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Development of Robust Marine Traction Voltage Battery Suspension System

Master Thesis in Product Development

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Cover: Wire Rope Isolator mounted for a battery unit.

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Abstract

This thesis examines the design and evaluation of vibration isolators for marine traction voltage battery packs under extreme conditions of vibration and shock. With growing marine electrification, the use of Energy Storage Systems (ESS) poses new engineering challenges since maritime environment is defined by unpredictable and frequently harsh dynamic loads. Traditional dampers used in automotive or fixed industrial applications are not suitable for marine conditions, which require safety, reliability, and system longevity.

This thesis explores whether Wire Rope Isolators (WRIs), which are utilized in rugged defense and industrial applications, can match or even exceed the marine battery systems damping needs. Several suspension configurations were assessed to determine their effectiveness in mitigating dynamic amplification and peak acceleration at the battery's center of gravity based on comparative simulation analysis. During the conceptual redesign of the WRIs, the ones configured in 45° compression, in particular, were noted for their promising low-frequency isolation.

Importantly, the best WRI design exceeded performance expectations on key metrics, including transmissibility and frequency response, aligned with manufacturability expectations, and even surpassed the benchmark hydromount system in several critical areas. The predictive WRI models developed in this research demonstrate that tuned WRIs can cater to marine vibration profiles. This study serves as the primary reference for building robust, modular, and high-performance isolation systems for modern marine propulsion platforms ESS in line with the Volvo Penta sustainable electrification initiative.

Keywords: Marine Electrification, Energy Storage System (ESS), Vibration Isolation, Wire Rope Isolator (WRI), Hydromounts. Finite Element Analysis (FEA), Modal and Random Vibration Analysis, and Sustainable Marine Propulsion.

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Since this thesis required input from multiple departments within the company, the willingness of different teams to clarify details, address specific technical questions, and provide timely feedback played a crucial role in the successful completion of our project. Their openness and guidance in resolving challenges, even at the smallest levels, were invaluable in helping us achieve the best possible outcomes for this thesis.

List of Acronyms

The list of acronyms used in this thesis is provided below:

2D	Two Dimensional
3D	Three Dimensional
CAD	Computer Aided Design
CAE	Computer Aided Engineering
FEA	Finite Element Analysis
DRM	Design Research Methodology
R&D	Research and Development
PSD	Power Spectral Density
DOF	Degree of Freedom
6DOF	Six Degrees of Freedom
MDOF	Multi-Degree of Freedom
ESS	Energy Storage System
WRI	Wire Rope Isolator
MP	Measurement Point
CG	Center of Gravity
RCA	Root Cause Analysis
ISO	International Organization for Standardization
IMO	International Maritime Organization
DNV	Det Norske Veritas (Maritime Classification)
Z-dir	Vertical Direction (Z-axis)
PA	Pre Assembly
LOS	Level of Service

Table 0.1: Abbreviations used in the marine battery isolation project

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Introduction

This thesis looks into the advanced and vibration-resistant suspension system for high voltage battery packs engineered specifically for usage in marine platform electrification. The more electric marine vessels there are, the more important the safety and dependability of battery systems become. The marine battery systems face unpredictable and continuous mechanical vibrations while submerged mid-ocean due to the operations of the electric engine, waves crashing, and hull flexing. The remaining four-dimensional dynamic loads can result in structural fatigue, electrical instability, and deadweight, and can also shorten the battery lifespan if not addressed in the right manner.
Speedboats and Hybrid marine crafts suffer more due to the extreme acceleration, as battery systems are installed in small to medium vessels. The rubbers, automotive vibration isolators or elastomer systems, grade elastomers for split-band vibration isolators don't seem to be advanced for the purpose. These mechanical systems are classified as blind and corrosion-safe mounts, unprotected from exposure to saltwater. This thesis is purpose-built to design systems for mounting high-voltage battery modules and protecting them from major mechanical vibratory disruptions.

Starting with the analysis of marine vibration characteristics and damping technologies, the project involved the design of numerous suspension concepts of different geometries and orientations to correspond with different battery configurations. This design phase involved the use of analytical models, as well as the utilization of simulation tools like ANSYS and MATLAB.

The intended design and analysis of the concepts seek to maximize integration, mechanical efficiency, and robustness to the environment. Assessing the design in accordance with the marine vibration benchmarks resulted in understanding the natural frequencies, transmissibility, stress distribution, and isolation bandwidth. This thesis strives to affirm that practical design considerations restated with simulation results would yield battery integration in marine electrical systems that are durable and safe.

1.1 Background

The growing use of electrification in marine applications has been across the commercial to leisure sectors which has also put a spotlight on the durability and safety that a high-voltage battery system should have if it is to be installed on a marine vessel. The larger and more powerful battery systems that are intended for the marine environment are becoming more and more powerful, and the mechanical environment in which they operate presents severe challenges in the design of these systems. Battery packs in marine platforms are not like those in electric vehicles that are land-based, as marine platforms expose them to complex and sustained mechanical excitations. These are such as continuous vibrations that come from hull dynamics, cyclic engine loads, and shock impacts that are induced by wave action. Over time, the continued nature of these dynamic loads can cause structural fatigue, internal cell degradation, a decrease in electrical efficiency, and, at the end of it all, premature battery failure. This situation represents a source of danger to the operation of the vessel, to safety and to the life expectancy of the battery - especially if we consider the high cost and high energy density of the modern lithium-ion battery system.

To address this issue, a project at *Volvo Penta* was launched in connection with the company's general electrification road map that envisions the delivery of a fleet of marine vessels with propulsion that is robust, reliable, and sustainable. The principal mission here is to come up with and create a suspension system that can work as an isolator for the vibration that comes from the marine battery pack thus both improving the performance reliability of the system and also the lifetime of the component. The conventional suspension methods are usually very bulky, subject to corrosion, and, therefore, unable to offer the whole range of marine-induced vibrations, thus they would not work in this particular case. The work reported in this thesis is related to the practical implementation of specially designed passive dampers and isolation systems that are characterized by their compact nature and that are tailor-made for the vibration features of marine hulls.

1.2 History of *Volvo Penta*

Volvo Penta is a Swedish company that is widely known for its marine and industrial power systems. Their history dates back to 1907, when the parent company, AB Volvo, was first established. In 1935, *Volvo Penta* was created as a collaborative project with the mission of developing marine engines, thus the first engine was the 4-horsepower B1 [1].Throughout the years, the company recorded several milestones like the MD1 diesel engine in 1959, the Aquamatic sterndrive, the IPS propulsion system, and most recently hybrid and fully electric propulsion platforms. These milestones have paved the way for *Volvo Penta* to be recognized as a leading global marine electrification player [1]. *Volvo Penta* is a renowned Swedish company specializing in marine and industrial power systems. Its origins trace back to 1907 when the parent company AB Volvo was founded. In 1935, *Volvo Penta* was formed as a joint venture between *Volvo* and *Penta*.The hybrid and fully electric propulsion platforms. These developments have positioned *Volvo Penta* as a global leader in marine electrification[2].
At the beginning of the twenty-first century, Volvo Penta solidified its innovative reputation with the launch of new electronic control systems and sterndrive technologies.

Besides that, the innovation journey also ended with the introduction of the Inboard Performance System (IPS) in 2005, which changed the marine propulsion industry forever. IPS uses an aft-facing, counter-rotating twin propeller setup along with underwater exhaust and joystick turning. These features were thus fuel efficient, lessened the noise on the vessel, and hence improved the vessel handling. The IPS system has become widely adopted in yachts up to 100 feet, with thousands of vessels equipped worldwide, reinforcing *Volvo Penta*'s reputation for pioneering reliable and efficient marine technologies[2]. In recent years, the focus has shifted toward environmental sustainability and energy efficiency. *Volvo Penta* has embraced digitalization and electrification as the future of marine technology, with growing investments in electric propulsion systems and hybrid drivetrains. This aligns with global trends aiming to reduce carbon emissions and improve operational efficiency across both recreational and commercial marine sectors [1].

1.3 Project Background

The engineering challenges posed by the electrification of marine vessels, especially concerning vibrational engineering and structural integrity, would, however, differ from those of land vehicles by a wide margin. Unlike land-based vehicles, marine vessels operate in an environment of considerable dynamism, ever subject to permanent vibration and shock of an eccentric nature induced by waves, propeller excitation, engine activities, and hull operations. These factors work in tandem as multi-axis loads across varied frequencies and a wide-bandwidth range.

Thus, the loads in a marine environment, as compared to a land or stationary environment, are exceedingly more aggressive on the battery systems. During the initial phases of this thesis, the focus was to offer general, wide support to the electrification goals of Volvo Penta. However, after going through stepwise discussions with Volvo Penta mentors and understanding the practical constraints of designs, the support shifted focus to the development of mechanical battery isolation systems. This involved studying the response of marine excitations and marine vibration isolators, and soft isolators for structural vibrations to determine the isolator performance and effectiveness and comparison of isolation solutions.

