NUMERICAL ASSESSMENT OF THE EFFECTIVENESS OF TRADITIONAL RESILIENT MOUNTING SYSTEMS IN MITIGATING VIBRATIONS OF NAVAL EQUIPMENT SUBJECTED TO UNDERWATER EXPLOSIONS

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ABSTRACT

Underwater explosions (UNDEX) generate shock waves and bubble oscillations that propagate through marine structures, inducing vibrations that may compromise onboard equipment performance and reliability. The dynamic response of marine structures to these events presents significant challenges to operational safety, particularly in non-contact scenarios. While traditional resilient mounting systems are commonly employed to mitigate these effects, their efficiency is often limited by design constraints such as stiffness, target frequency range and equipment mass. This study investigates the effectiveness of resilient mounting systems in reducing structure-borne vibrations in a patrol vessel subjected to UNDEX events. A coupled acoustic–structural numerical approach, implemented in ABAQUS CAE, is used to predict the transient response and frequency behaviour of a foundation-resilient-mass subsystem supporting onboard equipment. The system is located on the ship's double bottom at mid-hull length, with an explosive charge positioned directly beneath the structure to simulate a realistic non-contact UNDEX scenario. Numerical simulations evaluate the ability of resilient mountings to attenuate high-frequency shock-induced vibrations and lower-frequency oscillations caused by bubble dynamics. Results highlight performance limitations and provide insights into their effectiveness in maintaining operational reliability under extreme loading conditions. This study advances vibration control strategies in marine structures, offering a reference for optimizing anti-shock and anti-vibration solutions in naval engineering applications.

Keywords: underwater explosion, acoustic–structural simulation, resilient, vibration control, equipment safeguard.

1 INTRODUCTION

In naval shipbuilding and offshore engineering, comprehending the dynamic response of submerged and floating structures under pressure loads is crucial for ensuring both safety and structural integrity. Among the various types of pressure loads encountered, underwater explosions (UNDEX) are particularly significant due to their substantial effects on the structural resilience and operational functionality of marine systems.

UNDEX events are typically categorized as either contact or non-contact, depending on the proximity of the detonation to the structure [1]–[3]. Contact explosions occur in direct or near-direct contact with the hull, often resulting in severe structural damage such as ruptures. Conversely, non-contact explosions take place at a certain distance from the structure but still generate intense shock waves and oscillating gas bubbles, leading to both elastic and plastic deformations. Although these events are less likely to cause immediate hull breaches, they present considerable risks to onboard equipment and overall operational efficiency.

In non-contact UNDEX scenarios, two primary loading mechanisms dominate: high-frequency shock waves and low-frequency gas bubble pulsations [2], [4]. Shock waves induce significant structural vibrations, exciting the ship's hull across a broad spectrum of frequencies. These vibrations can propagate throughout the vessel, potentially affecting equipment and components far from the initial point of impact [5]. Meanwhile, gas bubble

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oscillations, despite their lower frequency, can generate large-scale global motions such as whipping, further intensifying the risks to onboard systems [6].

To mitigate the adverse effects of these vibrations on onboard equipment, resilient mounting systems are commonly employed. These systems, designed to absorb and dissipate vibrational energy, can be categorized as either elastic or elastic–plastic, depending on their ability to recover post-shock. However, designing effective resilient mountings is a complex task influenced by multiple factors, including the mass of the equipment, system stiffness, target frequency range, and mounting location [7].

This study investigates the effectiveness of resilient mounting systems in mitigating vibrations resulting from non-contact UNDEX events. A patrol vessel is selected as the case study, and a high-fidelity numerical model is developed using a coupled acoustic–structural approach within ABAQUS CAE. This modelling technique effectively captures the dynamic behaviour of the ship's structure and onboard equipment, allowing for a comparative assessment of different resilient mounting configurations in vibration reduction and equipment protection.

The paper is structured as follows: Section 2 introduces the case study vessel and outlines the numerical modelling approach. Section 3 discusses the traditional resilient mounting system as a solution for vibration control, detailing its design, implementation, and expected performance. Section 4 presents the comparative analysis results, and Section 5 concludes with key findings and recommendations for future research.

