Stiffness Variation in Bearing Supports of Marine Propulsion Systems

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Abstract

In some ship engine room designs, the bearing supports of the propulsion system shaft are not aligned with the primary structure, such as side girders and floors, which compromises the structural stiffness of the supports and leads to vibration problems in the propulsion train. This research aims to analyze how varying the height and position of a bearing support impacts its stiffness and natural frequency. The study focuses on parametric analysis, evaluating the results in the three main directions of motion—longitudinal, transverse, and vertical—using finite element models. The graphs and data obtained in this research should serve as a reference for installing bearing supports and to prevent vibration problems by having a stiffness that can vary depending on the location of bearing supports between primary structures.

Key words: Structural stiffness, Bearing support, Propulsion system, Resonance, Parametric analysis, Finite element analysis (FEA), Natural frequency, Structural vibrations.

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Introduction

Background

During vessel design and construction, optimizing construction and maintenance costs while minimizing structural weight is a primary goal. However, these strategies can increase the susceptibility to vibration problems in the propulsion system, derived from inadequate stiffness, caused by imbalances or dynamic sources such as the main engine, cardan shafts, propeller, or gears, which can be identified by knowing the internal geometry and operating speed. Drive shafts are subjected to demanding load situations such as:

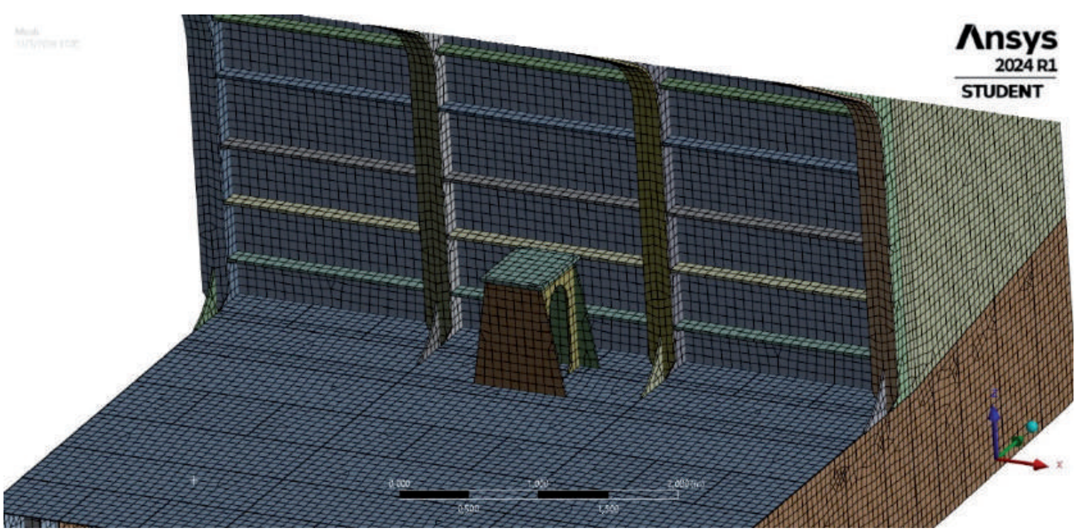
1. Transverse forces generated by the interaction between the propeller and the water, especially under maneuvering conditions;
2. Vertical forces, due to the weight of the shaft and possible misalignments caused by vibrations or shocks;
3. Longitudinal forces [8].
4. Torsional loading, as well as corrosion and marine fouling.

Failures can lead to grave consequences, resulting in high maintenance costs. Previous studies have reported on various failure modes including corrosion fatigue [10] or torsion fatigue [7], and cracking due to stress corrosion [9]. Resonance can cause excessive noise, leading to passenger discomfort [1][2][3].

To reduce vibrations, additional reinforcements could be added; however, this could increase the weight of the ship without ensuring greater stiffness. In contrast, when the excitation frequencies coincide with a natural frequency with sufficient energy, they induce resonance in the system, posing a significant risk to the stability and performance of the system, resulting in structural failures in the ship or propulsion components [3].

