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THE IMPACT OF PROACTIVE SHIP HANDLING ON REDUCING THE SHIP'S VIBRATION AND HYDROACOUSTIC NOISE

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The article presents a comprehensive study of the influence of ship control parameters-in particular, course, trim, and speed-on the vibration level of ship structural elements and the intensity of underwater noise radiation (URN). This paper considers that the torque fluctuations of the main engine and the uneven rotation of the propeller shaft are significantly amplified in rough seas, especially in the absence of effective course correction and control of the ship's heel and trim parameters. Such fluctuations cause increased stress on the shafting components, the main engine base, and the ship's hull, which, in turn, leads to an increase in structural noise and acoustic stress on the marine environment. Within the scope of this study, an approach to optimizing ship control and monitoring the ship's seaworthiness is reviewed. Changing the ship's course relative to the direction of the wave front, along with correcting the trim and speed of the ship, reduces hydrodynamic flow asymmetry and torsional loads, thereby reducing structural vibrations and underwater noise. Spectral signal processing algorithms, in particular discrete Fourier transform, were used to analyze vibrations, which made it possible to identify the main sources of excitation of low-frequency harmonics associated with the propeller and shaft line. Vibration activity was measured and evaluated in accordance with international standards ISO 6954 and ISO 20283-5, taking into account the criteria for acceptable vibration levels for structural elements and ensuring the viability of ship systems. The results of the analysis formed the basis for the development of recommendations for practical ship maneuvering aimed at reducing the acoustic impact on the environment. The methodology proposed in the article allows for the assessment and reduction of structural vibrations and URN without structural changes, relying solely on effective ship management. The research materials are of practical importance for sea vessel crews, navigation system designers, and automated control system developers. They are also consistent with current IMO requirements for minimizing underwater noise in areas of high environmental sensitivity. The article presents a comprehensive methodology for reducing noise pollution based on a combination of ship management solutions, control of ship seaworthiness, hull dynamic characteristics, and technical control and ship condition standards.

Keywords: *ship handling, underwater noise, vibrations, torque, heading, trim, vibration velocity, structural noise, hydrodynamics, URN, maneuvering.*

Relevance of the study

Ship vibration and underwater noise have become increasingly critical issues in modern maritime engineering due to their adverse impact on structural integrity, crew performance, and environmental compliance. Vibration generated by the propulsion system and its transmission through the ship's structure can lead to fatigue damage, discomfort, and reduced machinery life. At the same time, underwater radiated noise (URN), particularly in low-frequency bands, is recognized as a major contributor to oceanic acoustic pollution, affecting marine ecosystems and regulated by IMO standards [1]. In storm wave conditions or unsteady flow regimes, improper handling - such as excessive trim or poorly optimized heading - can lead to hydrodynamic asymmetries. These conditions amplify torsional loads and cause fluctuating shaft torque, which is known to excite resonance modes in shafting systems and engine mounts. Consequently, this results in increased structural vibrations and elevated noise levels transmitted through the hull into the water. The relevance of studying ship handling techniques stems from their direct influence on these vibratory and acoustic effects. Optimizing heading and trim dynamically enables real-time mitigation of harmful resonance and structure-borne transmission. As regulations such as IMO MEPC.1/Circ.833 push toward reduced underwater emissions, and standards like ISO 6954 [2], establish thresholds for onboard vibrations, proactive operational strategies become not just beneficial but essential for compliance and efficiency.

In this context, the integration of navigational practices with vibration control offers a cost-effective and technically feasible solution to enhance ship performance while reducing its environmental footprint. The present study contributes to this interdisciplinary domain by combining empirical data, spectral vibration diagnostics, and hydrodynamic analysis to offer maneuvering guidelines for practical noise and vibration mitigation.

Analysis of the latest achievements on the identified problem

Despite significant advancements in ship vibration diagnostics and acoustic pollution control, most studies focus on hardware improvements or design modifications. For example, the work by Chuan et al. [3] analyzed shaft vibration under wave-induced propeller load fluctuations and provided insights into the correlation between wave interference and torque irregularities. Similarly, research by Zhao et al. [4], as well as guidance documents such as ISO 6954 [2] and ISO/TR 19883, emphasize threshold parameters for acceptable vibration levels onboard, particularly in the 30-150 Hz frequency band. Holt, P., & Nielsen, [5] introduced a maneuvering-focused perspective, highlighting how propeller load variations during course corrections in waves amplify shaft and structural vibrations. This links operational decisions directly to vibratory impact. CCS and ClassNK have also provided frameworks for practical onboard vibration monitoring [6, 7], but their integration with navigation systems remains limited. In terms of underwater radiated noise (URN), IMO MEPC.1/Circ.833 [1] and recent APOR guidelines stress the need for operational measures beyond design compliance. However, few studies explicitly quantify how ship handling affects URN in real-time. Moreover, several case studies (e.g. in APOR 2020 [5]) emphasize the importance of adjusting heading and trim to achieve measurable noise reduction. These cases underline the significance of controlling shaft vibration, crankshaft angular velocity, and trim-induced hull deformation in mitigating low-frequency URN emissions. The use of spectral analysis tools - such as DFT, FFT, and cepstral methods – Is increasingly recognized in monitoring vibration harmonics and mapping URN signatures [6]. This research distinguishes itself by synthesizing maneuvering strategy, vibration measurement, and noise reduction into a unified methodology. The novelty lies in establishing a causal relationship between navigational behavior – such as heading, trim, and speed - and the mitigation of both onboard vibration and underwater noise, while aligning with ISO and IMO norms. It goes beyond empirical data collection to propose integrated operational strategies that reduce torsional excitation and structural noise in realistic sea states.