The vibration environment in marine applications is further complicated by spatial constraints, variable battery configurations, and the presence of corrosive elements such as saltwater and humidity. Most traditional isolation systems used in industrial or automotive applications are not directly transferable to marine conditions without significant modifications. Therefore, this project emerged as a response to the increasing need for tailor-made suspension systems that ensure reliability, safety, and performance under marine operation.[3].

1.4 Aim and Objectives

The primary aim of this thesis is to design and develop a vibration-tolerant and mechanically robust suspension system for high-voltage battery packs intended for marine electrification platforms. The system should be capable of isolating both low- and high-frequency vibrations commonly encountered in marine environments, thereby im-

proving reliability, safety, and operational life of the battery modules.
To support this aim, the following objectives were defined:

- To investigate and review existing vibration-damping technologies and characterize marine-specific vibration environments.
- To develop multiple suspension concepts adaptable to varying battery sizes, masses, and installation constraints.
- To analyze and simulate the dynamic response of these concepts using computational tools such as MATLAB and ANSYS, focusing on modal and random vibration behavior.
- To evaluate and validate the effectiveness of each concept against theoretical vibration isolation metrics and industry-relevant marine standards.

These efforts are intended to contribute toward safer, more reliable, and regulation-compliant electrified marine propulsion systems [4].

1.5 Challenges and Limitations

Creating suspension systems for high-voltage marine battery packs demands integrated mechanical, spatial, and environmental considerations. The foremost of these considerations is the very limited space available on the vessels. Solutions must, therefore, be compact and mountable without isolation performance coming under compromise [5]. Another important problem is the battery modules' mass irregularities, which affect the center of gravity. The result is an unequal load on the battery isolators, which is a leading cause of stress concentration and fatigue fracture. This makes the static center of gravity calculations, and equally distributed loads across the packs, core design objectives [6].

Saltwater and humidity exposure, and especially climate-driven temperature variations, cause the rapid deterioration of conventional dampening systems. Thus, isolation systems must be able to resist corrosion, offer mechanical strength and elastomeric systems, and dampen the viscous of the conventional elastomer materials [7]. Trade-offs between cost, performance, and corrosion resistance of materials such as stainless steel and marine-grade elastomers do not help the situation. The design simulation is also limited in accuracy due to the absence of high-resolution real-time data on vibration inputs[7].

Validating models becomes an invaluable yet difficult task because many marine excitation conditions need to be approximated [8]. Electrochemical degradation of lithium-ion cells to the point where electrodes become delaminated and batteries fail prematurely can be a result of vibration. Aggravated mechanical isolation to prevent structural failure will be necessary to preserve battery health over time [9]. In the context of marine electrification and the comments by *Volvo Penta*, structural vibrations highlight the importance of their mitigation for the reliability of battery vessels during their operation and for the entire savings through their battery-electric life [2].

1.5.1 Research Questions

This thesis addresses the need for a vibration-tolerant suspension system tailored to high-voltage marine battery packs. The research was guided by the following questions, which shaped both the conceptual design and simulation approach:

1. **What are the key design parameters**—such as natural frequency, damping ratio, and stiffness distribution—that influence the effectiveness of a suspension system in mitigating marine vibration for battery modules?
2. **How do different isolation technologies**, particularly wire rope isolators and hydro mounts, **perform under simulated marine vibration conditions, in terms of both low- and high-frequency attenuation?**
3. **What trade-offs emerge** when selecting the number, type, and placement of isolators, especially within the constraints of compact marine packaging and uneven load distribution?
4. **How can vibration isolation efficiency be evaluated and compared**, using metrics such as transmissibility, deflection limits, and frequency response (PSD) under random vibration inputs?
5. **Can a simulation-driven design approach**, using tools like ANSYS and MATLAB, **provide sufficient insight into isolator performance, or are physical tests required to validate the robustness of the final solution?**

1.6 Scope and Overview of the Report

This thesis was developed in the context of electrification *Volvo Penta* and the sustainable propulsion of batteries in marine propulsion. The primary scope was targeted towards the structural development of high-voltage batteries' mechanical suspension systems for the marine environment's dynamic exposure. In the electric propulsion, batteries are primary components, and systems are subject to complex vibration inputs generated by waves, engines, and hull structures while the batteries are mounted to the propulsion system. As such, the thesis exclusively addressed vibration isolation challenges, deliberately excluding thermal regulation, electrochemical aging, and electrical battery management systems to maintain a concentrated scope.

The investigation concentrated on isolator performance under both low- and high-frequency marine vibrations, taking into account the spatial limitations, material durability, and multi-directional loading typically observed in maritime environments. On this basis, various suspension configurations were designed and then evaluated. Analysis and simulations were carried out to assess performance, paying particular attention to the modal and stochastic vibration response, damping, and the stiffness and damping characteristics.

Ultimately, the report aimed to identify suspension solutions that are mechanically viable, environmentally resilient, and dynamically effective. The research and simulation efforts were intended to guide future implementation strategies and design decisions within *Volvo Penta*'s electrification roadmap, ensuring that marine battery systems remain safe, reliable, and compliant under real-world operating conditions.

2
Theory and Background Information

This chapter provides an overview of the theoretical concepts employed in this thesis.This chapter showed the theoretical groundwork for the incorporation of Energy Storage Systems (ESS) in the marine sector. It discussed how ESS integrates with and supports hybrid and fully electric propulsion systems to provide emission reductions and efficiency increases. The chapter discussed how different hull types influence the geometry and stability of a vessel while performing in varying marine conditions. The chapter described the influence of structural design on vessel durability and battery systems with respect to hydrostatic pressure, wave impact, vessel and battery temperature, and the structural and dynamic vibrations. The chapter discussed how vibrations impact battery performance and underscore possible mechanical deterioration, compliance with SAE J2380, and outlined and summarized relevant safety and compliance qualities derived from SOLAS, DNV and EMSA. Finally, the chapter examined mechanical ESS marine installations and described appropriate solutions to provide ESS marine installations the required ESS marine installations with the outlined vibration damping systems, which included isolation via wire rope, hydromounts, and rubber to metal isolation systems.

2.1 Overview of ESS in Marine Applications

Energy Storage Systems (ESS) are revolutionizing the Marine sector by facilitating enhanced, sustainable, and dependable ship operations. ESS is utilized in hybrid and all-electric marine propulsion systems, resulting in reduced emissions and increased energy efficiency. These systems generally operate in parallel with internal combustion engines or renewable energy sources. This co-existence enables vessels to maximize power distribution, minimize fuel consumption, and comply with ever-growing emissions legislation, especially in designated emission control areas.

The uptake of ESS has rapidly moved from initial hybrid integrations on smaller vessels to large-scale commercial adoption. It reached the biggest milestone with the Viking Lady in 2009, one of the first offshore vessels to feature a battery-supported hybrid propulsion system. The Viking Lady utilized a 442 kWh lithium-ion battery, which reduced the use of fuel, NOx, and greenhouse gas emissions. This success was followed by others, including the 2022 delivery of the Yara Birkeland, the world's first all-electric, autonomous container vessel. The Yara Birkeland uses a 6.7

MWh lithium-ion battery system, enabling operations that are zero-pollution and significantly reducing the use of diesel-fueled truck transport.[10]

Driven by advancements in battery management systems (BMS), energy density, and regulatory requirements, ESS has emerged as a booming technology powering the maritime industry's decarbonization.

2.2 Types of Hulls and Boats

The marine vessels are designed based on their different purpose and the environment they are used. The hull is one of the significant components that dictate the efficiency, stability, and performance of the ship. Displacement hulls, pontoon, flat-bottomed, deep V, catamarans, and multi-hull are some of the various hull types that serve their purpose for the different types of ships which is illustrated in Figure 2.1[11].

The construction of displacement hulls enables them to travel by displacing the water at low speeds. They are most commonly used in large ships such as cargo ships, tankers, and ocean liners, where stability and cargo space are necessary. The large volume of water displaced impedes the ship's speed. The performance of these hulls is dependent primarily on the shape and material of the hull. However, planing hulls, or hulls shaped to be high-speed forms, are lifted as they travel across the water surface, decreasing resistance and optimizing efficiency. Such designs are typical of smaller vessels like speedboats and pleasure yachts.

Catamarans feature twin parallel hulls, providing excellent stability and reduced water resistance. The wide stance of catamarans limits hull surface contact with the water, resulting in smoother movement, especially in choppy seas. These vessels are widely used for passenger ferries, high-speed transports, and luxury cruisers.[12] Multihull vessels, with three or more hulls, offer increased stability and load-bearing capacity. These designs are beneficial in heavy transport or research missions where strength and durability are essential. Across all hull types, maintaining structural resilience under varying sea conditions is critical. Each design must account for wave impact, load stress, and harsh marine environments to ensure safe and efficient operation.