The objective of this research is to parametrically analyze the stiffness of a bearing support installed on a section of a ship with a double bottom and longitudinal bulkhead, as a function of the position of the support between web frames and the height of the support. This analysis requires a 3D model of the aforementioned design, establishing a mesh, boundary conditions and the forces acting on the strategic points, in order to be able to configure in the finite element software, as shown in Fig. 1, where

Fig. 1. 3D model of bearing support in machine room.



the bearing support of initial height ht is located in an intermediate position between web frames.

Methodology to obtain Stiffness analytically by means of equations

The stiffness (K) of a structural component is determined from the relationship between the applied force (F) in a specific direction and the deformation (δ) in that same direction. This relationship is expressed by the equation Hooke's law [6]:

$$\vec{F} = -k\vec{d} \tag{1}$$

The stiffness of the double bottom—without considering the bearing support—is estimated using equation [4]:

$$K = EA/L \tag{2}$$

Deflection equation of a beam

Considering a simply supported beam of length (L), to which a point moment (M) is applied at its central point, the deflection equation can be expressed as: $EId^4y(x)/dx^4=0$.

Considering a beam subjected to a moment at some specific point of the beam, knowing its boundary conditions, where the displacement and the moment are null, we obtain [12]:

$$\begin{cases} y_{(x),\,a} = \frac{-Mx}{6LEI}\left(L^2 - 3(L-a)^2 - x^2\right) \\ y_{(x),\,(L-a)} = \frac{M(L-x)}{6LEI}\left(L^2 - 3a^2 - (L-x)^2\right) \end{cases} \tag{3}$$

This equation allows determining the stiffness value by knowing the force that generates the moment and substituting it into equation (1).

Determination of natural frequency

The natural frequency of the bearing support was obtained with the modal module of the finite element software, which allowed obtaining the vibration modes in the longitudinal and transverse direction.

Due to the difficulties encountered in determining the natural frequencies and the processing time of results in the software, the natural frequencies were estimated for two support height cases, 2/3ht and 1/3ht, considering that the same mass of the model was maintained, considering only the variation in static stiffness, based on the natural frequency obtained for height (ht), the masses are equalized and replaced in the frequency equation $\omega_i = \sqrt{K_i/M} = 2\pi f_i$

$$f_i = f_o\sqrt{K_i/K_o} \tag{4}$$

where f_o is the natural frequency of the support in the central position between web frames and f_i is the natural frequency of the model in another relative position between web frames and other support heights. Similarly, stiffness (K) stiffness is analogous to frequency (f) in this analysis.

Definitions and conventions

Coordinate System:

1.4.2.1. X-axis (longitudinal): is the longitudinal direction of the ship, aligned with the axis of the propulsion system.

1.4.2.2. Y-axis (transverse): is the direction perpendicular to the longitudinal axis that runs from the ship centerline to the side of the ship.

1.4.2.3. Z Axis (Vertical): is the direction perpendicular to the longitudinal axis that runs from the baseline to the deck.

Methodology

The stiffness was calculated with Ansys Finite Element software, A mixed, medium-quality structured mesh with an element size of approximately 73.52 mm was used. The independent variable is the position of the bearing support along the longitudinal axis between web frames, while the dependent variables are the stiffness of the double bottom without a bearing support, the stiffness of the isolated bearing support, and that of the combined double bottom–bearing support model.

Samples

The variation of the height of the bearing support (h_t) in three equal parts: initial height h_t, $2/3h_t$ and $1/3h_t$; and seven positions of bearing supports between web frames were analyzed using Finite Element Software.

Procedure

A section of the ship including four web frames was modeled including one bearing support. Initially, the bearing support center was located over a web frame (position 0), then this support was moved to the next web frame, in various positions of interest. Finally, the bearing support was positioned in the center of another web frame (position 3), as shown in Fig. 2, the procedure for positions 4, 5 and 6 are symmetrical with respect to the initial position. For the models including bearing support, the axial, transverse and vertical loads were applied in the center of the upper plate of the bearing support, and for the model of the double bottom without bearing support were applied on the lower edge of the bearing support, as shown in Fig. 3.