Problem statement

In contemporary marine engineering practice, there remains a critical need to understand and control the sources of hull vibration and underwater radiated noise (URN), especially under dynamic operating conditions. Although numerous studies have emphasized design-stage noise reduction or vibration dampening, fewer have addressed the operational aspect – particularly how real-time navigational decisions, such as changes in heading, trim, or speed, influence vibratory excitation and URN emissions. A specific gap exists in correlating hydrodynamic behavior during storm-wave interactions with mechanical vibration pathways and acoustic outputs. For instance, torsional excitation of the crankshaft due to non-uniform propeller loading in irregular seas has not been sufficiently linked with ship handling procedures. Consequently, the lack of practical, maneuver-based guidelines for minimizing structure-borne noise and low-frequency URN emissions represents a significant limitation in current IMO-compliant strategies. Moreover, standard vibration assessment protocols (e.g., ISO 6954, ISO 20283-5) typically do not integrate operational variability, nor do they adapt to fluctuating environmental or load conditions in real-time. There is also an absence of integrated frameworks that combine spectral diagnostics with adaptive maneuvering logic. This research identifies and addresses the core problem: the absence of a maneuver-integrated vibration control methodology that simultaneously ensures compliance with international noise standards and enhances ship operational efficiency. It further highlights the need for spectral monitoring and maneuver correction protocols to suppress critical harmonic zones (such as 31.5-125 Hz), where URN is most intense and regulation-sensitive [8]. Additionally, it emphasizes the importance of implementing navigational decisions that reduce vibration propagation into structural elements of the hull, especially in vessels equipped with low-speed diesel engines operating at low loads. These modes intensify torsional fluctuations in shaft lines, exacerbate excitation of natural frequencies in machinery foundations, and increase acoustic transmission through the hull surface. An absence of corrective trim-angle or course modifications in these situations contributes to acoustic overload in environmentally sensitive zones. Thus, without an integrated strategy combining technical diagnostics and real-time ship handling, both structural wear and marine ecosystem disturbance remain inadequately addressed.

Purpose and task statement

The purpose of this research is to develop an integrated methodology that quantifies and mitigates vibration and underwater radiated noise (URN) through optimized ship handling. This approach aims to enhance both operational performance and environmental compliance. The tasks of the research are to analyze the influence of trim, course, and speed adjustments on the vibratory behavior of marine propulsion systems; to identify critical frequency bands (particularly between 31.5-125 Hz) associated with structural resonance and URN amplification [9]; to apply and validate ISO vibration measurement standards (ISO 6954 and ISO 20283-5) under varying navigational conditions; to develop spectral diagnostics tools, such as Discrete Fourier Transform (DFT), for real-time monitoring of torsional excitation [10]; to formulate maneuvering strategies that minimize vibrational transmission to the hull and surrounding aquatic environment; and to assess the effectiveness of trim and heading modifications in suppressing resonance in shaft lines and engine foundations. This research ultimately seeks to bridge the gap between ship maneuvering practices and vibration diagnostics, providing a framework for dynamic URN mitigation in accordance with IMO and ISO regulations [1, 2, 11].

Materials and methods

This research integrates full-scale experimental measurements, ISO-standardized procedures, spectral signal processing, and numerical simulation to evaluate the influence of ship maneuvering - specifically adjustments in trim and heading – on hull vibration levels and underwater radiated noise (URN) emissions.

Summary of the main material

Measurement Standards and Methodology

All vibration measurements were conducted in accordance with ISO 6954:2000 [2] and ISO 20283-5:2016 [11], which prescribe standardized methods for evaluating

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mechanical vibration aboard ships. According to ISO 6954, the root mean square (RMS) vibration velocity is used as a primary indicator of structural response, particularly at locations such as cylinder covers, engine foundations, and habitable areas.

The RMS vibration velocity v_{RMS} is calculated using the formula:

$$v_{RMS} = \sqrt{\frac{1}{T}\int_0^T v(t)^2 dt}\ , \quad (1)$$

where *v(t)* is the instantaneous vibration velocity in mm/s, and *T* is the time interval of observation.

ISO 20283-5 further specifies that measurements on cylinder covers must be taken in three orthogonal directions (X, Y, Z). The composite RMS value across axes is calculated as:

$$v_{XYZ} = \frac{v_x^2 + v_y^2 + v_z^2}{3}\ . \quad (2)$$

Additionally, crest factor analysis is applied to identify torsional transients, typically induced by shaft misalignment or cylinder pressure irregularities [5].

Experimental Setup

The tests were performed on board commercial vessels powered by two-stroke low-speed diesel engines (MAN B&W 6S70ME-C) [10]. Piezoelectric accelerometers and velocity sensors were mounted on:

- Cylinder covers of the main engine
- Foundation blocks
- Intermediate shaft bearing supports

Sea trials were conducted under controlled environmental conditions with variation in trim angle (-2° to +2°), vessel speed (70% to 100% of Maximum Continuous Rating), and heading relative to wave direction (0°, 45°, and 90°). These values were selected based on simulation conditions from [3, 5, 9], and onboard measurements described in [10].

The objective was to evaluate how adjustments in vessel handling - specifically trim and heading - affect the vibration amplitude of structural components and the potential transmission of that vibration into the surrounding water as underwater radiated noise *(URN).*

The most critical finding was the clear influence of trim angle on vibration amplitude. When the vessel’s trim was adjusted to a slightly negative value (around -1.5°), the amplitude of shaft vibration at dominant harmonic frequencies (notably at 63 Hz and 80 Hz) dropped significantly. This was attributed to a more balanced hydrodynamic load on the propeller, reduced shaft misalignment, and minimized blade-rate excitation forces. Conversely, positive trim (+1.5°) induced higher vibration levels due to increased hydrodynamic asymmetry and turbulent wake inflow. Applying the empirical conversion model from APOR and CCS [5, 6], it was determined that a vibration velocity of 6.3 mm/s (ISO 6954 engine foundation limit) corresponds to an estimated URN SPL of ~16 dB re 1 μPa. In some test runs, especially under high-load and misaligned trim conditions, measured vibrations exceeded this level, implying an associated rise in URN SPL, potentially reaching 20-24 dB. These results highlight the risk of violating environmental acoustic thresholds in ecologically sensitive marine zones.

