtual displacement including the added mass of water (tons),
A_n, C_n – is natural frequency coefficient of vertical vibration of ship.

The natural vibration frequency of container ships 2000 TEU is illustrated in the Fig. 4.

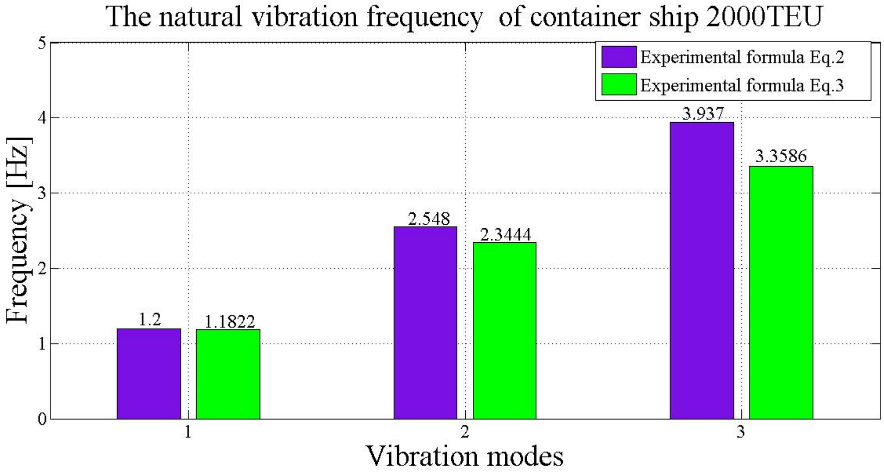


Fig. 4. Vertical natural vibration frequency according to the empirical formula

4. Comparison of the natural vibration frequency of ship container 2000TEU

In this section, the relative errors between the results of the vertical natural vibration frequency of 2000TEU container ship are obtained by empirical formula and the numerical model method considered. On that basis of assessing the accuracy of the numerical modelling method – implemented in the Nastran-Patran software platform applied to the analysis of ship structures. The vertical natural frequency for vertical bending vibration of two 2000 TEU container ship with the first three modes obtained according to the empirical formula and the numerical modelling method are presented in Tab. 2.

Tab. 2. The first three modes of natural frequency of vertical bending vibration

Ship type	Vertical natural vibration frequency / Hz			
	Order	Experimental formula Eq. 2	Experimental formula Eq. 3	Numerical method
Container Ship 2000TEU	1	1.200	1.1822	**1.2068**
	2	2.548	2.3444	**2.2521**
	3	3.937	3.3586	**3.4223**

The relative error between the natural frequency results of the two container ships obtained by the numerical modelling method and the empirical formula is illustrated in Fig. 5.

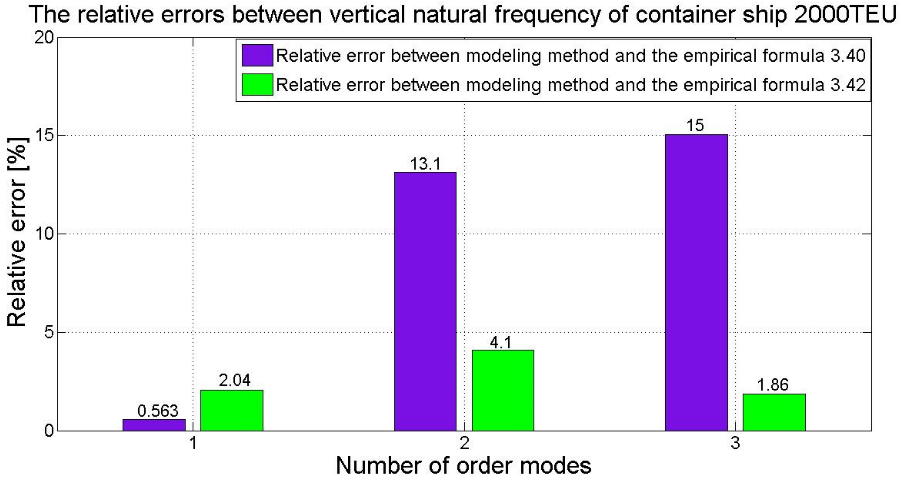


Fig. 5. Comparison of vertical natural frequencies of 2000TEU container ships

From Fig. 5, the practical formula Eq. 2 and Eq. 3 gives relatively accurate results with the numerical modelling method. The smallest error with 2000TEU container ships is 0.563%. The largest error for 2000TEU container ships is 15.045%. The calculated results by empirical formula with large errors can be up to 15% or more. The 3D digital model based on finite software implemented in the Patran-Nastran commercial software platform makes it easier to determine the vibration characteristics of the ship during the design phase. Numerical models can be applied to many ships with complex and different shapes. This helps the shipbuilding designer limit the unwanted effects of ship hull girder vibrations.