Finally, the resulting deformations were measured for each configuration at each direction, obtaining the stiffness with equation 1, the natural frequency was obtained visualizing the modal bearing support deformation in longitudinal and transverse directions.

The stiffness values of the double-bottom model with bearing support will be identified with *Ki_t+b*, for the double-bottom without bearing support *Ki_b*, and the stiffness of the isolated bearing support (without double bottom) *Ko_t*.

Results

Relationship between stiffness of the double bottom and isolated bearing support

Fig. 4 shows the stiffness behavior curves, varying the height and position of the bearing support between web frames. The value of the stiffness of the isolated bearing support (*Ko_t*) varies only with the height (h_t), while the stiffness of the double-bottom (*Ki_b*) varies only with the virtual positions of the bearing support. Thus, the stiffness variation between the central position between web frames and over a web frame varies approximately 2%, 15% and 660% for the longitudinal, transverse, and vertical direction, respectively. In the longitudinal direction, one of the critical situations observed, as it goes against the trends of the other directions of analysis, the deflection was lower when the bearing support was located between web frames, which implies greater stiffness.

Fig. 2. Position of the bearing support along the longitudinal direction between web frames.

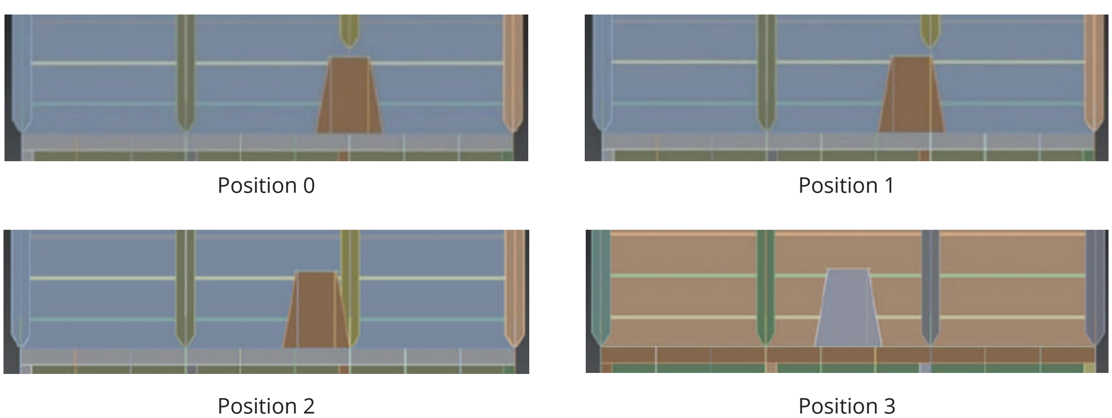


Fig. 3. Bottom edge of bearing support where force was applied for the double-bottom model.