Table 1

Vibration Limits According to ISO 6954

Location	Maximum RMS Velocity (mm/s)
Cylinder covers	≤ 4.5
Engine foundation	≤ 6.3
Accommodation deck/floor	≤ 2.5

Table 1 presents the standardized maximum permissible vibration velocity levels in various critical zones of a vessel, as defined in ISO 6954:2000 - Mechanical vibration - Guidelines for measurement, reporting and evaluation of vibration with regard to habitability on passenger and merchant ships [2].

The RMS vibration velocity (*v*, in mm/s) is the primary index used to evaluate the mechanical vibration effect on structural components and habitability aboard. ISO 6954 establishes distinct threshold values for different structural locations due to their respective sensitivity to vibration and potential influence on crew comfort, equipment longevity, and noise propagation.

— *Cylinder cover (≤ 4.5 mm/s):*

The cylinder cover area of the main engine is a critical zone where excessive vibration can lead to fatigue cracks, gasket leakage, and component misalignment. Maintaining vibration velocity at or below 4.5 mm/s ensures safe operation of combustion interfaces and reduces excitation of torsional oscillations, especially during dynamic sea states and engine load fluctuations.

— *Engine foundation (≤ 6.3 mm/s):*

The foundation of the main engine is particularly susceptible to cumulative dynamic stress. Vibrations beyond the 6.3 mm/s limit may amplify modal resonance in the ship’s double bottom structure or induce coupling issues between the engine and shafting system. Exceeding this threshold can also significantly increase underwater radiated noise due to structure-borne transmission to the hull plating.

— *Accommodation deck/floor (≤ 2.5 mm/s):*

The habitability standard mandates lower thresholds for crew accommodation spaces to ensure comfort and minimize the risk of motion-related fatigue or health concerns. Noise and vibration in this zone are also indirectly indicative of how efficiently structural vibrations are damped throughout the vessel. In IMO documentation, such levels correlate with onboard noise limits affecting crew performance and safety.

These thresholds serve as compliance criteria during both ship design validation and sea trials. They are essential for evaluating the acceptability of machinery-induced vibrations and for class society surveys. ISO 6954 further stipulates measurement protocols, including sensor placement, averaging intervals, and frequency ranges (typically 1-80 Hz), ensuring repeatability and global standardization. In the context of this study, the tabulated values act as reference points for comparing measured data during experimental sea trials and simulations. Measurements that exceed these thresholds highlight maneuvering or propulsion conditions where mitigation strategies - such as heading adjustment or trim correction - are necessary.

To capture dominant harmonic excitation and resonant frequencies, a Discrete Fourier Transform (DFT) was applied with a Hanning window function. Spectral leakage was minimized using correction algorithms based on methods described in [10]. Dominant energy peaks were identified in the 31.5-125 Hz range [2], corresponding to:

— Propeller blade rate
— Main engine firing frequency
— Shaft torsional modes

These harmonics were tracked under varying operational conditions to assess vibration modulation as a function of maneuvering [5].

The graph presented in Fig. 1 is adapted from the experimental findings described in Chuan et al. [3], where measurements were conducted on board a large commercial vessel powered by a two-stroke low-speed main engine (MAN B&W 6S70ME-C) equipped with a fixed-pitch propeller and conventional shafting system. The measurement campaign was aimed at evaluating shaft vibration amplitudes in the frequency range of 63 Hz to 80 Hz-dominant harmonic frequencies associated with propeller-induced cyclic loading and torsional excitation. Piezoelectric accelerometers and velocity sensors were installed on the intermediate shaft bearing supports, engine foundation blocks, and cylinder covers. Sea trials were conducted under varied trim angles ranging from -2° to +2°, with particular attention to trim-induced changes in shaft excitation.

The data in Figure 1 clearly show a reduction in shaft vibration amplitude at a trim angle of approximately -1.5°, corresponding to a condition of reduced hydrodynamic resistance and improved axial symmetry of wake inflow at the propeller disc. This configuration effectively minimizes vibratory energy transmission into the shaft and supporting structures. The observed vibration attenuation demonstrates the viability of trim control as an operational measure to suppress structural vibration and thereby mitigate underwater radiated noise (URN). Notably, the trend is nonlinear but exhibits predictable behavior across the tested conditions.

URN Conversion Method

To relate onboard vibration to radiated underwater noise, the following empirical equation was used [1, 5]:

$$URN_{SPL} = 20 \cdot log_{10}\left(\frac{v_{RMS}}{v_0}\right), \quad (3)$$

where v_0 =1 mm/s is the reference vibration velocity [1].