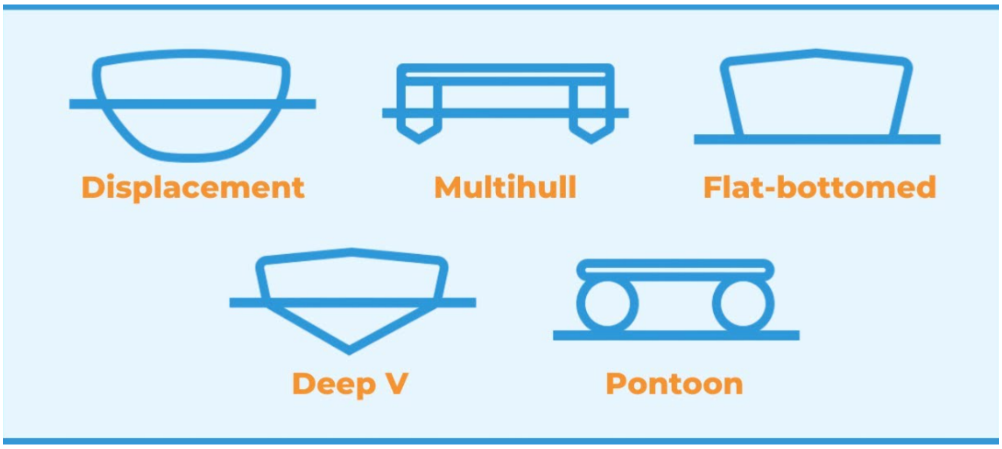


Figure 2.1: Comparison of hull geometries.

2.3 Structural Loads and Stresses in Marine Environments

The marine vessels have to deal with a lot of forces while traveling in the sea, which include hydrostatic pressure from the surrounding water, shifting wave loads, wind, heat, impact, and mechanical vibrations. All these factors have to be addressed to make sure the vessel holds up structurally and how reliably it operates.

The deeper the ship went, the higher the hydrostatic pressure.[13] It required consideration in both material selection and design since it operates steadily on the hull. It was harder to predict the waves. Particularly in the centre of the ship, they resulted in bending and twisting, and this constant strain frequently caused weariness. Furthermore, additional pressure was added by wind and current, increasing the overall weight that the structure had to support.

Further, there are some sudden forces, like when a vessel hits floating debris or during hard docking. These didn't spread out evenly but hit one area hard. That's why certain sections of the hull were reinforced—to absorb that shock. Temperature variations were also significant. As ships moved through warm and cold waters, certain parts of the structure expanded and contracted. Misalignment or increased internal stress could result from improper handling of that.

There were numerous sources of vibration, including gearboxes, engines, pumps, and even the waves slapping the hull. These vibrations could cause long-term damage as the items moved throughout the ship, especially in places where they were bolted or welded. Because it interfered with the natural frequencies of onboard equipment, like battery modules, frequencies often fell between 5 and 1500 Hz, which led to problems. These include:

- **Longitudinal stress** from wave patterns—causing hogging (upward bending) or sagging (downward bending).
- **Transverse stress** across the hull due to internal and external forces.

- **Local stress** from heavy machinery or localized vibrations.

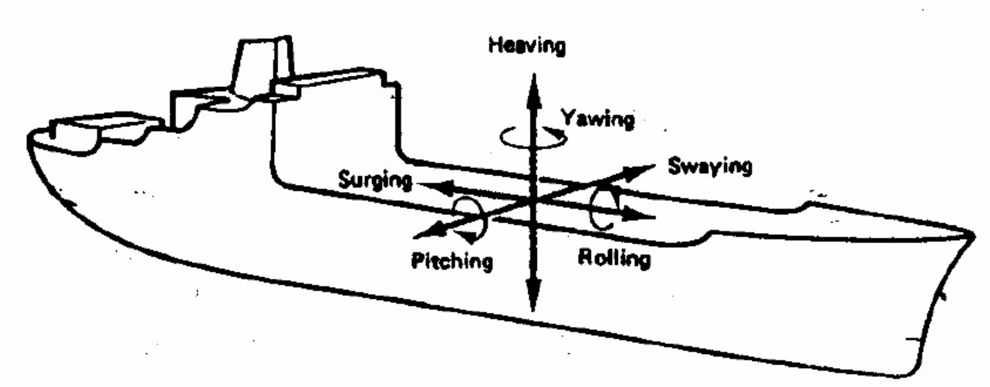


Figure 2.2: Dynamic forces acting on a Ship

Vessels in motion have six degrees of freedom: rolling, pitching, and yawing (rotational); and surging, swaying, and heaving (linear) as shown in the Figure 2.2. Dynamic forces are amplified by large amplitude motions, which can also cause slamming (forceful re-entry into the water) and panting (repeated hull flexing at the bow). It is necessary to secure containers, including those that house ESS units, against these movements. Accelerations are up to 0.8g laterally and 1g vertically. They may result in fatigue failures, container deformation, or component misalignment if improperly handled. As a result, knowing these structural loads is essential for protecting delicate subsystems as well as for hull design. In marine electrification, where battery modules must maintain mechanical stability under intricate and fluctuating loading conditions, this is especially crucial.[14]

2.4 Effects of Vibration and Shock on Battery Performance

In marine and industrial environments, battery systems aren't just stable. They're constantly exposed to wave-induced motion and engine vibration. All of this puts mechanical stress on energy storage systems (ESS). Over time, those forces start to add up. Inside a battery cell, repeated vibrations can wear down components. Electrodes may crack. Separators can deform. Once that happens, internal resistance goes up, and performance starts to drop. In some cases, things can get worse, delaminated electrodes or internal shorts. Cylindrical cells are particularly prone to these problems. Unlike pouch cells, they have more internal structure that can come loose—mandrel, CID, and other safety features included. What's tricky is that these issues often don't show on the outside. A cell can look fine but still be damaged inside, so a Micro-CT scan in Figure 2.3 illustrates the bus bar deformation.[15]

There's also the issue of how vibration affects the rest of the pack. Connections and welds can weaken. Electrolytes might shift inside the cell. Terminals can fail if subjected to constant stress. Most battery tests don't even catch these problems because they're usually done at lower frequencies—under 10 Hz. But in real use, especially on ships or heavy industrial platforms, vibrations can exceed 300 Hz. Drives, compressors, and powertrains all contribute to that.[16]

To manage it all, companies are integrating vibration-damping mounts, reinforcing cell bonding, and adding better sensors through BMS. There's also more emphasis on testing. SAE J2380, for example, puts battery packs through multi-axial vibration tests using shaker tables based on real shipboard conditions using Power Spectral Density (PSD) curves that represent actual shipboard vibration frequencies and amplitudes. It helps make sure batteries won't just survive on paper—but hold up in the field. Compliance with SAE J2380 ensures that ESS can endure continuous vibration exposure without mechanical degradation, connector failures, or compromised operational safety.[17]

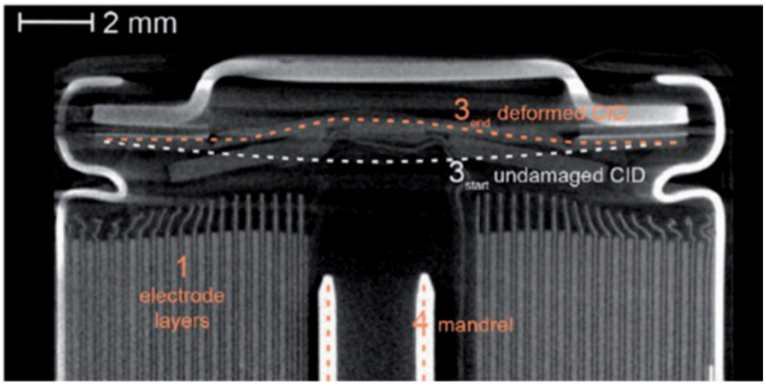


Figure 2.3: Deformed 18650 cylindrical lithium-ion cell after 300 shocks in z-direction according to UN 38.3 T4 standard, visible in mCT image.35

2.5 Safety Standards and Regulatory Compliance for Marine ESS

The installation of Energy Storage Systems (ESSs) on ships falls under the tight international regulations that cover the design, installation, and operating procedures of such equipment. The general regulatory scheme lies with the International Convention for the Safety of Life at Sea (SOLAS), which sets the mandatory criteria for the design of ships and equipment on board to protect the health of the crew and passengers. To reduce the likelihood of thermal runaway and electrical faults, SOLAS requires that Energy Storage Systems (ESS) be equipped with fire suppression mechanisms, flame-retardant materials, appropriate ventilation strategies, and emergency shutdown capabilities. These measures were intended to ensure that any onboard energy system remained stable and contained, even under abnormal conditions.