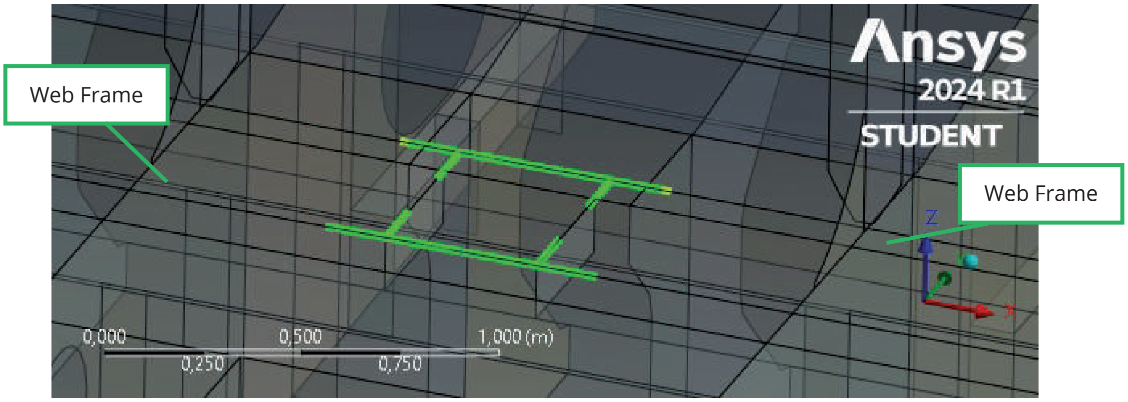
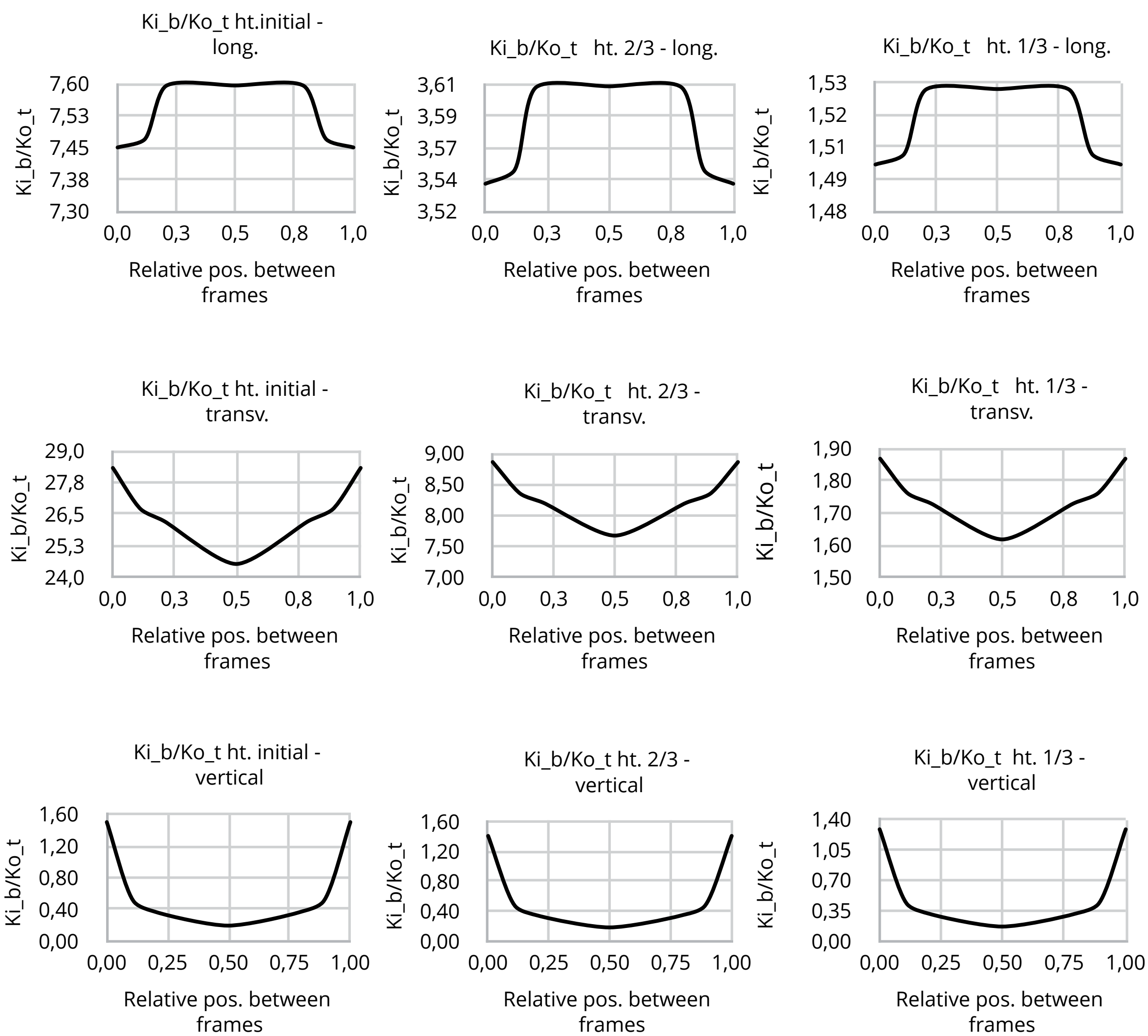


