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VIBRATION OF MARINE DIESEL ENGINE FOUNDATION

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Abstract

The fact that ships are, from time to time, delivered with unsatisfactory vibration conditions reflects that the whole procedure from project to actual ship in service is subjected to compromises which consider other aspects than prediction of vibrational behavior. This paper presents useful guidelines to contribute in the reduction of vibration problems caused by marine propulsion system in new built vessels. A procedure to build up a finite element model of the engine foundation is outlined. This is required to ensure and confirm that, engine foundation has natural frequencies far away from the exciting frequencies of the engine at different loading conditions to avoid resonance. The modeling has been applied to a foundation of a 2-stroke, 6-cylinder diesel engine. The effect of water damping has been taken into consideration. The results show that the fundamental frequency of the engine foundation is about 13 times greater than the exciting frequency of the engine at its maximum continuous rating. It is recognized that, the magnitude and orders of engine external exciting moments must be considered when deciding hull /engine particulars at the early design stage in order to reduce the risk of server disturbance due to these moments.

The analysis of the vibration response of the shafting system, the engine foundation model and the incompatibility of the propulsion machinery with hull would together specify the critical speeds that have to be avoided for better dynamic behavior of the whole propulsion system.

Keywords: vibration, engine foundation, propulsion machinery, critical speed, dynamic behaviour

1. Introduction:

The internal combustion engine produces ample possibilities for excitation of the engine structure itself, the shafting, the supporting structure as well as the hull girder [1]. Structural vibration is generally a result of the exciting force and dynamic properties of the structure. In modern engine development work, excitation, structure and vibration response can be analyzed and taken into account at the design phase itself, in order to prevent resonance by moving the natural frequency of the component away from the harmful excitation frequency [2]. Different vibration aspects of marine propulsion systems had been reviewed in order to predict forced vibration response to machinery loads. Three main aspects should be investigated in order to find out the critical engine speeds:

- The torsional vibration of the shafting system
- Dynamic properties of the engine foundation, i.e. natural frequencies and mode shapes.
- Incompatibility of the exciting forces and moment caused by the propulsion machinery with hull.

- This paper is concerned with the last two aspects. The dynamic properties can be determined by using the Finite Element Method (FEM), or by means of experimental modal analysis. The use of a finite element model, the evaluation of the engine exciting forces and moment and the hull/machinery incompatibility are outlined and demonstrated throughout the study of the foundation of a large low-speed two-stroke diesel engine. Such engines are most commonly used and may cause significant hull structural vibration when the frequency and magnitude of free moments coincides with one of the lower hull modes.

2. Excitation sources

2.1. External Forces and Moments

The engine's reciprocating and rotating masses produce cyclic forces of first and second orders at each cylinder. The resulting vertical and horizontal inertia forces per cylinder produce a torque expressed as [3]:

$$M_t = \frac{1}{2} M_{rec} \Omega^2 R^2 [\frac{R}{2L}\sin(\Omega t) - \sin(2\Omega t) - \frac{3R}{2L}\sin(3\Omega t)] \qquad (1)$$

where:
M_{rec} = reciprocating mass per cylinder, tonnes
L = stroke length, m
R = crank radius, m
Ω = angular velocity of crankshaft, rad/s

The vector sum of the resultant forces from all the cylinders is zero in engines with regular firing sequences. The free mass forces, however, generate free moments as shown in Fig. 1, principally the first-order vertical moment M_{1V}, the first-order horizontal moment M_{1h} and the second-order vertical moment M_{2V}. The values of these moments are given in the "Dynamic Characteristics Booklets" for each engine type. The external or free mass forces and moments are always transmitted through the engine seating into the ship structure and directly affect the hull-girder response. The engine 2[nd] order exciting frequency can be calculated as follows:

$$F_{ne} = n.\ N \qquad (2)$$

where:
n = 2 for the 2[nd] order
N = engine rpm

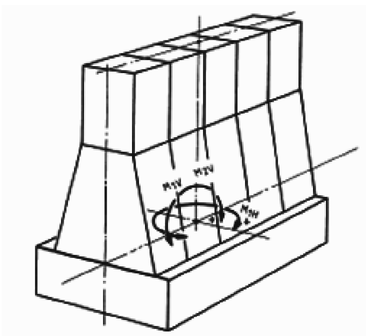

Figure 1: Free external moments from the engine

2.2. Internal Mass Forces and Moments

These directly disturb the engine frame, foundation and local structural supports; they are only retained as internal forces and moments if the foundation is infinitely rigid and the frame of the engine is designed to resist these forces and moments with minimum distortion. Ordinarily, the supporting structure in the ship is far from being rigid and some engine designs are more flexible than others. To minimize these effects it is desirable to have maximum rigidity in the form of high moments of inertia of the engine bedplate and engine frame by respecting the recommended construction of the engine foundation from the engine builder [4].

2.3. Lateral or Guide-Force Moments

Lateral forces act on each engine crosshead and crankshaft main bearing in counter phase. They result from the gas forces and mass inertia forces at each cylinder, and vary with the rotation angle of the crankshaft. The vector sum of the harmonic forces and moments for all the cylinders and for a given harmonic order depends on the firing order, number of cylinders and the harmonic order. Although this lateral vibration is not detrimental to the engine itself, it may lead to damage in attached parts such as the turbocharger supports, and may cause local vibration in the engine room and double-bottom structure. The usual remedy for lateral vibration amplitudes is to fit side stays at the engine top as shown in Fig.2. These are normally required for engines with four, five, eight and 12 cylinders while need for fitting them ought to be made with six-cylinder engines in case they are shown to be necessary on sea trials [5].

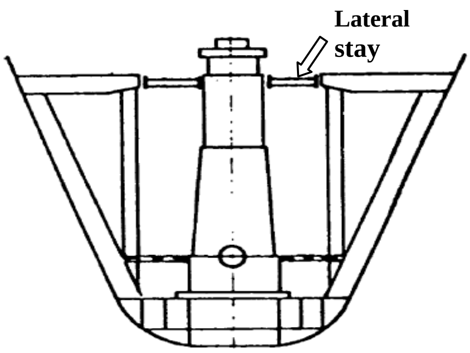

Figure 2 Installation of stays between engine and ship structure

The side stays modify the stiffness of the engine/ship structure combination, thereby increasing the natural frequency of the system. Stays have to be fitted at one or both sides of the engine. Their efficiency is very good if they are mounted at a very stiff location on the ship hull.

3. Dynamic Analysis

In order to perform a numerical vibration simulation of an engine, it is necessary to know the main excitation forces and the dynamic properties of the engine or foundation or both. Building up a Finite Element (FE) model intended to be used in dynamic simulation is a demanding job. To get reliable results from the response analysis the model must be highly accurate [2, 6]. A modal analysis is used to determine the dynamic vibration characteristics of a structure or a machine component while it is being designed. The dynamic properties of a structure essentially consist of its natural frequencies and mode shapes, which depend on the mass and stiffness properties. The input required consists mainly of material properties which can be linear, isotropic or orthotropic, and constant or temperature-dependent [7,8].

4. Effect of Water Damping

Since marine engine foundation by its nature is a submerged panel, it is of interest to consider the effect of water damping by calculation of the reduction factor for the existence of water on one side of the panel. The natural frequency of submerged panel can be calculated from an empirical formula such as [1]:

$$\delta_w = \omega_L / \omega_n \tag{3}$$

where:

ω_L = the natural frequency in submerged condition, rad/s
ω_n = the natural frequency in air, rad/s
δ_w = reduction factor which can conveniently expressed as:

$$\delta_w = 1/\sqrt{1+\varepsilon} \tag{4}$$

$$\varepsilon = 0.04 A_p\, c / t_e \sqrt{1+(a/L_p)^2} \tag{5}$$

Where:

$$c = \begin{cases} 1 \text{ if one side is submerged} \\ 2 \text{ if both sides are submerged} \end{cases}$$

t_e is the equivalent thickness of the panel given by

$$t_e = \left(t + A_x n_x / L_p + A_y n_y / B_p\right)(\tag{6}$$

B_p = breadth of panel, m
L_p = length of panel, m
A_x = cross sectional area of stiffeners parallel to x-axis
A_y = cross sectional area of stiffeners parallel to x-axis
n_x = number of stiffeners parallel to x-axis
n_y = number of stiffeners parallel to y-axis