In the absence of finalized IMO regulations tailored for Battery Energy Storage Systems (BESS), organizations such as Det Norske Veritas (DNV) and the European Maritime Safety Agency (EMSA) took the lead in shaping safety practices for marine battery installations.[18] Their guidelines addressed both the operational risks and mechanical demands faced by lithium-ion battery systems on board.

DNV's Handbook for Maritime and Offshore Battery Systems provided a comprehensive set of criteria aimed at improving mechanical safety. It included provisions for protecting systems from ship movement, minimizing vibration impact, securing enclosures structurally, and requiring Battery Management Systems (BMS) for real-time performance monitoring. These measures were intended to maintain battery integrity in dynamic marine environments.

Classification Society	Document ID
RINA[19]	Rules for the Certification, Installation and Testing of Lithium Based Storage Batteries, June 2016.
RINA[20]	RINA Rules for the Classification of Ships, Part C Machinery, Systems and Fire Protection, January 2019.
LR[21]	Battery installations – Key hazards to consider and Lloyd's Register's approach to approval, Lloyd's Register Guidance Note, 2nd ed., January 2016.
LR[22]	Rules and Regulations for the Classification of Ships, July 2022.
DNV[23]	Ships - Additional class notations, Chapter 2 Propulsion and Auxiliary Systems, July 2020.
BV[24]	Rules for Classification of Steel Ships - Part F, NR 467.F1 DT R12 E, Jan 2020.
ABS[25]	Guide For Use of Lithium Batteries in Marine and Offshore Industries, Feb 2020.

Table 2.1: Summary of classification society guidelines relevant to marine lithium-ion battery installations

Around the same time, EMSA released its Guidance on the Safety of Battery Energy Storage Systems on Board Ships (2023), offering further direction on system layout, emergency response, and failure mitigation.[26] The report emphasized the need for effective thermal control, proper isolation between battery modules, reliable pressure relief mechanisms, and housing units rated at least IP44 for ingress protection. It also recommended that mounting structures be robust enough to tolerate the continual motion experienced at sea.

Though the documents differed in style, both DNV and EMSA focused on the same critical issues: fire prevention, mechanical durability, and overall system resilience. Their combined efforts provided shipbuilders and operators with practical frameworks for installing safe and reliable battery systems in marine applications, especially in a period where international guidance remained in development.[18] Various classification societies, including ABS, DNV, LR, and RINA, provide detailed technical guidelines for the safe installation and certification of lithium-ion battery systems on ships (see Table 2.1). In parallel, fire safety strategies, such as those discussed in [27], offer insights into thermal event prevention and suppression tailored for marine ESS environments.

2.6 Review of Vibration Damping Technologies

There are several unique challenges when trying to control vibration in the sea due to the several dynamic and unpredictable forces while a vessel is operated. The effect caused by these factors is especially pronounced when it comes to vibration-damping technologies used in Battery Energy Storage Systems (ESS) in electrified marine propulsion. The presented review is focused on the basic principles of vibration damping, performance parameters, and the importance of the isolator technologies in the severe conditions of the marine environment [3].

Vibration isolation systems are designed to achieve the intended goal of isolating the excitation source from the sensitive mass or structure. The elastomeric materials, mechanical springs or composite systems that incorporate damping and compliance are mechanisms that are used to achieve this intended goal. There are systems performance characterizing parameters of natural frequency, damping ratio, transmissibility and isolation efficiency. Of these parameters, the transmissibility plays the most crucial role in the design, showing the amount of the vibration input that is transmitted to the protected structure over a wide range of excitation frequencies. An ideal isolation system would show high damping above its natural frequency and would have a flat response within the working range [4].

In this case, different isolator technologies have been researched and assessed for use in marine batteries. Wire rope isolators provide excellent shock and vibration isolation with coil stainless steel cable flexure. Additionally, wire rope isolators have extreme load capacities, multi-axis compliance, and resistance to corrosion, which makes them ideal for marine use. Hydro mounts, in comparison, provide vibration and dynamic load attenuation through a combination of hydraulic damping and elastomeric flexibility, which is effective for low-frequency hydrodynamic pressures. ISAs, which incorporate rubber/metal bonding and have been used in automotive for a long time, will offer low-cost isolation of marine batteries; however, they will not survive in salt water for a reasonable time unless properly encapsulated [28].

As the above paragraph describes, there will have to be a reasonable compromise in vibration-absorbing technology to be used for marine batteries for the environmentally driven, performance-driven, and packaging-driven demands of the market. The identified concepts isolators in the above paragraph will provide the optimal vibration isolation needed and will comply with the structural and environmental requirements needed for Volvo Penta next next-generation electrification marine sites [29].

3
Research Methodology

3.1 Methodology

This chapter described the design and research systematic integration on the ground work vibration isolator system for marine batteries. It started from the integration of design methods which included the use of the *Black Box* method, *Function Decomposition Tree*, *Morphological Matrix* and *Pugh Matrix*. They all aided in functional breakdown, design creativity, and the selection of the design concept. An elaborate market study on trends in the marine and automotive suspension systems market was carried out, focusing on the demand for vibration-damping in electrified systems. With the target market study for vibration isolator, key application areas in construction, industrial, and marine sectors were identified and the innovations were inter-industry transferable. An analysis on vibration isolator suppliers such as AMC Mecanocaucho, Trelleborg and Vibratec offered insights on the current technology applicable to the marine environment. Customer needs analysis and patent analysis were performed to formulate the design requirements and the innovation gaps. These analyses formed the basis for the concept generation and assessment for the marine battery suspension system.

3.1.1 Black box

The *Black Box* technique helped in the capture of the main inputs and expected outputs of the system while avoiding unnecessary internal design decisions and concentrating on the functional requirements. It played a good role in defining the objectives of the projects and improving communication within the team. The Black Box approach is the abstraction in the definition and design of systems, components, or processes, where only the inputs, outputs, and functions are described and everything else about the inner workings of the system is omitted. This strategy allows designers to concentrate on the objectives and outcomes of a design while ignoring the intricate means of achieving those objectives, thus helping them to capture or advance the initial stages of a design. Ignoring internal details allows for more streamlined communication on what is truly needed, aiding cross-discipline collaboration, more open-ended design exploration, defined limits on technical implementations, and clearer expectations on functions [30].

3.1.2 Function Decomposition Tree

Focusing on the project as a whole, the *Function Decomposition Tree* is used to progressively divide the system's major functions into simpler, smaller sub-functions, which enhances cross-disciplinary clarity and collaboration. It assisted in the combination of different alternative concepts that were created in the later design phases. A Function Decomposition Tree is a tool within the design methodology that enables function allocation within a complex system to its constituent manageable sub-functions. These breakdowns are visualized hierarchically to foster a designer's understanding of the goals versus the underlying intricate work to be done for any system. The Function Decomposition Tree is also capable of guiding function decomposition sequentially and facilitates orderly thinking around the problem definition, supporting the design needs, and crafting numerous alternative designs for each sub-function. FDT helps in collaboration within cross-disciplinary groups by establishing a common understanding of how various components of the system converge to yield the desired product performance.[31]

3.1.3 Morphological Matrix

The project utilized the *Morphological Matrix* to identify and incorporate different options for each self-function of the suspension system for the scope of the project in support of the fostering of creativity and the functional requirements for the project within the scope. This allowed the generation of and the opportunity for the team to evaluate varying design configurations. An example of the Morphological Matrix is a design table that deconstructs a system into its constituent sub-functions and for each one lists a set of possible solutions. Working with the designer's combinations makes it possible to evaluate a broad system configuration within and for trade-off selection to establish the most advantageous configurations for advancement to the next phase of the design process. This approach guarantees that the functional demands are completely addressed, new solutions are formulated, and a coherent approach is taken in complex product design projects.[32]

3.1.4 Pugh Matrix

In order to conduct systematic evaluation and comparison of all design alternatives of the suspension system, relative to the criteria defined and target the most promising concept, *Pugh Matrix* appeared very useful for deciding design alternatives for the suspension system which concept of which gained the most priority. In this example, the system of ordering the designs, which ranged the most from the objectives of the project, their performance, and their feasibility, was the most useful. A *Pugh Matrix*, is a systematic design methodology that dissects and ranks a concept or design from the rest of the alternatives by comparing the concept to a defined target design or a baseline design. Each alternative is scored corresponding to the baseline, which enables designers to optimize the entire design by knowing the strengths, weaknesses, and the most optimal design. Custom-made designs are made possible due to the rational evaluation range of the Pugh decision matrix. It ensures that the evaluation is consistent and the selected design satisfies all functional needs of the project.[33]