Fig. 4. Ratio of the stiffness of the double bottom and the bearing support for all directions.



Relationship between stiffness of the double bottom model with and without bearing support and isolated bearing support

Longitudinal Direction Analysis

Fig. 5 shows a behavior similar to that established in the section 3.1, where the stiffness is greater for the position between web frames. Additionally, reducing the height of the bearing resulted in less deflection in the central position and consequently, an increase in the stiffness of the system. The ratio (*Ki_t+b/Ki_b*) should approach the value of *1* decreasing the bearing support height, and the percentage increase in stiffness should be greater than 590% with respect to the height of the initial bearing support.

Finally, to understand the increase in the curve at the relative positions 0.1 and 0.9, it was observed that at this position coincides one end of the bearing support with the web frame, increasing its stiffness by avoiding a greater deflection.

Analysis in the cross-sectional direction

Fig. 6 shows greater stiffness when the bearing support was located over the web frame. Regarding the height of the bearing support, the same behavior as in the longitudinal

Fig. 5. Relationship between the stiffness of the double-bottom model with bearing support and double-bottom without bearing support (left) and the relationship between the double-bottom model with bearing support and isolated bearing support (right) in the longitudinal direction.

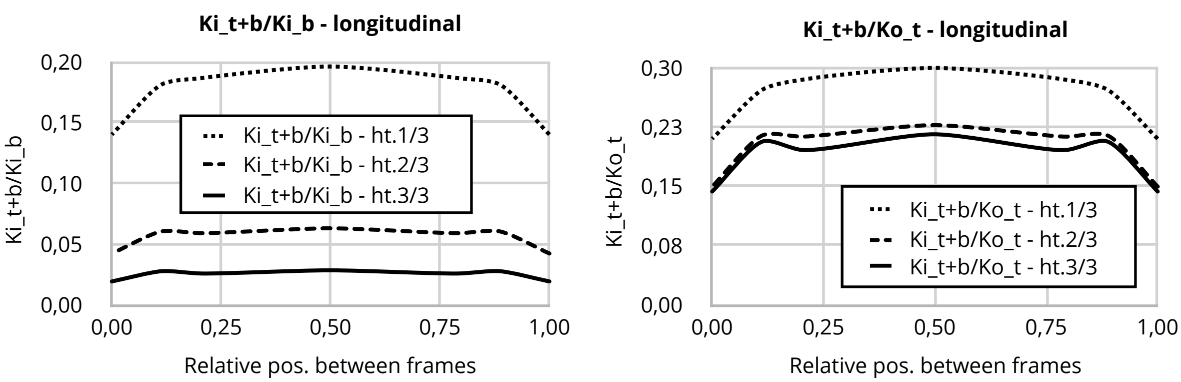
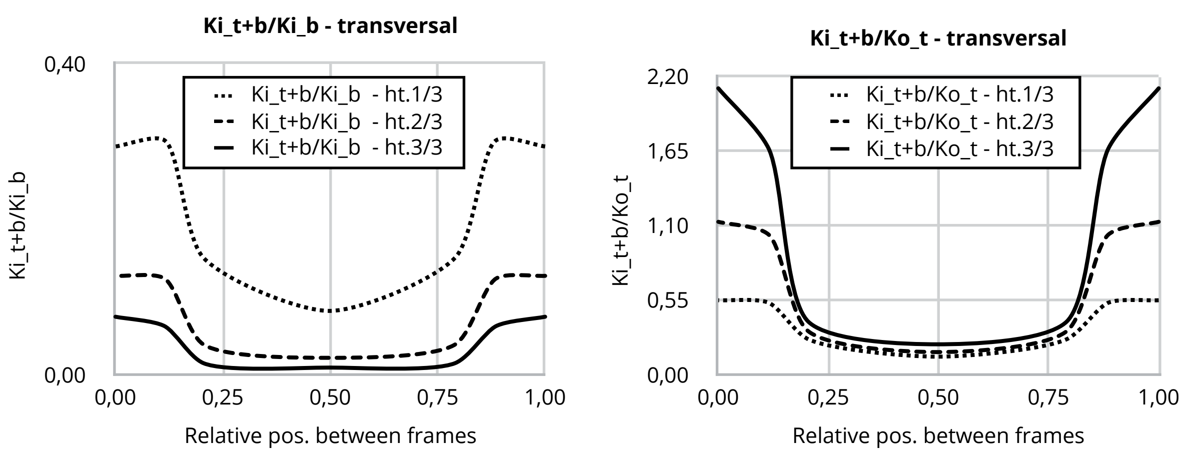