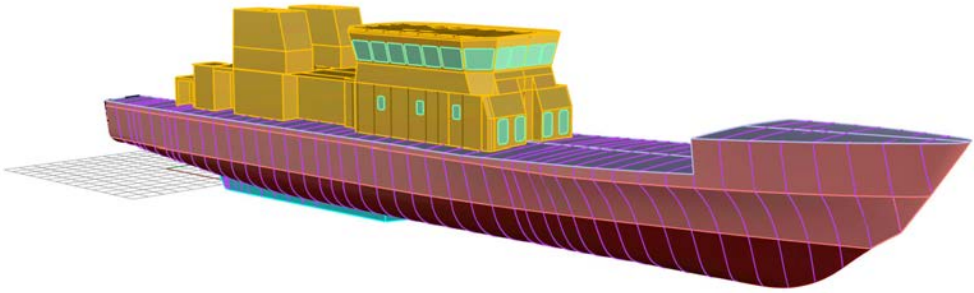
2 NUMERICAL MODELLING SET-UP

This section outlines the computational framework employed to investigate the structural response of a patrol vessel subjected to far-field underwater explosions (UNDEX). A representative geometry of the Swedish patrol vessel KBV 202 (Fig. 1(a) and (b)), belonging to the KBV 201 class, is utilized to validate the proposed methodology. The vessel has a displacement of 476 tons, a length of 52 m, a beam of 8.6 m and a designed draught of approximately 3.2 m. Its structural configuration follows a conventional mixed design, incorporating both longitudinal and transverse reinforcements. A view of the structure is depicted in Fig. 1(c).

The numerical model is developed to accurately capture the vessel's behaviour under extreme loading while maintaining computational efficiency. Implemented within ABAQUS CAE, it employs a coupled acoustic–structural approach to account for fluid–structure interactions. Due to the lack of detailed information regarding internal arrangements and secondary stiffeners, a simplified structural representation is adopted. This model derived using Smith's method and the MAESTRO software for ship hull strength evaluation [8], assumes a uniform plating thickness of 0.04 m.

The structural domain is discretized using S4 shell elements with an average mesh size of 0.1 m. This resolution is determined based on established guidelines for acoustic analyses [9], ensuring that the modal behaviour of the vessel is accurately represented while optimizing computational resources. The maximum frequency of interest is set at 100 Hz.

The surrounding fluid domain is meshed with 1,374,293 AC3D8R acoustic brick elements. The mesh size is chosen following a criterion that guarantees at least 12 internodal divisions per shortest acoustic wavelength. Considering a maximum frequency of 300 Hz, the upper limit for element size is set at 0.96 m. Non-reflecting boundary conditions are applied at the outer domain edges, while a free-surface boundary condition is enforced at the top to accurately capture wave propagation. The domain extends to a radius of 15 m, meeting the necessary conditions for effective wave absorption. Furthermore, cavitation effects –



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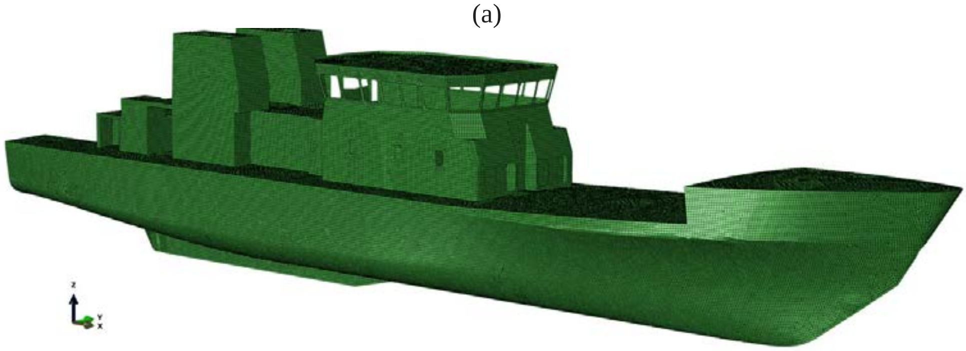

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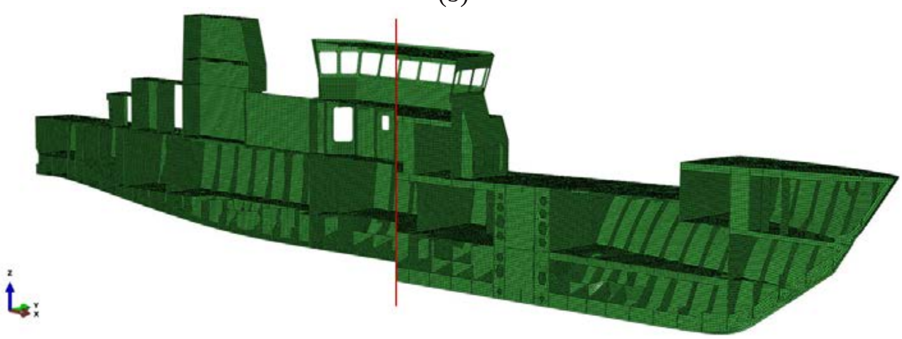