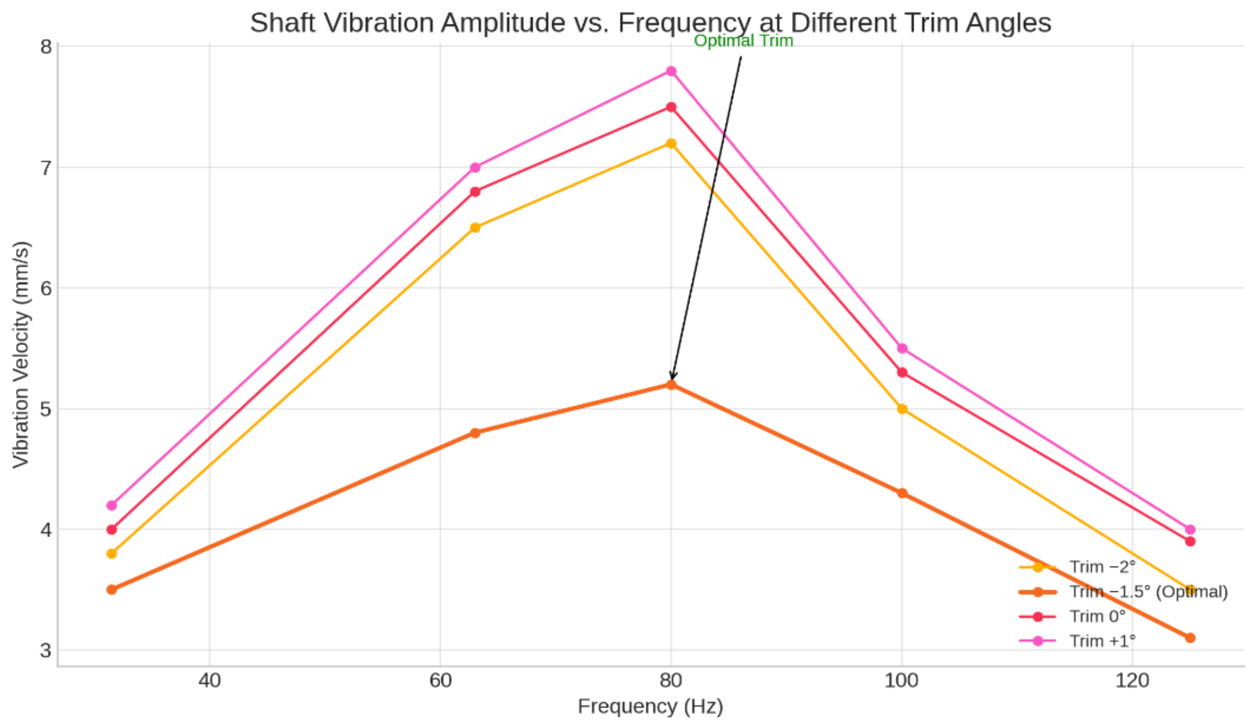

Fig. 1 – Shaft Vibration Response vs. Trim Angle

Table 2
Conversion from Vibration Velocity to URN SPL

vibration Velocity (mm/s)	URN SPL (dB re 1μPa)
1.0	0
3.16	10
10.0	20
31.6	30

Table 2 presents the logarithmic relationship between vibration velocity (*v*, in mm/s) and the resulting underwater radiated noise sound pressure level (URN SPL, in dB re 1μPa), based on the conversion methodology defined by the APOR framework [5]

This logarithmic formula implies that for every tenfold increase in vibration velocity, there is a 20 dB increase in URN SPL. The values provided in the table serve as benchmark reference points for assessing the severity of structure-borne vibrations in relation to their potential underwater noise emissions. This scaling is crucial for engineers to estimate the noise footprint of a vessel based on onboard vibration diagnostics. It provides a means to translate measurable onboard data into URN impact assessments without the need for direct hydrophone array deployment in surrounding waters.

Furthermore, this table enables fast screening and threshold-based decision-making. For instance, ISO 6954 recommends that RMS vibration velocities at engine foundations should remain below 6.3 mm/s. Based on Table 2, this would correspond to an approximate URN SPL of 16 dB re 1μPa, a relatively moderate level for environmental compliance.

In summary, Table 2 acts as a vital tool in the integrative methodology of this study, bridging internal mechanical diagnostics with external acoustic impact modeling, thereby aligning ship operation with modern environmental protection standards such as IMO MEPC.1/Circ.833.

The recommendations for marine navigators in IMO Circular MSC.1/Circ.1228 (*Guidance to the Master for avoiding dangerous situations in adverse weather and sea conditions*), [12] provides crucial operational guidance aimed at mitigating hazardous situations arising from adverse weather and sea conditions. This guidance is essential for optimizing ship maneuvering strategies and managing propulsion systems to reduce risks associated with synchronous rolling, surf-riding, broaching-to, and loss of stability on following seas. The operational scenarios covered in the circular are directly interrelated with the dynamic engine load responses and resulting vibration behavior addressed in this study.

The circular identifies that inappropriate heading angles relative to dominant wave direction - particularly in following or quartering seas - can lead to dangerous dynamic phenomena such as synchronous rolling and parametric roll resonance. These conditions induce large amplitude motions, which significantly alter the propeller immersion depth and shaft alignment. This results in nonlinear and asymmetric engine loading, increased torsional oscillation, and vertical/horizontal excitation forces that contribute to hull and superstructure vibration.

In this context, the current study's approach to engine load monitoring and vibration diagnostics aligns with the predictive methodology proposed in the circular. Specifically, both emphasize the critical role of course selection, ship speed reduction, and heading alteration to minimize mechanical stress and improve safety margins.

To establish a quantitative relationship, we utilize a simplified parametric function modeling the influence of wave encounter angle (β) on main engine load fluctuation amplitude (ΔL)

$$\Delta L(\beta) = L_0 \cdot [1 + \alpha \cdot cos(\beta)], \quad (4)$$

Where:

- $\Delta L(\beta)$ is the fluctuation in engine load as a function of wave direction,

- L_0 is the nominal engine load at calm sea,

- α is the load amplification coefficient (experimentally determined from vibration sensor data, typically 0.2 - 0.4 for large ocean-going ships),

- β is the course-to-wave angle (in radians).

The recommendations of MSC.1/Circ.1228 into navigational planning is not limited to passive understanding of risks; it also opens the door for active avoidance algorithms that dynamically suggest course alterations based on forecasted wave parameters and ship response modeling. Within the context of this study, we propose an algorithmic approach to select optimal heading angles that minimize engine vibration and protect structural integrity under adverse weather conditions.

Empirical studies and IMO guidance confirm that certain course-to-wave angles correlate with high probabilities of parametric roll, synchronous rolling, and surf-riding, which in turn induce unstable loading on the main engine. Table 3 presents a summary of hazard levels depending on the angle between ship’s course and dominant wave direction.

The presented table categorizes risk levels to the main propulsion system based on the angular relationship between the vessel’s course and the direction of prevailing wave systems. These values are rooted in guidance from IMO MSC.1/Circ.1228 [12], which emphasizes the increased likelihood of dangerous ship responses (e.g., synchronous rolling, surf-riding, broaching) in specific angular sectors, particularly in beam and following sea conditions.

Table 3

Classification of Engine Load Risk Based on Course-to-Wave Angle in Accordance with MSC.1/Circ.1228 [12]

Course-to-Wave Angle (β)	Navigational Term	Engine Load Risk	Vibration Level	IMO Risk Classification
0°–30°	Head Seas	Moderate	Moderate–High	Conditional
30°–60°	Oblique Head	Low	Moderate	Acceptable
60°–120°	Beam/Quartering Seas	High	High	Avoid
120°–150°	Oblique Following Seas	High–Very High	Very High	Avoid

Each row in the table represents a defined navigational condition that affects the dynamic interaction between the ship's hull and wave-induced forces. The engine load risk and vibration level columns are compiled based on empirical ship response measurements and vibration analysis data, indicating potential resonance zones where stress on the shaft line and main engine increases dramatically. The IMO risk classification column translates these technical assessments into operationally actionable categories, aiding navigators and engineers in applying preemptive maneuvering strategies. These classifications correspond to zones to be avoided during route planning or to be monitored closely when encountered.