Fig. 6. Relationship between the stiffness of the double-bottomed model with bearing support and double-bottomed model without a bearing support (left) and the relationship between the double-bottomed model with a bearing support and an isolated bearing support (right), in a transverse direction.



analysis section, the stiffness increases as the height of the bearing support decreases. The bearing support model can reach up to 2.11 times its stiffness when the bearing support was located over the web frame.

Analysis in the vertical direction

The ratio between the double-bottom model with bearing support and without bearing support have the same behavior to increase of stiffness near to the web frame, as shown in Fig. 7, the stiffness can increase up to 1.6 times that of the central position between web frames. Finally, the relationship between the stiffness of the double-bottom model with bearing support and isolated bearing support was similar to the curve obtained in the analysis in the transverse direction, increasing the stiffness ratio with respect to the central position between web frames up to 168%.

Estimated natural frequency

The finite element software displays modal deformation using a color map representing its magnitude. Thus, the frequencies of the double-bottom model with bearing support and isolated bearing support were determined by observing the motion in the longitudinal and transverse directions as shown in Fig. 8, where the black lines indicate the initial position of the bearing support before exciting the system.

Fig. 7. Relationship between the stiffness of the double-bottom model with bearing support and double-bottom without bearing support (left) and the relationship between the double-bottom model with bearing support and isolated bearing support (right), in the vertical direction.