5. Hull/Machinery Incompatibility

The natural frequency corresponding to the two nodes vertical vibrations can be estimated with reasonable accuracy by Kumai's formula [1, 11]

$$N_{2v} = 3.07 .10^6 \sqrt{\frac{I_v}{\Delta_i L^3}} \text{ , cpm} \tag{7}$$

where:

I_v = moment of inertia of midship section, m^4

$\Delta_i = (1.2 + \frac{B}{3T})\Delta$ =displacement including virtual added mass of water, tonnes

B = beam, m

T = Draft, m

Δ =displacement, tonnes

The higher modes can be calculated based on the following formula:

$$N_{nv} \approx N_{2v}(n-1)^{\mu} \tag{8}$$

$$\mu = \begin{Bmatrix} 0.845 & General\,Cargo \\ 1.0 & Bulk\,Carriers \\ 1.02 & Tankers \end{Bmatrix}$$

6. Case study:

The dynamic analysis is outlined for a given engine supporting foundation in order to determine its natural frequencies and associated mode shapes. The objective is to evaluate the engine exciting forces and moment and to study the hull /machinery incompatibility, and the vibration response of the system. The particulars of the candidate ship and its propulsion system are given in Table 1.

Table 1: Candidate ship and propulsion system

Ship Particulars		**Engine Data**	
Ship type	Ro-Ro	Engine type	2-stroke diesel engine
Displacement	27531 tonnes	Number of cylinders	6 cylinder
Dead Weight	15725 tonnes	Bore	600 mm
LBP	183.0 m	Stroke	2400 mm
Breadth	27.40 m	Crank pin radius	1200 mm
Depth	19.3 m	Connecting rod length	2460 mm
Draft	9 m	Oscillating mass/cylinder	5003.0 kg
Speed	20.75 knots	Firing order	1-5-3-4-2-6
Block Coefficient	0.604	Maximum pressure	15.0 MPa
Propeller Data		Mean indicated pressure/MCR	2.00 MPa
		Max. continuous output	13530 kW
Type	fixed pitch	Max. continuous speed	105 rpm
No. of blades	4	Span of bearings	1020 mm
Diameter	4600 mm	Diameter of bearings	720 mm

6.1. Engine foundation

The particulars and scantlings of the foundation block according to IACS requirements [10] and recommendation of the manufacturer are shown in Fig.4 and Fig.5.