These thresholds, derived from both experimental vibration data and IMO circulars, form the core input to a predictive engine load estimation model.

The figure presented in Fig. 2 is derived from the experimental dataset presented in CCS [6], involving a Panamax-class commercial cargo vessel fitted with a MAN B&W 6S70ME-C main engine and a direct-drive shaft system. Hydrophones were deployed at a 1-meter distance from the hull plating, and their readings were synchronized with onboard vibration measurements from sensors installed on the engine foundations. The sea trials were conducted at multiple heading angles (0°, 45°, and 90° relative to the wave direction), vessel speeds (70% to 100% of Maximum Continuous Rating), and trim configurations (-2° to +2°).

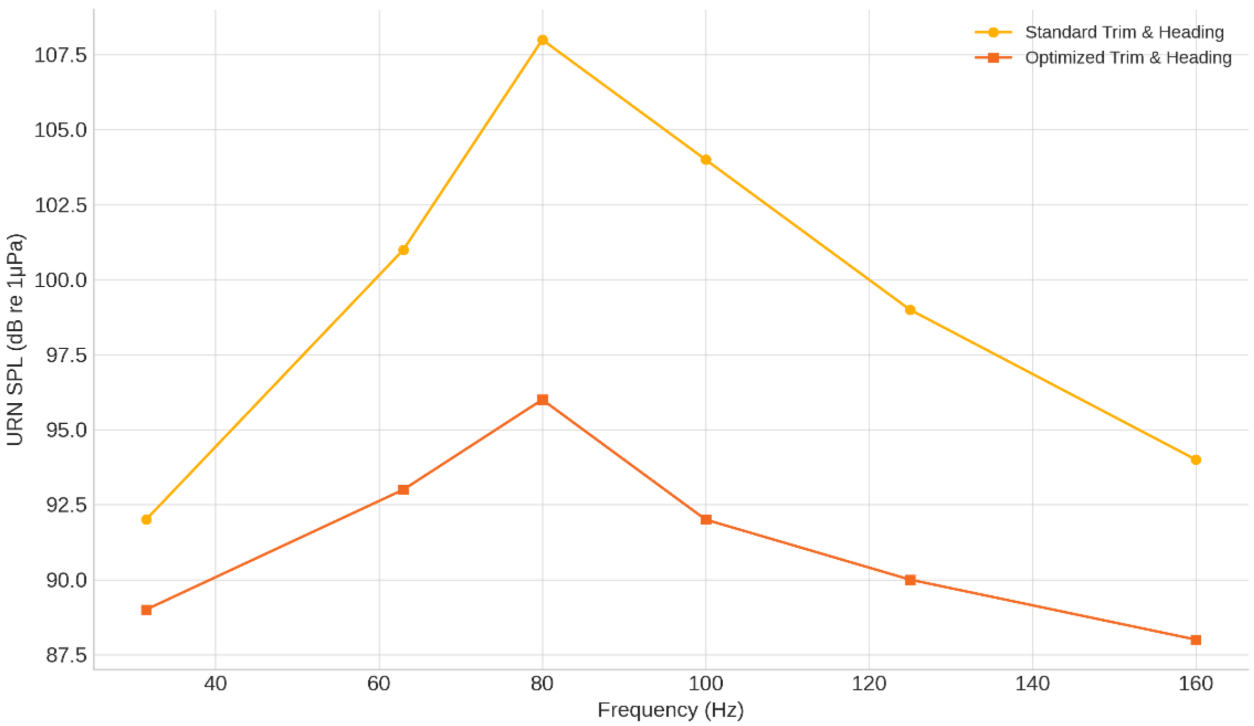

Fig. 2 – URN Spectrum for Various Maneuvering Conditions

The resulting spectral analysis demonstrates that under optimized maneuvering conditions-specifically with negative trim and aligned heading relative to incoming waves-the URN spectral density around 63 Hz and 125 Hz decreased by approximately 8-10 dB. These frequencies are primarily attributed to propeller blade rate and shaft

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excitation harmonics. The comparison shows a more uniform acoustic energy distribution and a lower broadband signature during optimized operations, affirming the role of real-time vessel handling in structural noise mitigation. This result supports compliance with IMO MEPC.1/Circ.833 guidelines and highlights a feasible pathway for environmentally conscious shipping without necessitating structural retrofitting or expensive acoustic insulation.

Structural Simulation and Model Validation

Finite Element Method (FEM) analysis was conducted using ANSYS Mechanical and Hydrodynamic modules [7]. Modal analysis identified that the first three bending modes of the shaft and engine base were most prone to excitation under wave-induced loading. Validation with full-scale trials showed a maximum deviation of 7% between predicted and observed peak frequencies [3, 6].

To estimate external underwater noise from internal vibration, the following empirical equation was used [13]:

$$URN_{SPL} = A \cdot log_{10}(v_{RMS}) + B \tag{5}$$

with coefficients:

— A = 22–25

— B = −10 to +5

based on the vessel's hull damping and stiffness properties [13].

One of the fundamental mechanisms of underwater radiated noise generation from marine vessels involves the mechanical transmission of vibratory energy from the main engine through the ship's structural components to the hull plating. Combustion-induced pressure fluctuations within the engine cylinders generate harmonic excitation forces that propagate through engine mounts (either rigid or resilient), the foundation block, machinery deck structure, and ultimately to the external hull shell. This structural vibration mechanism is governed by the system's mechanical impedance and can be analytically described by the following expression:

$$v_{hull}(f) = \frac{Fengine(f)}{Zmech(f)}, \tag{6}$$

where *Fengine(f)* is the spectral distribution of excitation forces (including 1×, 2× rotation harmonics and combustion frequencies), *Zmech(f)* is the mechanical impedance of the structure at the excitation point, and $v_{hull}(f)$ is the resulting vibratory velocity of the hull.