3.2 Market Analysis

The evolution of the marine battery market is bolstered by technological advancements and development in the battery sector, as well as policies, increasing fuel prices, and a turn toward electric and hybrid propulsion systems in the marine industry. Safety, energy efficiency, and effectiveness of deployment are all experiencing the benefits of advancements in lithium-ion and dual-use batteries. In addition, growing funds and the modernization of marine energy storage systems are propelling the market towards boundary-less development.[34]

Currently valued at over 882 million USD, the battery industry is predicted to grow at a CAGR of 9.3 to 16.5%, potentially reaching 1.5 to 1.66 billion USD in 2030. The growth is attributed to increased operational costs, hybrid vessel propulsion systems, and more electric operational policies. The market is rapidly shifting towards more environmentally friendly policies, which has accrued funds for research and development of long-lasting marine lithium-based batteries.[35]

The expansion of the global battery suspension system for electric vehicles continues to grow rapidly due to the increased electrification of the automotive sector, the demand for comfort in the active suspension system, and the advancements in active suspension technologies. EVs' specialized suspension systems are required to optimize the ride with heavy battery packs and performance, along with the progressing AVs and CVs. The market for EV suspension systems was around 4.5 billion dollars in 2024 and is expected to reach around 12 billion dollars in 2034, which implies a CAGR of approximately 11. 3% over that period. This emphasizes the market now focuses on a more adaptive design that increases vehicle dynamics, boosts battery range, and integrates systemic sophistication to every vehicle.[36]

To design an effective vibration isolation system for battery energy storage systems (BESS) in marine environments, it is essential to understand the regulatory standards that govern vibration measurement and evaluation onboard ships.A systematic literature review was conducted to explore the mechanical behavior of shipborne equipment under dynamic loading conditions, emphasizing the relevance of concepts such as natural frequency, damping ratio, transmissibility, and resonance. Particular focus is given to the dynamic response of mounted systems across varying frequency domains, including amplification, critical transition, and isolation regions knowledge essential for developing an effective vibration mitigation strategy.Although the standard primarily addresses vibration from the perspective of human comfort and safety, its framework offers valuable insight into the types of vibrational phenomena that also affect mounted systems, such as electrical enclosures and battery modules.

3.2.1 Target Market

To address the problem of vibration in marine battery packs, the focus of the target market is on identifying suitable vibration isolators and dampers that can be integrated into the final design. The primary purpose of an isolator to refers to a device or a piece of material strategically placed in between a source of vibration (a machine, for instance) as well as the support structure in a bid to mitigate vibration transmission. It diminishes the intensity of the isolation. The Isolator has elasticity at the node for the forces in the structure. Isolators dampers vibration freely at time of release cycles and cushion structural elements and equipment against impact/ shocks.[37]
Target market starts with a study of relevant performance parameters of various types of isolators, along with their iso-filters, and their pros and cons. This involves investigating different manufacturers, suppliers, and providers of techno-vibration control solutions for industrial and marine use. 2.1The marine and energy storage market will, however, first require competition benchmarking, patent reviews, and the mapping of currently available solutions.

All the suppliers will be evaluated by the technical parameters along with the criteria of ease and the degree of serviceability of the mounted battery pack, product configuration diversity, and the required modification. Market analysis is expected to result in a compiled database of companies and dealers with relevant isolators and dampers solutions associated with marine and battery applications. This will facilitate the focus on subcomponents of the project where sophisticated components are already available for design and testing. These vendor and market studies will be complemented by a thorough analysis of the user needs and priorities, and the subsequent analysis of the specification requirements. This multi-step process will help define the following design and development stages.

To find the best approaches to vibration isolation for use in marine batteries, a cross-spectrum of different industries was required for vibration isolators. This was to ensure as many potential use case scenarios as possible were included, in which effective vibrational control additionally optimizes the equipment in its performance, safety, user comfort, and compliance with regulatory standards. In the major industrial domains of construction, manufacture, transportation and electronics, a great depth of understanding of these technologies.

3.2.1.1 Construction and Architecture

The architecture and construction industries serve as a major positive market for vibration isolators which are implemented extensively in the separation of noise and vibrations from the HVAC, mechanical and structural elements of tall towers, commercial and domestic buildings. This is because of the stringent regulations on the noise and safety of the structure. Also, the urbanization and vertical constructing has emphasized on the comfort of the tenant, the durability of the structure and the compliance of the ever-changing environmental regulations. New age smart isolators and advanced materials integration on acoustic panels increases the functionality and flexibility of modern designs. [38]This integration is a boon for the modern designs as it increases the functional performance.Also, base isolators in buildings designed to withstand earthquakes are formulated to ‘soak up’ massive shifts and shocks, principles that can be ‘plugged’ into marine battery mounts that cater to wave-induced motions.Smooth elastomeric pads and tuned mass dampers that sit in skyscrapers for the reduction of structural sway, give pointers to scalable vibration management appliances that are applicable to heavy marine energy storage systems.[39]

3.2.1.2 Industrial and Manufacturing

Vibration isolators or acoustic panels are essential in the protection of sensitive industrial and manufacturing machinery. Misalignment, mechanical wear, and disruption in vibration cycle can cause damages or even total failure of the machinery and components. By minimizing the vibration transmission and structural isolators, the equipment life is enhanced, the noise in the workplace is controlled and the quality of production is increased which enhances workplace safety. [40]This is notably true for the heavy machinery in the extreme operating conditions where the controlled vibrations can boost productivity and safety.Additionally, spring and wire rope isolators employed in rotating machines and compressors to lessen the resonance effect afford a pathway for use in systems of marine propulsion. Active vibration control systems mounted in precision manufacturing lines present a backward compatible topic that could be pursued in marine systems requiring fine tolerance and lower fatigue on electrical joints. [41]

3.2.1.3 Transportation

Isolation mounts are needed for passenger and equipment comfort for all modes of transport including rail, auto, marine, and aerospace. Isolators in rail systems, for example, reduce vibrations and structural damage while improving the passenger experience. In aerospace and automotive, isolators improve control system precision while NVH levels decrease. The marine environment has a unique isolator problem that requires rugged isolators that protect equipment and operational stability.[42]In railways, isolators mounted on bogies and pads designed to lessen impact manage both vertical and horizontal forces of self propulsion give a straightforward comparison to how marine battery enclosures manage multi-directional vibration inputs. In the aerospace, lightweight, high-damping composites are used to lessen the impact of vibrations while adding minimal weight, an important concept for the isolation of battery packs with weight restrictions.[43]

3.2.1.4 Electronic Industries

In the electronics industry, vibration isolators are essential for the protection of the system and instrument from the damaging effects of structural and ambient vibration. When sensitive equipment is exposed to vibrations, the signals become distorted, the accuracy of the measurement drops, and in several cases, a precision-operated system may malfunction.[44] Such cases are best illustrated by laboratories, data centers, and production units where the slightest vibration can cause an operational issue.As an example, optical benches and semiconductor fabs rely on pneumatic and elastomeric isolators to attain vibration stability on the order of nanometers, which underscores the necessity of effective damping of the sensitive electronics in battery management systems (BMS).In the same way, server racks in data centers employ rack-mounted dampers to diminish the vibration-induced failures of hard drives and sensors, teaching lessons on the safeguarding of marine battery electronics such as BMS controllers and power conversion modules. [45]

3.2.1.5 Marine Industry

Because of the intertwining effects of wave motion, hull vibration, and excitations resulting propulsion, the marine sector is also the most demanding for vibration isolators. Battery segments and electric systems, onboard, are particularly exposed to the negative impacts of resonance, such as structural fatigue, loosening of bus-bars, and failing electronic sensors. Not only are isolators in this industry needed to absorb multi-directional dynamic loads, but also to endure long-term exposures to humid, fluctuating temperatures in salt water. According to the classification of DNV in 2021, hydromounts, resilient mounts, and wire rope isolators are used in marine engines, generators, and propulsion systems to control the vibration caused by the rotating and engine equipment to the hull.[46] Wired isolators, because of their reliability as compared to fluid mounts, are often used in naval and offshore systems where wire isolators are fail fail-safe. Isolators are more dependable than fluid-based mounts because they still maintain support even if partially damaged. In these passenger vessels, as reported in 2022 by the American Bureau of Shipping, Acoustic and anti-vibration mounts are intended to overlap and are used for the added purpose of improving comfort through noise and vibration reduction. In commercial shipping, the major focus is working with the regulations and standards such as DNV-GL, IMO, and SOLAS which the vessel needs to be compliant. Unlike the other sectors, this one provides better and more relevant benchmarks. The other ones is engine electronic systems, and propulsion systems isolation systems in marine are similar to the needs of marine battery packs.[47]