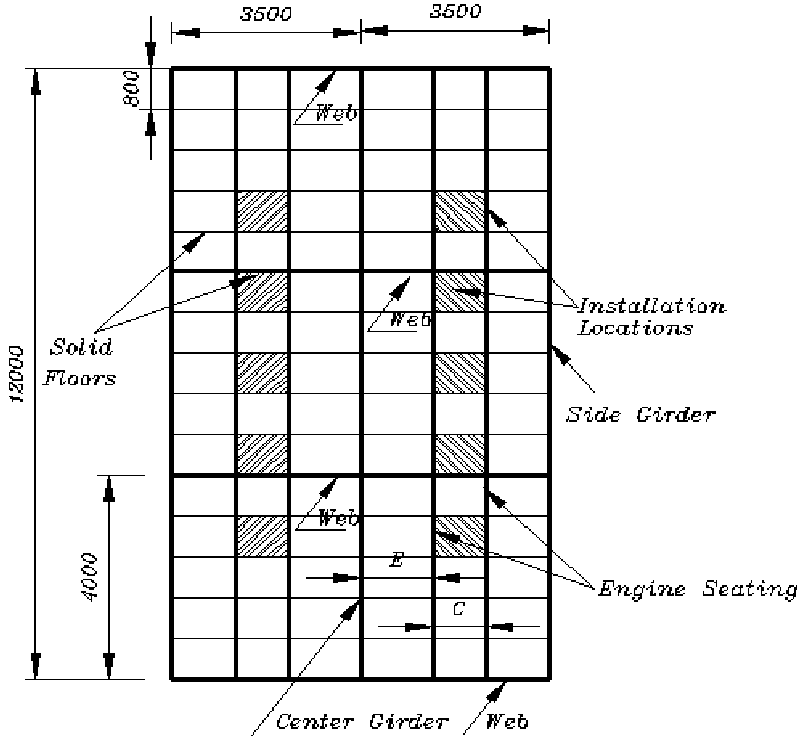

Figure 3: Plan view of foundation block

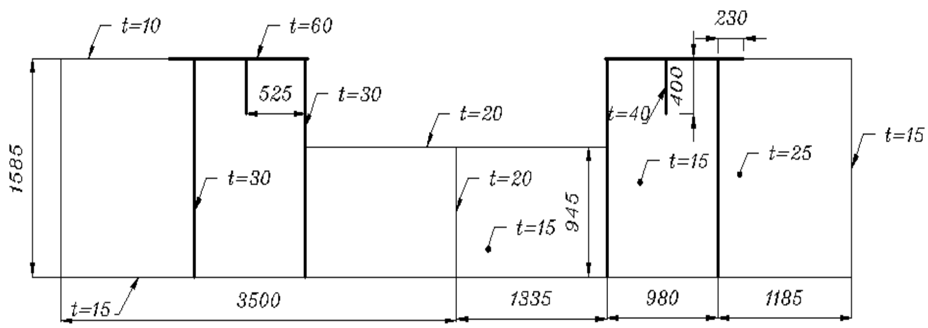

Figure 4: Transverse sections in engine foundation

The foundation is modeled as semi-infinite shell elements of different thicknesses. The model is then fully meshed into elements of 0.2 m edge length. The values used for the present model are 210 E+10 N/m^2 for Young's modulus and 7.862 t/m^3 for density. Modal analysis options had been set to extend 10 natural frequencies with their corresponding mode shape, to make sure that all are away of the engine running speeds. To take into account the effect of water damping for the model under consideration, the reduction factor is calculated as

$$\Delta_w = 0.389$$

The corrected natural frequencies for the effect of water damping are shown in Table 2.

Table 2 Water damped natural frequency

Mode Number	Natural frequency in air, Hz	Natural frequency in water, Hz
1	88.81	46.6
2	150.48	79.0
3-7	184.75	97.0
8,9	189.19	99.3
9,10	190.57	100.0

6.2. Engine exciting forces:

For the engine under consideration the vector sum of all exciting forces tends to zero, leaving an exciting moment of the 2nd order in the vertical direction. The amplitude of this moment can be calculated by Equation 1 and illustrated by Fig.6 for different engine speeds.

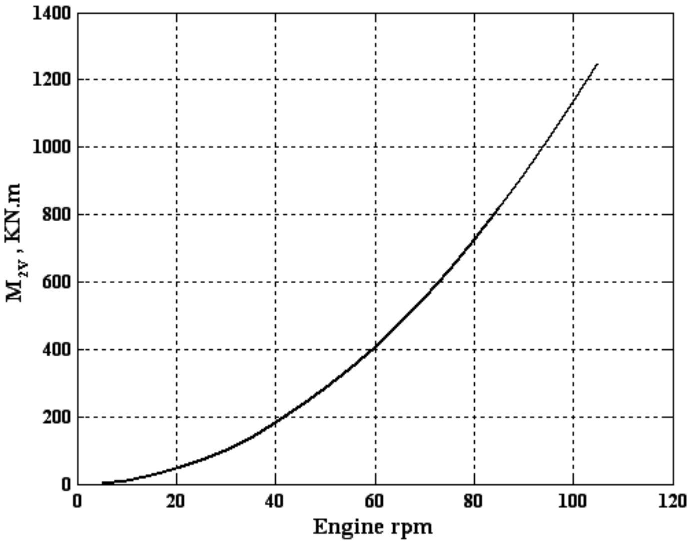

Figure 5: Amplitude of the 2nd order vertical moment

From the figure, the value of the 2nd order vertical moment of the engine at the MCR (105 rpm) is 1251 KN.m; this value is very close to that given in the maker catalogue which is 1266 KN.m[33]. Equation 1 seems to be quite adequate to evaluate the engine exciting moment in the absence of detailed data.