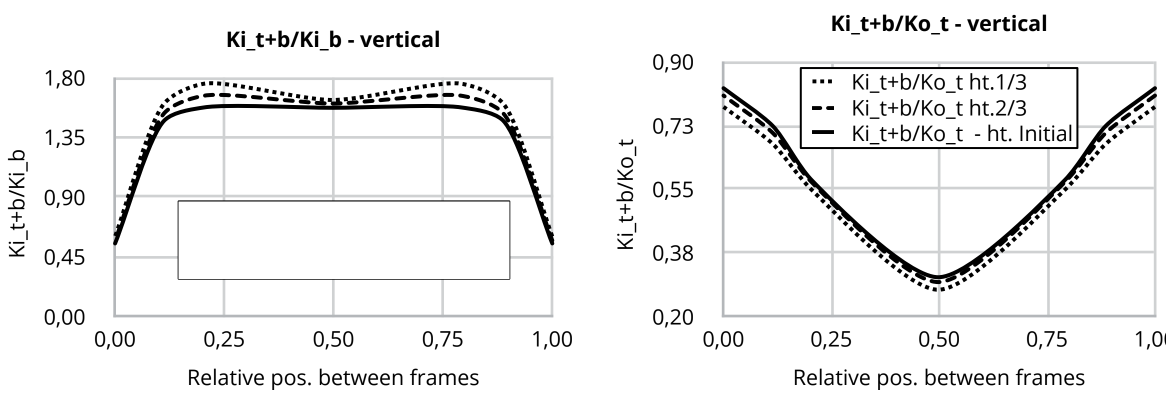
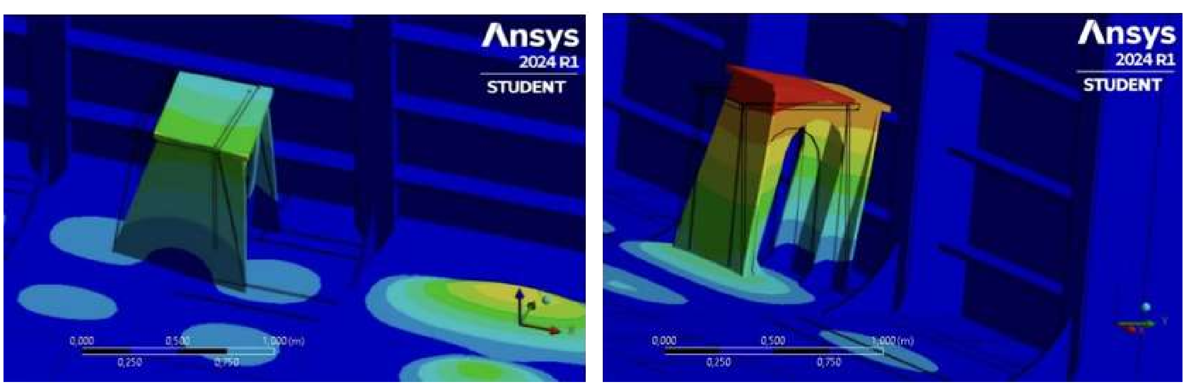


Fig. 8. Natural longitudinal and transverse frequency of the bearing support.



(a) Longitudinal frequency

(b) Transverse frequency

Fig. 9. Analytical natural frequency of bearing support model in longitudinal and transverse direction.

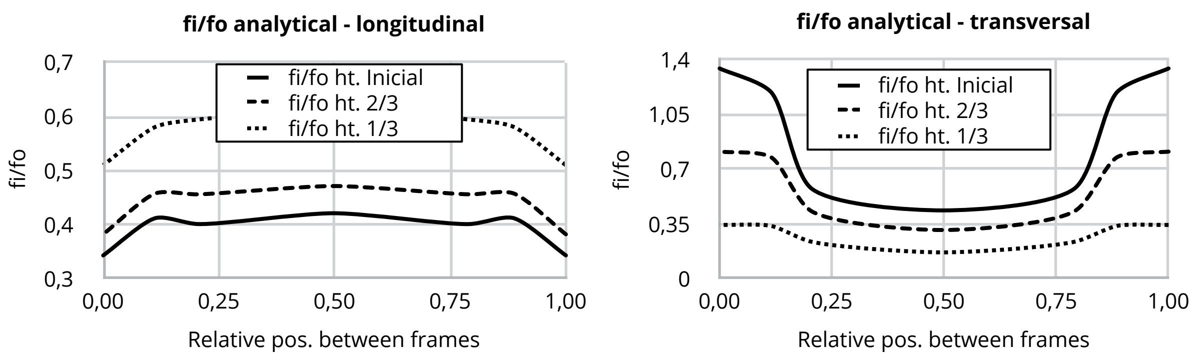


Fig. 9 shows the curves of variation of the natural frequency of the bearing support with respect to its position and height.

Discussion

The results of this study allow us the preliminary estimation of the behavior of the stiffness of the bearing support when the position between web frames and/or the height of the bearing support were modified. It was observed that the stiffness in the longitudinal direction is greater in the central position between web frames, this behavior differs from that in the transverse and vertical direction.

It is important to analyze the stiffness and frequencies together, as discrepancies could influence the dynamic performance of the powertrain.