3.2.1.6 Market Suppliers

During this market assessment, potential suppliers of vibration isolation technologies, each offering unique vibration isolation technologies for the suspension systems for batteries for marine applications, were identified. AMC Mecanocaucho manufactures a wide variety of hydraulic and elastomeric mounts, including Cone/MD, BRB, and BSB series mounts, which for vibration and shock control in marine and engine applications [48]. Also, Vibratec develops hydraulic and elastomeric isolators for engines and batteries, including heavy-duty marine and propulsion applications and provides customized works for naval and offshore markets [49]. Isoflex aims at the elastomeric and hydraulic mounts for the marine dampers and suspension systems and so the marine dampers and suspension systems ares of high interest for the energy storage modules of ships [28]. Also, Trelleborg (Novibra/Metacone) provides elastic cones, bushings and mounts with a wide range of marine variants for the reduction of hull-borne vibration [50]. Hutchinson Paulstra / Barry Controls manufactures hydro-elastic mounts which strongly damp structural and propulsion vibration, functioning as a key frame of reference in naval technology. [51]

Another notable supplier group includes firms such as Christie and Grey, Rubber Design (NL), GMT Rubber-Metal, Mackay Consolidated, and AV Industrial Products (UK). Christie and Grey supply resilient mounts and turnkey systems for marine and industrial applications [52]. Rubber Design focuses on marine resilient mounts and is well known for engine and propulsion system isolation for the harsh seals [53]. GMT Rubber-Metal offers a wide variety of products for engine and battery mounts with unique custom elastomeric mounts for tough damping interface conditions [54]. Mackay Consolidated offers bonded rubber-metal mounts that are highly regarded for their wide availability and engineering expertise in naval and industrial applications[55]. AV Industrial Products (UK) supplies marine mounts of anti-vibration devices for battery enclosures and electronic isolation providing systems compliant with EU/UK treaties for marine applications [56]. VETUS also forwards the segment to include hydraulic and elastomeric mounts for small to medium craft battery and propulsion isolation [57].

A third vendor cluster offers highly specialized rope isolator and air-spring solutions. ITT Enidine focuses on the WR series rope isolators and integrated shock control. They offer design assistance for military and marine applications with high strains and shock control [58]. Socitec / IDC has combined wire-rope and elastomer isolators and integrated shock and vibration analysis. They are well-suited for isolating battery modules under variable load conditions (Socitec,IDC). Mason Industries and ACE Controls offer more compact wire-rope isolators and compact enclosed spring isolators, marine elastomer isolators, and battery platform solutions (Mason Industries, ACE Controls)[59]. Similarly, Vibrostop (Italy) offers marine-certified rope and elastomer isolators with auxiliary and propulsion isolation and docking systems [60]. Also, high-performance structural damping and control isolators for naval applications are provided by Getzner (Sylodyn) with resonance control pads and isolating air-spring products [61]. Other major contributory vendors are Fabreeka, Kinetics Noise Control, AirLoc / Firestone / ContiTech with structural spring-rubber isolators, air-damping springs and ultra-soft dampers for battery systems (Fabreeka, Kinetics, AirLoc, Firestone, ContiTech)[62]. Ultimately, VULKAN provides coupling and support isolation systems focused on propulsion integration and NVH (noise-vibration-harshness) control for marine applications, which directly supports battery-pack suspension development [63].

3.2.2 Customer and User Needs

When determining the type of suspension system to implement, it is important to first understand the needs and expectations surrounding the system. Knowing these needs and expectations helps in setting design performance measures that are reliable, safe, and operationally viable. Within engineering practice, this is often described as converting customer needs and user needs into workable technical specifications.

S.No	Requirement	Priority
1	**Vibration absorption** – Must absorb vibrations in the 5–1000 Hz range and minimize transmission to the battery pack.	4
2	**Structural integration** – Must fit seamlessly with the battery housing and overall marine frame design.	9
3	**Controlled damping** – Must provide damping to reduce shock loads and extend fatigue life of joints and bus-bars.	2
4	**Compliance** – Must satisfy SOLAS, IMO, and DNV vibration and safety standards.	7
5	**Corrosion resistance** – Materials must resist saltwater, humidity, and temperature variations.	1
6	**Maintainability** – Isolators must be easy to install, inspect, and replace with minimal downtime.	10
7	**Cooling compatibility** – Suspension design should not obstruct airflow or liquid cooling channels.	3
8	**Weight efficiency** – Structure should support loads without adding excessive mass.	6
9	**Reliability** – Design should remain fail-safe even if individual isolators degrade.	8
10	**Compactness** – Should occupy minimal space to suit tight marine enclosures.	5

Table 3.1: Functional Requirements with Priorities (Randomized)

Focused on integrating functionality whilst seeking to enhance vibration performance and meeting all marine industry standards. Scale for prioritizing requirements starts from 1-10, with 1 as the highest and 10 as the lowest. See Table 3.2.2 for all the requirements with the corresponding prioritization.Customer needs often are the more generalized requests of the system, which may include the system to be economically viable, durable, and to comply with industry standards. User needs revolve more around the system's installed, maintainable, and operational performance. With regards to the suspension system, specific needs such as vibration isolation, accommodating compressive and tensile loads, agility to different frequency ranges, and serviceability must be taken into account. Addressing those needs and demands systemically guides the selection of a reliable system.

3.2.3 Patent Analysis

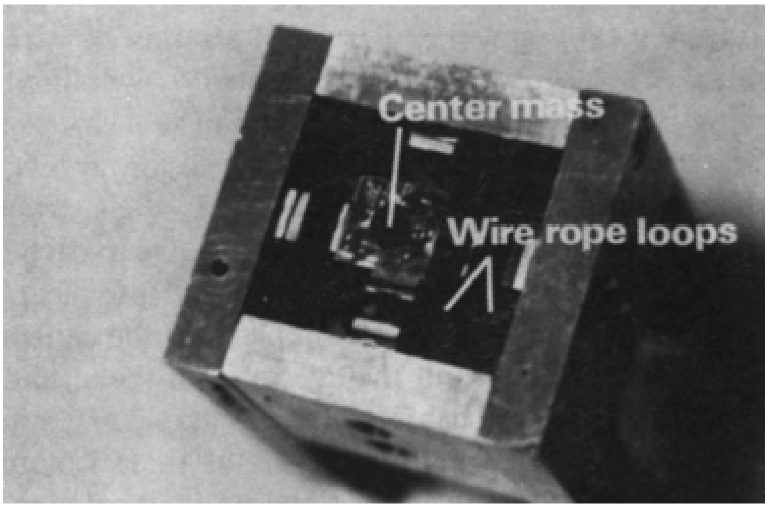


Figure 3.1: Wire Rope Isolator Model

The patent, "Damping Phenomena in a Wire Rope Vibration Isolation System", from the Journal of Sound and Vibration in 1992, where Tinker and Cutchins focus on the significant engineering and mechanical characteristics of helical wire rope isolators. They derived key damping features from static curves, hysteresis loops, phase trajectories, and the response functions of different frequencies. Within the experimental framework, by the analysis of the curves, stiffness, and other functions, the authors of the article came up with damping mechanisms which include nonlinear stiffness, at power velocity damping, and Coulomb friction drying. To carry through with a semi-empirical model, the authors coupled the system with thermal feeling and friction. The model, which was derived from experimental results, was also proved the other way about. This type of evidence, which is abundant in the analysis of wire rope isolators, sets the bar apart from elastomeric and fluid dampers. It patent analysis refers to the intrinsic properties and energy dissipated and mechanical behavior of wire rope isolators, which is supported by other evidence. It therefore describes the technical innovation and merit, which the author proposes is centered on the stratified friction and nonlinear dynamic response.[64]

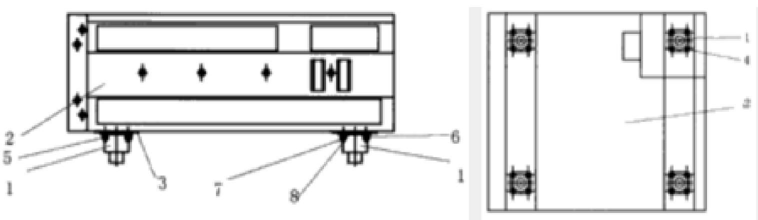


Figure 3.2: Marine Computed Damper Patent with Metal Cusion

The works of Javanmardi et al. (2020) focus extensively on the metallic dampers and their development, assessment, and application. The dampers are intricately classified, subdivided into steel, aluminum, lead, copper, and shape-memory alloys. The authors also mention the merits of the dampers, among which are low fabrication price, uniform hysteresis behavior, temperature tolerance, dependability, and high-energy dissipation ability. Among the dampers, mild steel is the most popular due to its price.[65]