5. Conclusions

In order to check if the hull vibration modes are being excited by the main engine and propeller, the hull resonance diagrams often use. This is one of the most widely used methods to test the threatens of vibration of the ship hull. In this case, only the vertical modes of hull beam vibration are considered. The hull resonance diagram is also used to determine the number of propeller's blade and the number of main engine's cylinders needed to avoid resonance. In this section, from the global vibration frequency of the hull, the hull resonance diagram of the capacity container ship 2000TEU is defined. The 2000TEU container ship has the main engine MAN B7W 8S70MC-C, the normal speed is 91 cycles per minute, the 5-blades propeller. Determine the excitation frequency of the main motor and the propeller. Main engine excitation frequency of container ship 2000TEU is: $f = \frac{91}{60}x8 = 12.13\ Hz$, propeller excitation frequency of container ship 2000TEU is: $f = \frac{91}{60}x5 = 7.58Hz$.

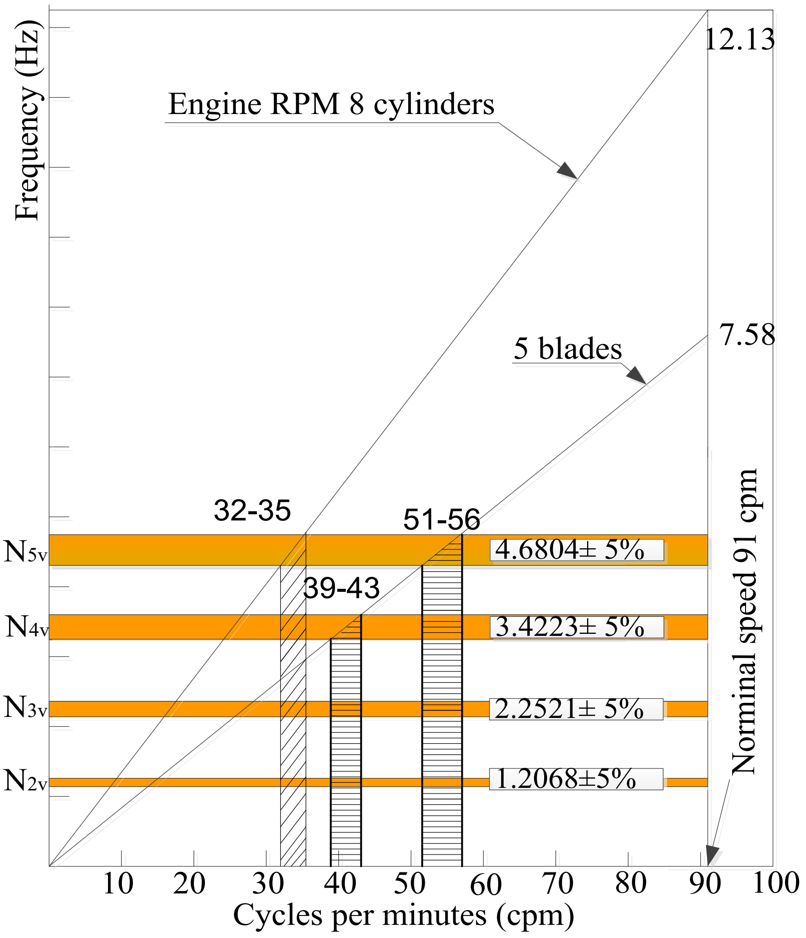


Fig. 6. The Hull Resonance Diagram of the container ship 2000 TEU

The vertical axis denotes the natural frequency values of vertical, horizontal and torsional vibrations of the hull girder. The horizontal axis indicates the rotation value at the normal speed condition of the main engine. From the horizontal axis, draw a vertical line at the value of 91 cycles per minute (normal working speed of the main engine).On this line, take two points at frequency values 7.58 Hz and 12.13 Hz. Connecting the origin of the coordinates axis with the frequency of 12.13 Hz, the author obtains the line for the 8 cylinders main engine. Connecting the origin of the coordinates' axis with the frequency of 7.58 Hz, the author obtains the line for the propeller with 5 blades. The hull resonance diagram is illustrated in Fig. 6. N_{2V} , N_{3V} , N_{4V}, N_{5V} are the second, third and fourth, fith modes of vertical hull girder vibration of the container ship 2000TEU.

Once these values are obtained, they are plotted on the axis, and a tolerance of 5 percent is taken for the factor of safety. Therefore, the shaded bands in the diagram represent each mode with 5 percent tolerance. At 91 rpm, the main engine MAN B7W 8S70MC-C, 8 cylinders, excitation frequency 12.13 Hz, region with higher vibration level within the rotation range of 32-35 rpm, resonates with vertical vibration 5 nodes of the ship hull – the area with diagonal lines on the hull resonance graph. The area with higher vibration level excitation coming from the propeller within the rotation range 39-43 rpm and 51-56 rpm with 4 nodes hull vertical vibration and 5 nodes hull vertical vibration, respectively – the area with horizontal lines on the hull resonance graph. With the application of numerical modelling method for vibration analysis of hull girders, the results are relatively accurate, convenient, and effective in the calculation.

Finite Element Method is a good tool for natural vibrations estimation for ship hull. The resonance area can be predicted with sufficient accuracy. One of the most important problems is added water mass estimation. This factor has a big impact on the results. Empirical formulas are good only for very low frequency and may be used only for preliminary estimation.

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