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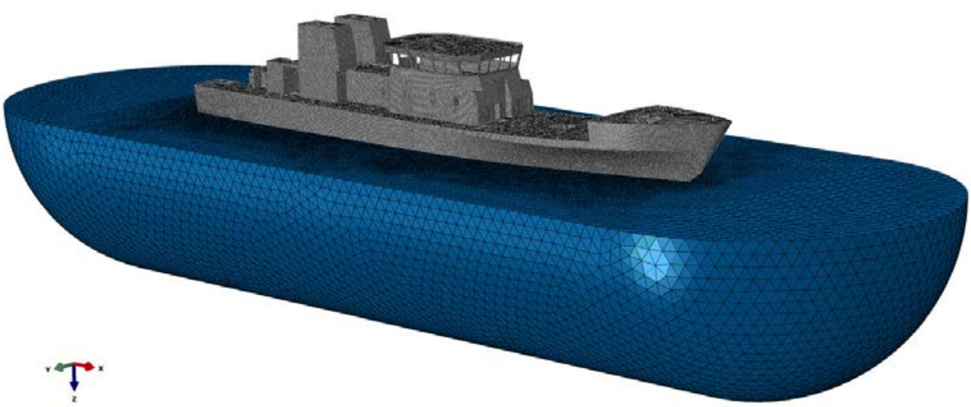

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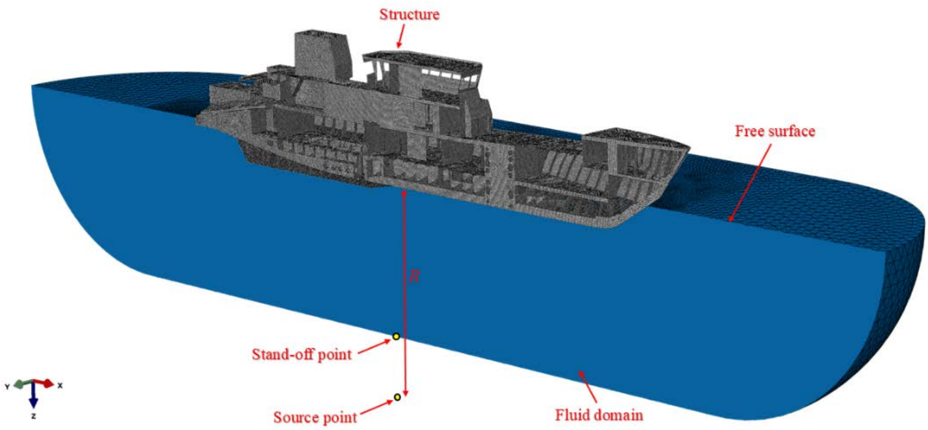


(e)

Figure 1: (a) CAD geometry of the vessel created in Rhinoceros suite; (b) Numerical model of the ship structure; (c) Internal structural arrangement; (d) Global FEM model of the ship portion surrounded by the external fluid; and (e) Vertical section of the model presented in (d).

including both local and bulk cavitation – are incorporated using the total wave formulation in the transient analysis. The coupled acoustic–structural numerical model is illustrated in Fig. 1(d) and (e).

The vessel's primary structural material is naval mild steel, characterized by a Young's modulus of 210 GPa, a Poisson's ratio of 0.3, and a density of 7850 kg/m^3. Plastic behaviour is modelled using the Johnson-Cook material law, with parameters sourced from Lin et al. [10]. However, damage modelling is excluded as deformations remain within the elastic regime. The water properties are defined with a bulk modulus of 2.03 GPa, a density of 1024 kg/m^3, and a sound velocity of 1500 m/s. Fluid–structure interaction is enforced through surface-based tie constraints along the wetted interface.

To simulate a torpedo detonation, a 516 kg TNT charge is placed at a depth of 31.6 m and a stand-off distance of 28.4 m. The total simulation duration is set to 1 s to capture gas bubble pulsations, which are modelled using the Geers and Hunter approach in ABAQUS. The secondary shockwave arrival time is estimated at 0.771 s, following Cole's empirical formulae [1].