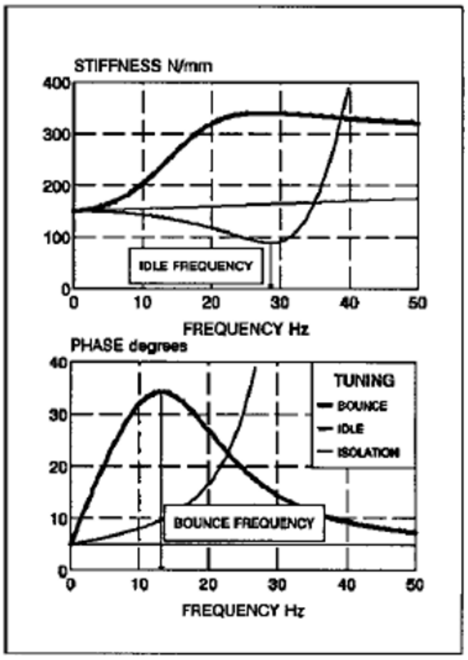


Figure 3.3: Different optimal tunings of a hydraulic engine mount

Metallic dampers have technical improvements and notable benefits compared to conventional elastomeric and fluid dampers. The granular descriptions of the materials and the mechanisms of damping mechanisms articulate the novelty and non-obviousness of certain technologies, e.g. how wire rope isolators or hybrid technologies could be considered inventive with respect to the materials used, hysteresis modeling, and application tailored engineering. The coupling of their insights constitutes a strong basis to market the isolator patens for marine batteries which derive the specific damping features tailored to the designed hybrid marine batteries.[65]

In his 1993 SAE technical research paper, “Research for New Vibration Isolation Techniques: From Hydro-Mounts to Active Mounts,” Gennesseaux deals with first-of-a-kind research in the technique of moving from passive hydraulic mounts to adaptive, active vibration isolation systems. He demonstrates the way in which active mounts, with built-in sensors, actuators, and feedback control, adapt to a range of vibration profiles, “flying” fluid mounts for the major deficiencies of fluid mounts: resonance insensitivity and high transmission at certain frequencies. This fundamental research justifies the patent claims of novel configurations with feedback control, real-time active adjustment of member stiffness, and meshed formation for vibration isolation, with central control systems. Such configurations rest on the emphasis provided in the control-intelligence systems, which separate the statement constructions from mounting in passive systems, providing high value for the patent ability of marine active or adaptive battery isolator systems.[66]

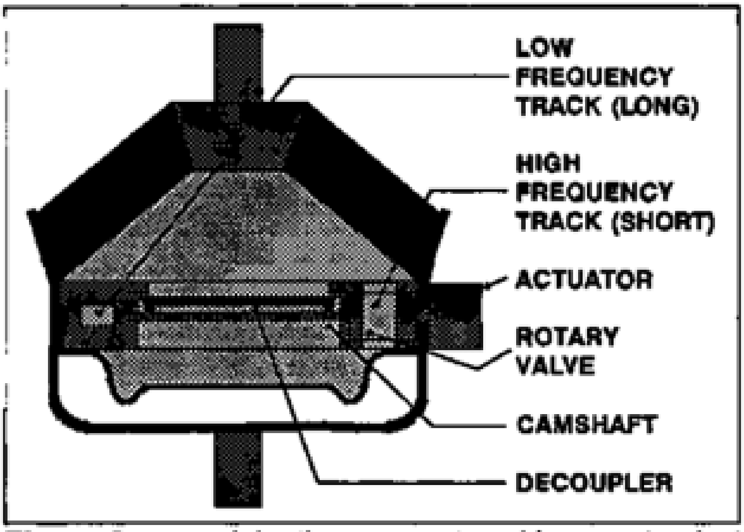


Figure 6 Adaptive mount with mechanical actuation.

Figure 3.4: Adaptive Mount with Mechanical Actuation

The innovation behind adaptive hydromounts lies in their ability to real-time change stiffness and damping characteristics to overcome the disadvantages of passive systems. Once mechanical actuation systems, such as electromagnetic and vacuum-driven systems, are integrated, the mounts are capable of switching different inertia tracks, and adaptive isolators can cater to differing conditions. For example, a long inertia track is typically needed for low-frequency vibrations such as engine bounce, while a short track is needed for attenuation of high-frequency excitations at idle. This dual-track system architecture gives adaptive hydromounts versatility, providing robust isolation over a wider range of frequencies. Operational stability in harsh environments is further enhanced by smart-fluid-based actuation, such as Electro-Viscous Fluids (EVFs) and Ferro Fluids, which change damping properties with an electric field and enhance damping with a magnetic field. Controlling the stability, viscosity, and adaptability of the fluid is an open problem, and the lack of a solution doesn't diminish the promise smart adaptive technologies hold for marine vibration isolation systems.

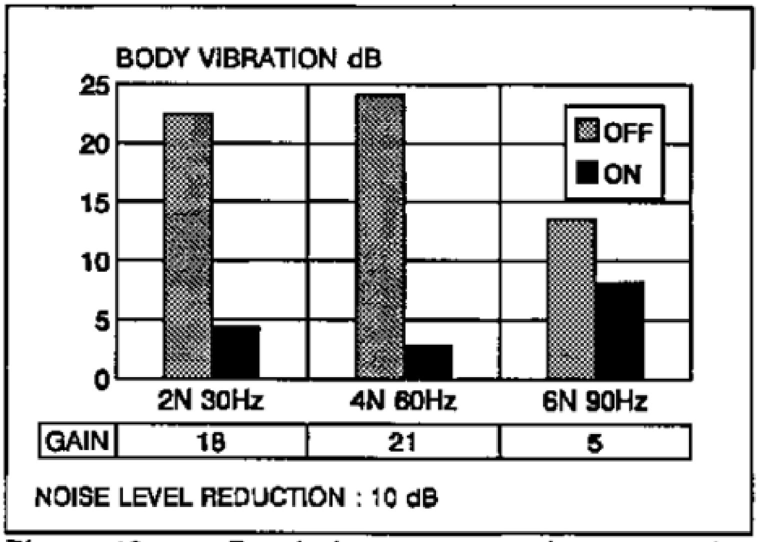


Figure 10 Proof of concept experiment : results.

Figure 3.5: Proof Of Concept

Active hydromount systems take the principles of adaptive mounts even further by adding the capability of detecting and countering with anti-vibration forces thanks to the addition of sensors, actuators, and controllers. Active isolation detects unwanted vibrations and counteracts them by creating secondary vibrations that cancel them out through interference. In the proof-of-concept study, active cancellation was proven effective with reductions of up to 20 dB in engine-induced vibrations around 30 Hz using an electrodynamic shaker. Working with size, cost, and practicality constraints, initial phases of the project incorporated actuators such as the variable reluctance motor, which proved to be compact, effective, and economical. Such systems in marine battery packs have the potential to actively suppress broadband wave-induced vibrations and high local structural resonances, thus protecting sensitive components.

Another relevant contribution includes the robust optimization and design of Adaptive Hydraulic Engine Mounts (AHEMs) focused on improving vibration isolation without the use of external energy devices. Rational changes in the size and cross-sectional area of inertial channels can provide mounts with designed dynamic behavior over a wideband (0–250 Hz) frequency range. In practice, AHEMs were shown to enhance vibration isolation performance nearly 20 % over conventional hydraulic mounts. Moreover, robust optimization minimized the likelihood of performance degradation due to uncertainty in the manufacturing, aging of materials, or installation of the AHEMs. This degree of robustness is especially important for marine applications, where reliability and the absence of failures in variable conditions is critical.

All patents and technical studies, taken in their entirety, show the evolution from passive vibration isolation systems to systems with adaptive and active components. Every new generation of system inventions brought in new materials, methods of actuation and optimization, and other devices and techniques for vibration attenuation over a broad frequency range. These, along with addressed durability and dynamic adaptability, offer a novel approach to the problem of marine-battery structures.

3.3 Concept Generation

This chapter explained the systematic method applied for concept generation for the design of a marine battery pack vibration isolator. Beginning with the Black Box model, the system's inputs hull and wave induced vibrations and outputs focused on diminishing loads and enhancing connection reliability. Following this, the Function Decomposition Tree was utilized to further divide the overarching system goal into primary sub-functions namely vibration absorption, shock resistance, marine environmental adaptability, and simplification of maintenance. In order to investigate possible design solutions, a Morphological Matrix was constructed, offering several design alternatives for various sub-functions including: wire rope isolators, adaptive hydraulic dampers, and quick release mounting mechanisms. The organized approach facilitated the design of multiple concept combinations, which were then screened on the basis of marine safety, manufacturability, and integration, forming the basis of the next stage in concept evaluation and selection.