In order to the design process of the bearing support in a propulsion system, the following initial conditions are required:

1. Define stiffness priorities:
   - Transverse: High priority to resist lateral forces produced during propeller rotation, especially in sudden maneuvers.
   - Vertical: Moderate priority to support the weight of the shaft and minimize deflection.
   - Longitudinal: Low priority, as axial loads are supported adequately.
2. Analysis of stiffness curves:
   - Transverse stiffness: Maximum over the web frames (relative positions x = 0 and x = 1).
   - Vertical stiffness: Similar to transverse, it is greater with bearing supports over web frames and lower in the center between web frames (x=0.5).
   - Longitudinal stiffness: Not uniform, slightly less between frames.
3. Optimal support placement:
   - For the propulsion system shaft, place the bearing supports near x = 0.1 or x = 0.9. These positions maximize transverse and vertical stiffness, ensuring that the system adequately supports lateral forces and shaft weight.
4. Technical justification:
   - Location close to the web frames reduces lateral deformation of the shaft, which improves power transmission and minimizes wear on the bearing and coupling.
   - Although the longitudinal stiffness is lower, the axial loads in the propulsion system are usually handled by the gearbox or external thrust bearings.

As an expected result, the optimal position of the support ensures transverse and vertical stability by minimizing lateral vibrations and vertical shaft bending, increases the service life of the system by reducing unnecessary loads on the bearing and shaft, and ensures efficient operation of the propulsion system by allowing power to be transmitted uninterrupted to the propeller.

Among the limitations of the present work, the exclusion of additional reinforcement structures, the meshing of the model and the assumption of ideal conditions in the finite element model stand out. These simplifications could influence the extrapolation of results to real systems, especially in vessels with complex structural configurations or with a lack of structural mooring.

A complete propulsion line analysis should include shaft lateral and axial vibration analysis to determine the optimal position of bearings and to avoid resonances with the structure, bearing supports stiffness, excitation forces and damping.

Shaft alignment and structural mobility calculation should be included to analyze the bearings stresses and structure damping to find optimal settings for adequate system operation without vibrations or failures.

Contributions

- Franklin J. Dominguez: Conceptualization, supervision, writing and 3D model – review & editing.
- Salim A. Dominguez: 3D modeling, Software development, Writing – abstract, introduction, methodology, results, tables, figures, discussion, conclusion, and references.
- Lino A. García: Validation, document review, translation, writing – review & editing.

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Conclusions

This study shows that the stiffness of the bearing support is overly sensitive to its position between web frames and to the height of the associated bearing support.

The ratio between longitudinal stiffness of the double-bottom model with bearing support and without bearing support can decrease 32% in the position over the web frame with respect to the central position and can increase 86%. reducing the height of the bearing support to a third of the initial height *ht*.

The results of the stiffness relationship between the double-bottom model with bearing support and isolated bearing support follow the same behavior as mentioned in the previous relationship, however, they vary because in the isolated bearing support model it is considered clamped at the bottom.

In the transversal and vertical analysis, the stiffness relationship between the double-bottom model with bearing support and isolated bearing support are similar and can increase up to 700% and 170% respectively, in the position over the web frame with respect to the central position. It is suggested to locate the bearing support near the web frame to increase the transverse and vertical stiffness, despite reducing longitudinal stiffness. Including new longitudinal reinforcements can offer significant improvements in structural performance.

Finally, it is recommended to integrate advanced dynamic analysis to validate findings and to optimize support designs in real applications.

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List of symbols.

i = 0, 1, 2, ...

Ki	Stiffness [N/m]
∂, ∂y, ∂x	Deformation [m]
fi	Frequency [Hz]
E	Modulus of elasticity [N/m2]
A	Cross-sectional area [m2]
L	Effective length [m]
M	Mass [Kg]
F	Force [N]
tp	Plate thickness [m]
t	Bearing support or bearing bracket
b	Base or double bottom only
ht	Bearing support height
Long.	Longitudinal
Pos.	Position
be	Effective width [m]
Transv.	Transversal
eq	Equivalent