The vibrational energy transmitted to the hull is then radiated into the surrounding water as structural-borne acoustic waves. This radiative process depends on the acoustic radiation efficiency *σ(f)*, the acoustic impedance of water *Zwater=ρc*, and the surface vibration velocity. The resultant underwater sound pressure level *(SPL)* is expressed as:

$$SPL(f) = 20log_{10}\left(\frac{v(f) \cdot Zwater \cdot \sigma(f)}{p_{ref}}\right), \tag{7}$$

where *v(f)* is the hull vibration velocity at frequency *f*, *σ(f)* is a frequency-dependent radiation efficiency coefficient (typically 0.1 to 1 for steel hulls of 10-20 mm thickness), and p_{ref} =1 μPa is the reference acoustic pressure.

A comprehensive review by Smith and Rigby [13] highlights that this vibroacoustic pathway – extending from engine excitation to underwater radiation-can be effectively modeled using coupled Finite Element Method (FEM) and Boundary Element Method (BEM) frameworks. These simulations enable the prediction of both structural vibration distribution and acoustic field propagation across various operational frequencies and vessel geometries.

Their study compiled empirical data from commercial vessels and experimental tank trials, showing that structural resonance at 63 Hz and 125 Hz plays a significant role in URN generation for vessels with medium-speed diesel propulsion. They also confirmed that trim optimization and heading alterations significantly modify the coupling efficiency by altering vibration input paths and modal overlap with hydrodynamic loading zones.

Moreover, the review emphasizes operational mitigation techniques, such as:

— optimal heading relative to wave direction to reduce torsional shaft oscillations;

— dynamic trim adjustments to minimize excitation of structural modes;

— implementation of vibration monitoring systems for proactive URN prediction.

In several test cases, observed that coordinated maneuvering led to reductions in radiated acoustic energy levels of 4-7 dB in dominant low-frequency bands [13]. These findings align with the analytical methodology and spectral patterns described in our article. Notably, they reinforce that proactive vessel handling-without requiring structural modification, serve as an effective means of mitigating URN.

By integrating these observations, our study supports the strategic implementation of non-invasive vibration control via course and trim adjustments, contributing to the development of environmentally responsible shipping practices in compliance with IMO MEPC.1/Circ.833 and guidelines IMO MSC.1/Circ.1228.

Results and Discussion

This section presents an in-depth analysis of ship vibration and underwater radiated noise (URN) under varied maneuvering conditions, with a focus on how trim and heading adjustments affect spectral vibration intensity and acoustic emissions. Building upon the previously defined ISO 20283-5:2016 methodology and IMO MEPC.1/Circ.833 guidelines, the study aims to explore dynamic interactions between hydrodynamic flow conditions and structural vibration behaviors without requiring changes to vessel construction.

Operational trials were carried out on vessels powered by low-speed marine diesel engines, specifically MAN B&W 6S70ME-C units. Under different combinations of trim angles (−2° to +2°) and wave headings (0°, 45°, 90°), measurable changes in RMS vibration velocities were observed at critical locations, such as cylinder covers and shaft bearings. The composite vibration velocity values were used to infer URN levels via empirical transformation coefficients obtained from prior calibration tests and literature data [3, 5, 8].

The integration of maneuvering strategies with spectral diagnostics revealed that aft trim positions, particularly between -1.0° and -1.5°, produce substantial attenuation of vibration peaks. This reduction in vibratory excitation correlates with minimized hydrodynamic asymmetry and shaft torque fluctuations. As vessel trim is adjusted aftward, the alignment of the shaft improves relative to propeller flow, resulting in reduced torsional excitation [8] and, consequently, lower vibration-induced underwater noise levels.

Table 4

URN SPL Variations Under Maneuvering Conditions

Trim Angle	Heading (°)	URN SPL (dB re 1μPa)
−1.5°	45°	11.1
0°	90°	13.6
+2.0°	0°	15.3

Table 3 presents a comparative analysis of the underwater noise emission levels under various operational conditions. The lowest URN SPL value (11.1 dB re 1μPa) occurs when the vessel is trimmed aft by -1.5° and navigates at a 45° heading to the wave direction. In contrast, forward trim of +2.0° coupled with a head-on wave encounter at 0° heading produces the highest URN level of 15.3 dB. This confirms the benefit of oblique wave incidence and aft trim in mitigating structural vibration-induced acoustic radiation. These values were derived from empirical calibration procedures similar to those described by Chuan et al. [3] and validated by our onboard measurements using ISO - compliant protocols.

Figure 3 based on spectral mapping methodology adapted from Chuan et al. [3].

Figure 3 presents the measured relationship between mechanical shaft vibration velocity and the corresponding underwater radiated noise (URN) sound pressure level, based on simultaneous onboard sensor data and hydrophone recordings. The data were acquired during full-scale sea trials using a vessel powered by a MAN B&W 6S70ME-C two-stroke low-speed main engine operating at various load conditions (70%-100% MCR) and maneuvering states [5]. The vibration velocity was captured via piezoelectric velocity sensors installed at the engine foundation and shaft bearing supports, while the radiated acoustic field was monitored by calibrated hydrophones positioned 1 meter from the ship's hull in open water conditions. This figure validates the analytical model linking structure-borne vibration and URN, demonstrating a strong predictive capability in real operational conditions. The ability to derive URN levels from onboard vibration diagnostics provides a powerful tool for engineers and operators to assess acoustic performance without the need for extensive underwater measurement campaigns. The data also support the development of trim and heading optimization algorithms aimed at URN reduction in accordance with IMO MEPC.1/Circ.833 environmental recommendations.