3 TRADITIONAL RESILIENT MOUNTING SYSTEM AS SOLUTION TO VIBRATION CONTROL

To assess the vibrational effects on onboard equipment, a representative subsystem is included in the model. A schematic of this configuration is presented in Fig. 2. The subsystem comprises a foundation (explicitly modelled), resilient elements (spring-type connectors), and a cylindrical mass representing a generic equipment to be protected. The resilient supports, selected from the Vulkan MG series [11] (Fig. 3), feature a stiffness of 1.5×10^5 N/m. The cylindrical mass is assumed to be made of steel (density 7850 kg/m^3) and weighs 270 kg, with height constraints dictated by spatial limitations within the compartment.

This subsystem is positioned within a compartment at the extreme aft section of the vessel, near the primary shock arrival location, as shown in Fig. 4. The foundation is meshed with shell elements and affixed to the deck using tie constraints, while the spring connectors are kinematically coupled to the mass. Since ABAQUS Explicit does not allow spring elements to function in a single direction, additional kinematic constraints are introduced to restrict in-plane motion.

The selection of this type of resilient mount from the catalogue (Fig. 3) was based on the specific application requirements and the nominal load of the equipment, ensuring an appropriate balance between vibration isolation efficiency and structural compatibility.

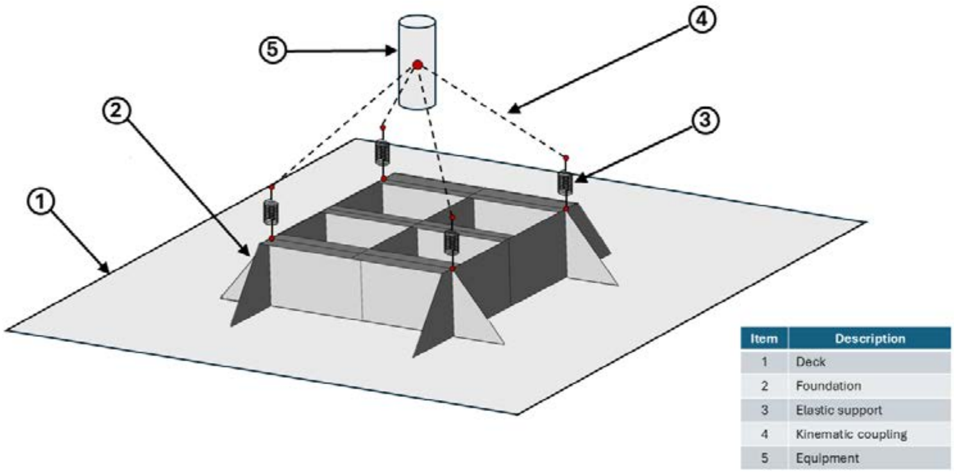


Figure 2: Schematization of the subsystem composed of the foundation, resilient elements, and equipment.

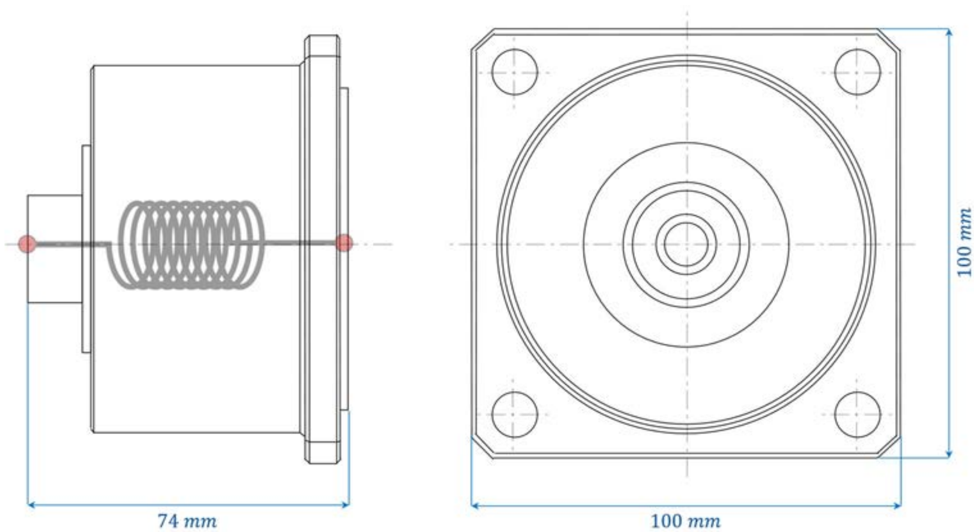


Figure 3: The actual geometry of the elastic supports modelled as spring elements and inspired by the Vulkan Group's MG Series [11].