6.3. Hull/engine/foundation compatibility

The possibility of resonance due to the lower hull girder vertical modes with the second order moment engine exciting frequency is demonstrated by Figure 7.

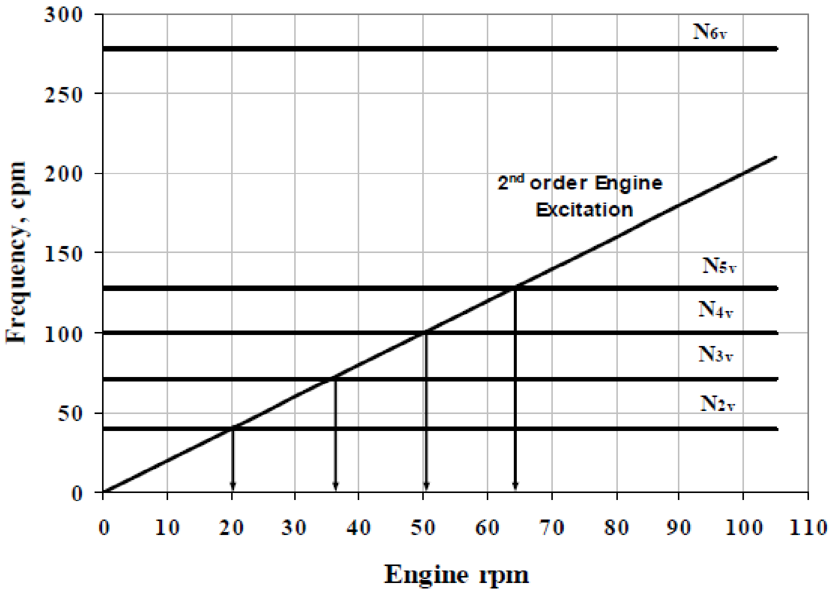

Figure 6: Hull girder natural frequency and engine exciting frequency

The results of modal analysis summarized in Table 2 show that, the fundamental frequency which in general is the most important one, equal 46.6 Hz. Fortunately this result is 13 times greater than the exciting frequency of 3.5Hz at the engine MCR as calculated from equation(2); all higher modes are insignificant and can be completely ignored.

For the situation of hull /machinery incompatibility represented by Fig .7, the designer can catch the critical engine speeds which coincide with the hull girder vibration as summarized in Table 3. The engine exciting frequencies are compared with the engine foundation and hull girder natural frequencies in Fig. 8. According to the aforementioned analysis the best operating range for the whole propulsion system and the candidate ship is from 65 to 105 rpm [13].

Table 3: Engine critical speeds

Item	Global hull	Engine foundation
Natural frequency, Hz	From0.66 to 4.63	From 46.6 to 100
Critical engine speeds, rpm	20; 37; 51 and 64	None

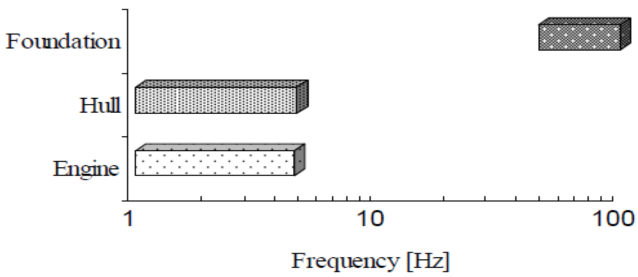

Figure 7: Calculated frequency ranges

7. Conclusions:

- A finite element model intended to be used for prediction of the natural frequencies of the engine foundation is required to confirm that, engine foundation has natural frequencies far away from the exciting frequencies of the engine at different loading conditions to avoid resonance. The modeling has been applied to a foundation of a 2-stroke, 6-cylinder diesel engine. The effect of water damping is taken into consideration; the result show that the fundamental frequency of the engine foundation is about 13 times greater than the exciting frequency of the engine at its MCR for the analysis output results.
- The magnitude and orders of engine external exciting moments must be considered when deciding hull /engine particulars at the early design stage in order to reduce the risk of severe disturbance due to these moments.
- The purpose of the analysis presented is to protect the engine, its supporting structure and the ship hull from excessive vibration levels by avoidance of the resulting critical frequencies.

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