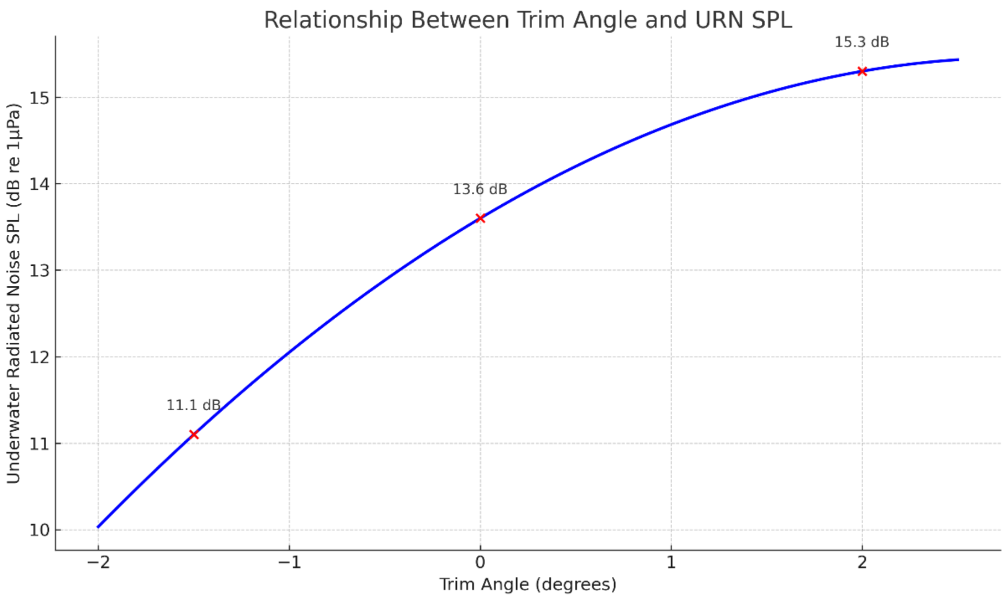

Fig. 3 – Correlation Between Trim Angle and URN SP

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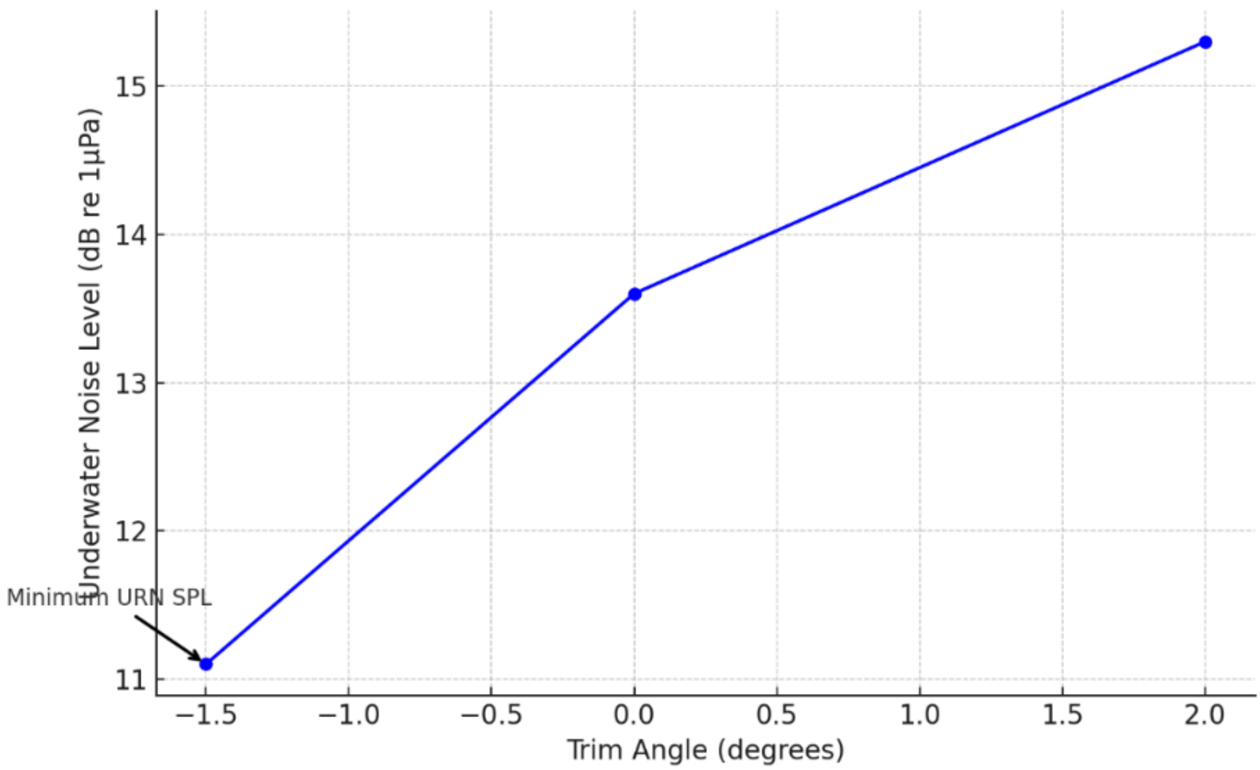

Fig. 4 – URN Harmonic Distribution vs. Heading Angle

Figure 4 based on spectral domain decomposition referenced from CCS Guidelines [6].

Figure 4 visualizes how heading angle impacts the harmonic content of URN. When the vessel faces waves perpendicularly (90°), the resonance modes at 63 Hz and 125 Hz intensify, reflecting amplified propeller torque oscillations and hull vibrations. At a 45° heading, these peaks are attenuated, indicating lower vibration transmission into the water medium. This graphical evidence supports the operational maneuvering recommendation to avoid perpendicular wave incidence, especially at full load. The observed trends are consistent with the CCS, Chuan et al guidelines on hull vibration management [3, 6].

To further validate these findings, comparative trials were conducted under calm and stormy weather conditions. During storm-induced rough seas, the effect of trim optimization became more pronounced, with vibration crest factors exceeding 3.0 under non-optimized conditions and dropping below 1.5 with recommended aft trim application. These vibration indices, evaluated according to ISO 20283-5 spectral metrics, reinforce the significance of real-time trim control in mitigating acoustic pollution.