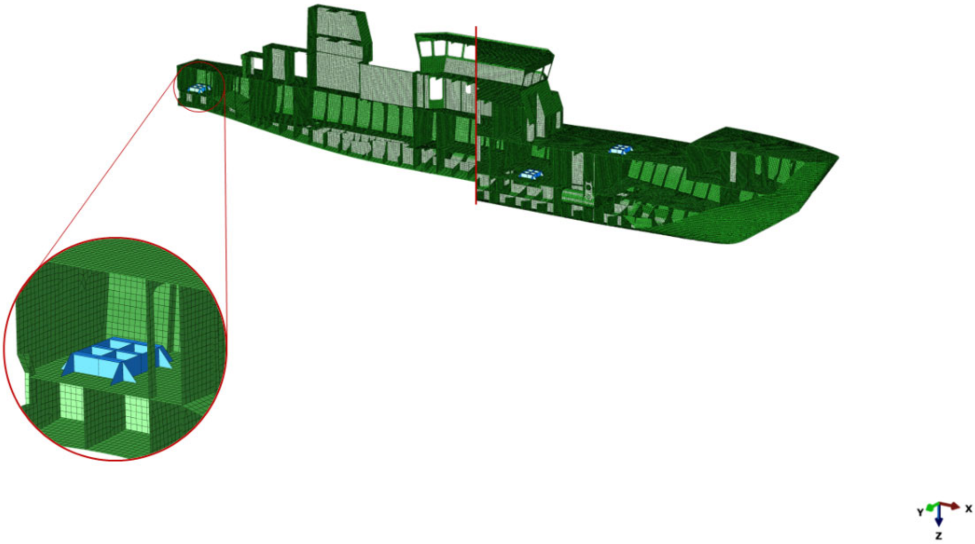


Figure 4: Installation of the foundation-resilient-equipment subsystem inside the patrol vessel.

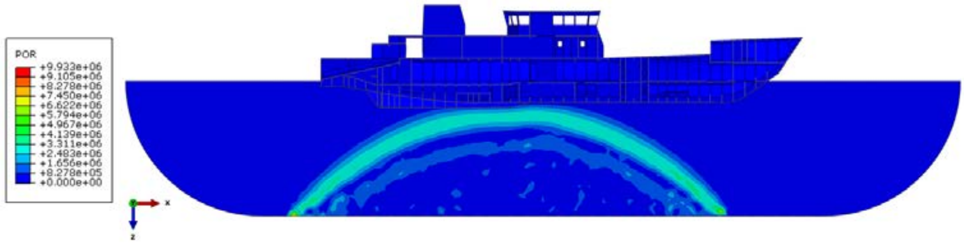
4 RESULTS AND DISCUSSION

This section provides a description of the response of the foundation-resilient-equipment subsystem subjected to the UNDEX event outlined in the previous sections. As an example, Fig. 5 documents the dynamic acoustic pressure (POR) in a longitudinal section of the entire numerical model, at the time instant where the primary shock wave reaches the structure. The recorded POR values are consistent with those provided by analytical formulations available in the literature, demonstrating the numerical model's reliability and accuracy in predictions.

Fig. 6 presents the simulation results for the foundation-resilient-mass subsystem over a 1-second interval. The plot compares the vertical acceleration recorded on the mass (black) with that measured at the central point of the foundation's upper surface (red). The system's dynamic response to the underwater explosion follows three distinct phases: an initial sharp peak upon the arrival of the primary shock, a subsequent phase of oscillations, and a final phase characterized by the first gas bubble pulsation.

The foundation's vertical acceleration initially peaks at -1000 m/s^2 (upward), while the mass responds with a much lower peak of ± 50 m/s^2. In the next phase, the foundation's oscillations gradually diminish, with the mass showing a smoother response. Around 0.8 s, distinct peaks in the mass's acceleration correspond to the first gas bubble pulsation, while the foundation continues exhibiting sharper oscillations.

The results of Fig. 6 confirm that the resilient mounting system – featuring the Vulkan material – effectively reduces the transmission of high-frequency vibrations from the foundation to the mounted equipment. The comparison between the two acceleration curves clearly demonstrates the system's ability to decouple the mass from the more severe and higher-frequency dynamic content of the foundation, thus protecting the mounted equipment. Nonetheless, the response to low-frequency excitations, such as those associated with bubble pulsation, remains partially transmitted due to the limited damping effectiveness in that frequency range.



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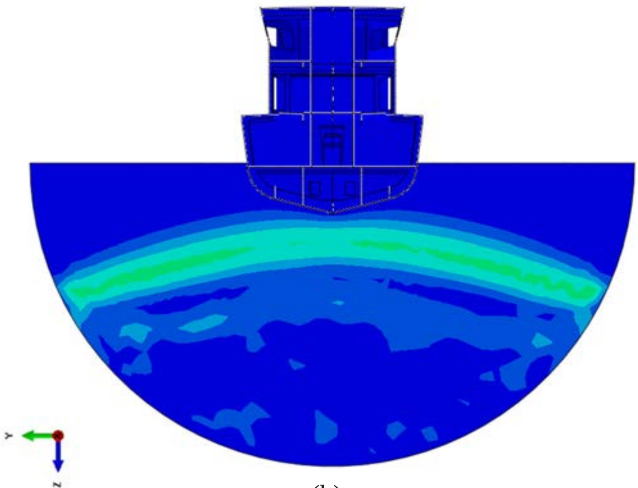

(b)

Figure 5: Total dynamic acoustic pressure (POR) field (in Pa) at the time instant where the shock hits the structure: (a) t = 0.007 s (longitudinal section); and (b) t = 0.007 s (transversal section).

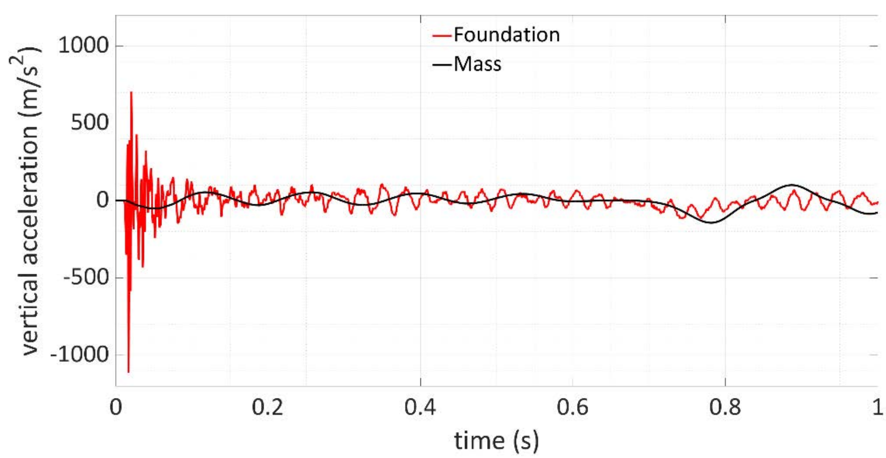

Figure 6: Comparison between the vertical acceleration versus time plots of the masses under study and its respective foundations accelerations.

5 CONCLUSIONS

The dynamic response of marine structures to underwater explosions (UNDEX) poses a significant challenge to operational safety and structural integrity, especially in non-contact scenarios. Shock waves and bubble oscillations from UNDEX events generate vibrations that propagate through the hull, adversely affecting onboard equipment and its performance. While traditional resilient mountings are commonly used to mitigate these effects, their efficiency is often constrained by design limitations, such as stiffness, target frequency range, and equipment mass.

This study investigates the effectiveness of traditional resilient mountings in mitigating vibrations induced by non-contact UNDEX events and explores the potential of advanced metamaterials as a future enhancement. A patrol vessel served as the reference military ship model for this study. A foundation-resilient-mass subsystem, designed to support onboard equipment, was positioned inside a compartment located at the aft section of the hull. Its dynamic response was assessed during a non-contact UNDEX event, with the explosive charge placed directly beneath the hull.

The results showed that traditional resilient mountings provided a degree of vibration attenuation, particularly in response to the primary shock wave. However, their effectiveness was limited when dealing with low-frequency oscillations induced by the gas bubble. These findings emphasize the need for further research into alternative vibration mitigation strategies [12]–[15].

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