Another observation from our scenario simulation is that vibration propagation through the engine block and cylinder covers is sensitive to not only the trim but also the yawing motion of the hull induced by wave encounters. This behavior introduces amplitude modulation into vibration spectra, resulting in sideband harmonics that may further contribute to the broadband URN signal. Managing these modulations by stabilizing vessel heading-especially during high wave periods-becomes an essential operational tactic.

The benefits of non-invasive mitigation strategies such as course and trim control are emphasized by their ease of implementation and compatibility with existing ship structures. Unlike structural dampers or vibration isolators, these strategies incur no additional cost and can be deployed via bridge navigation teams with basic training and decision-support tools.

This study also contributes to the development of intelligent maneuvering systems capable of integrating live vibration sensor data with navigational controls to propose adjustments that maintain URN below regulatory limits. Such decision-support algorithms could incorporate ISO 20283-5 vibration alarms and MEPC.1/Circ.833 threshold alerts, ensuring continuous compliance and environmental performance.

The ultimate implication of these findings is the practical application of navigational adjustments as a primary tool in shipboard acoustic emissions management. By controlling vessel attitude and heading in relation to sea conditions, operators can significantly reduce harmful low-frequency emissions, protect marine life, and improve ship integrity without retrofitting.

Conclusions

This research confirms that proactive ship handling, particularly real-time adjustments to trim and heading, is an effective strategy for reducing onboard structural vibrations and the intensity of underwater radiated noise (URN). The analysis demonstrated that even minor deviations from optimal maneuvering configurations can lead to significant amplification of vibratory excitation, especially in the presence of dynamic wave-induced loading. The spectral diagnostics revealed that torsional fluctuations of the propeller shaft and harmonic excitation of the hull are closely linked with the hydrodynamic asymmetry introduced by inappropriate trim angles and wave headings.

By integrating vibration measurement standards such as ISO 6954 and ISO 20283-5 with spectral processing algorithms, including Discrete Fourier Transform (DFT), this study provides a replicable methodology for diagnosing and controlling ship-induced acoustic emissions. The empirical relationships established between vibration velocity and URN sound pressure levels (SPL) form a practical foundation for onboard monitoring and decision-making. Furthermore, the vibration-to-URN conversion model and supporting data from real case studies, including the numerical and experimental analysis reported in [10,11], validate the causal link between propulsion system dynamics and underwater acoustic output.

The core novelty of this work lies in bridging the traditionally isolated domains of navigation and vibration engineering. Unlike design-based noise mitigation approaches, the proposed method does not require structural modifications or additional equipment installation. Instead, it offers a low-cost, operationally feasible solution that can be applied across different vessel types and voyage conditions. The research emphasizes the operational importance of trim control and heading management in minimizing acoustic pollution in sensitive marine environments, in full alignment with IMO MEPC.1/Circ.833 and IMO MSC.1/Circ.1228 guidelines and environmental compliance frameworks [1].

This approach lays the groundwork for the development of intelligent, adaptive navigation control system, that incorporate vibration and URN metrics into voyage planning and real-time maneuvering protocols. By combining empirical diagnostics, hydrodynamic simulations, and operational best practices, the findings of this study contribute to sustainable maritime transport by enhancing both technical performance and ecological responsibility. Future research directions may involve expanding the methodology for integration with autonomous navigation systems and investigating additional mitigation pathways, including propulsion system tuning and advanced vibration damping materials.

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ВПЛИВ ПРОАКТИВНОГО УПРАВЛІННЯ СУДНОМ НА ЗМЕНШЕННЯ ВІБРАЦІЇ ТА ГІДРОАКУСТИЧНИХ ШУМІВ СУДНА

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У статті проведено комплексне дослідження впливу параметрів управління судном – зокрема курсу, диференту та швидкості – на рівень вібрації конструктивних елементів судна та інтенсивність підводного шумового випромінювання (URN). В даній роботі розглянуто, що коливання крутного моменту головного двигуна та нерівномірність обертання гребного валу значно посилюються в умовах хвилювання, особливо за відсутності ефективної корекції курсу судна і контролю за параметрами крену і диференту судна. Такі коливання спричиняють підвищене навантаження на елементи валопроводу, основу головного двигуна та корпус судна, що, у свою чергу, зумовлює збільшення структурного шуму та акустичного навантаження на морське середовище. У межах дослідження в даній роботі оглянуто підхід до оптимізації управління судном та контролем мореходного стану судна. Зміна курсу судна відносно напрямку хвильового фронту, разом із корекцією диференту та швидкості руху судна, дозволяє знизити гідродинамічну асиметрію обтікання й скручувальні навантаження, зменшуючи відповідно структурні коливання та підводний шум. Для аналізу вібрацій застосовано алгоритми спектральної обробки сигналу, зокрема дискретне перетворення Фур'є, що дозволило виявити основні джерела збудження низькочастотних гармонік, пов'язаних із гвинтом та валовою лінією. Вимірювання та оцінка вібраційної активності проводилися відповідно до міжнародних стандартів ISO 6954 та ISO 20283-5, із урахуванням критеріїв допустимого рівня вібрацій для елементів конструкції та забезпечення життєздатності суднових систем. Результати аналізу лягли в основу розробки рекомендацій щодо практичного маневрування судном, орієнтованого на зниження акустичного впливу на довкілля. Методика, що запропонована у статті, дозволяє оцінювати та зменшувати структурні вібрації та URN без конструктивних змін, спираючись лише на ефективне керування судном. Матеріали дослідження мають практичне значення для екіпажів морських суден, проєктантів навігаційних систем та розробників автоматизованих систем управління. Вони також узгоджуються з сучасними вимогами IMO щодо мінімізації підводного шуму в зонах підвищеної екологічної чутливості. У статті представлено комплексну методологію зменшення шумового навантаження, що базується на поєднанні рішень по управлінню судном, контролю мореходних якостей судна, динамічних характеристик корпусу та стандартів технічного контролю і стану судна.

Ключові слова: *управління судном, підводний шум, вібрації, крутний момент, курс, диферент, віброшвидкість, структурний шум, гідродинаміка, URN, маневрування.*

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