3.3.1 Black Box

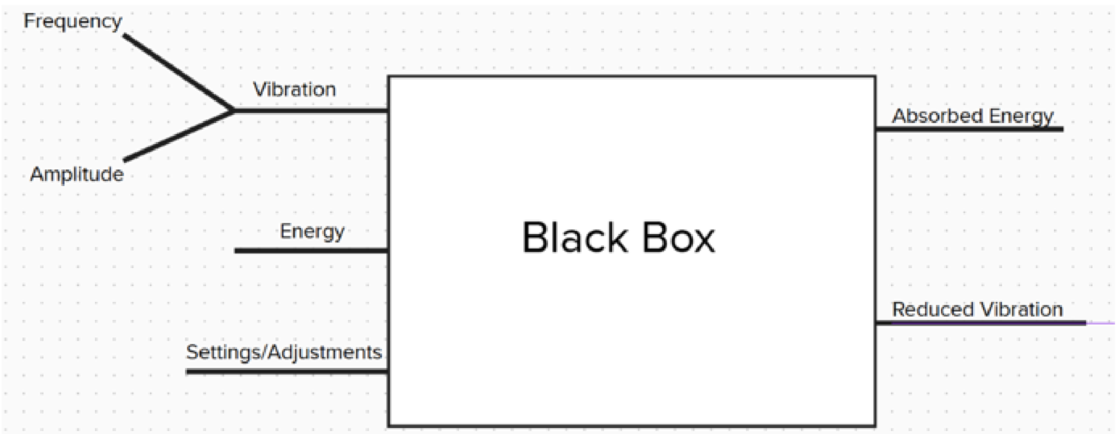


Figure 3.6: Black Box Diagram

A model black box was created to abstractly describe the operational limits of the proposed marine battery pack vibration isolator subsystem. The system inputs will be the vibrating characteristics of the wave and hull of a marine vehicle, externally excited wave, and propulsion system. In addition, the system inputs are the vibration isolators themselves, which, due to design parameters, can be 'set' in a given configuration, as well as the control and tuning mechanisms that govern the system operationally. The outputs of the system serve to perform two primary functions. The primary subsystem would be to capture and absorb a part of the system's incoming energy that enters through the damping mechanisms in order to reduce transmission of harmful loads. This drastically correlates to the amount of vibration amplitude reduction, thereby improving the reliability of the mechanical and electrical connections in the battery pack.

This approach to the abstract box metaphorically 'closes' the box in which the model is constrained to achieve the objectives of the thesis. This is to design a suspension system that a marine domain vibration isolater is capable of damped compliance with marine safety standards. It emphasizes the need for simultaneous energy absorption with vibration control in turn shaped the subsequent generation and evaluation of design concepts.

3.3.2 Function Decomposition Tree

Beyond the black box, a Function Decomposition Tree was constructed to functionally describe and systematically break down the operational goal of the battery system to carry out its work safely and stably within the marine domain, along with its subordinate objectives. The principal target breakdown structure, which anchored and drove the system focus, was mechanical structure and stability, vibration and shock absorption, shock resistance, adaptability to the marine environment, maintenance, and system and subsystem docking. These were picked as they fundamentally capture critical requirements of the suspension system project objectives and design compliance. Establishing these breakdowns and objectives was, however, challenging and not trivial, as it involved setting a balance between highly granular technical performance targets and system functional objectives. The exercise of breakdown structures, however, was important as it systemized the problem space, clarified interdependency, and streamlined and illuminated the next phase of concept generation.

3.3.3 Morphological Matrix

The Morphological Matrix was made to methodically formulate alternative solutions for sub-functions that were deemed pivotal to the expedition for the design of a marine battery suspension system. The morphological approach offers methodical aids in the conceptual design of the systems by enumerating and then integrating first-order solutions for each subsystem to formulate a full system design.

In this case, the main sub functions captured in the matrix were vibration and shock absorption and control, structural stability and light weight and compactness, ease of maintenance, active monitoring and self-diagnostics, and self-adaptation to the marine environment. For each instance, several alternative solutions were proposed and explored. For vibration absorption were wire rope isolating, adaptive hydraulic dampers, coating and dip Piezoelectric dampers, tuned mass systems, and spring–gel dampers. Structural stability was also possible with ranges from bolt-on metal rubber isolators to dual-axis shock-absorbing brackets. For ease of maintenance, quick-release mounting clamps, interchangeable spring modules, and self-locking rubber mounts were proposed.

The matrix provides a high degree of variability and a high number of potential embodiments by combining all the options available from the different sub-functions. In all, the morphological matrix that has been developed has a maximum potential of offering 2400 combinations of concepts. This is derived from a multiplication of the number of solution principles provided for each function. However, combinations that are practically achievable need to be emphasized. A good number of solutions do not function for the operational marine environment, do not comply with safety and certification regulations, and are overly complicated and expensive.

The morphological matrix was used in the design process as the starting point of ideation, as the broadest possible solutions needed to be mapped out first. A large number of possible designs were narrowed down and filtered to the most probable and relevant options with respect to compliance with the safety standards, ease of manufacture, weight and size effectiveness, and ease of integration. These concepts were developed and refined as the basis for further analysis in the next phase of concept selection.A.1

4

Concept Selection and Screening

This chapter described the critical evaluation and selection phase of the proposed marine battery suspension concepts using systematic screening and analysis. Five design concepts from wire rope isolators with silicone pads to hydro-mount based and honeycomb structural systems were developed and assessed regarding their vibration isolation capabilities, structural integrity, thermal handling, and overall marine applicability. The working principles of each concept were evaluated, along with their respective benefits and drawbacks. This was followed by a comparative analysis using the Pugh Matrix method with several datum references for the sake of impartiality. This methodical analysis contributed to identifying the most promising design elements and compromises, forming the basis for the creation of a final hybrid concept. The design achieved incorporated elements of wire rope and hydro-mount systems, which were configured to a crib-and-cage system designed to marine engineered environments to be lightweight, rugged, and enable efficient, effective vibration isolation across all six degrees of freedom.

4.1 Concept screening

The screening of concepts has profound significance for the reduction of design alternatives by focusing on rational examination and comparison of devised concepts. Concepts suspension systems of marine batteries for the sake of screening not only include the positive attributes that each has but also attempt to define the boundaries of each. The objective is to define solutions that best meet the requirements of vibration isolation functionality versus the secondary restrictions of structural strength, isolation of the element in an overheating environment, and a final element of safety in marine systems.

To aid in the identification and screening of the solution, a philosophy describing the design, the technical means, or the operation principles of each of the five concepts is tersely expressed as the metaphorical title of a feature or a mechanism befitting the philosophy. This approach in titling encourages all the members of the design teams and other contributors to understand and communicate faster, easier, and use the title to track or associate the design concept with the project goals. The screening process takes on an attitude that encourages ease of use, possible difficulties of exploitation, and correspondence to the objectives of operation.

The next parts of the report will focus on each concept separately, discussing its working principle, its merits and demerits, and its suitability for marine applications. This examination will act as the basis for selecting the concept and its subsequent elaboration in the course of the design development.

4.1.1 Concept-1

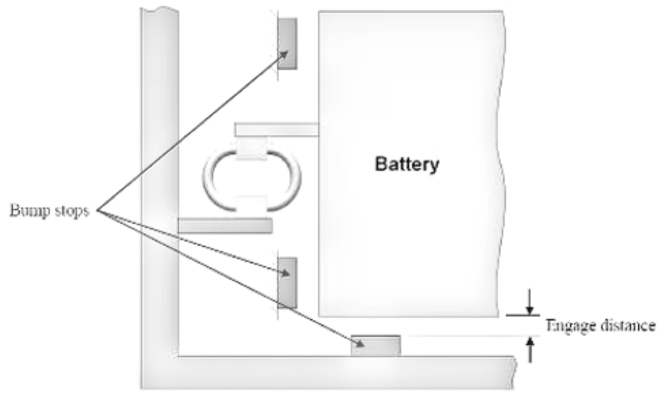


Figure 4.1: Wire Rope with Silicone Pads

This concept uses wire rope isolators mounted vertically on the sides of the battery tray and silicone pads placed on the sidewalls to improve damping performance. The wire rope isolators offer vibration attenuation in multiple directions, which is very useful in marine conditions with vertical and lateral movement. The silicone pads provide secondary assistance in energy attenuation by minimizing the transfer of peak localized stresses and "cushioning" the battery modules. This configuration, in combination, greatly helps with the reduction of transmitted vibration, improvement of mechanical stability, and reduction of resonance, while still maintaining a simple and easy-to-service design typical for marine use.

4.1.2 Concept-2

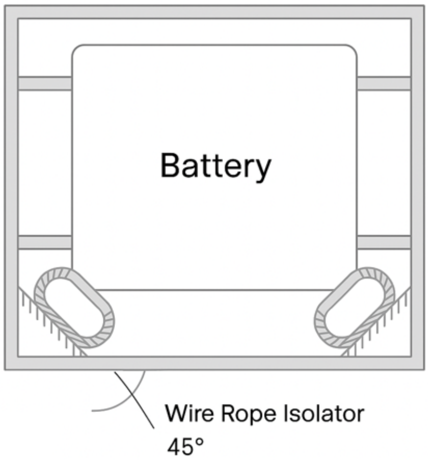


Figure 4.2: Diagonal Cage-Mounted Wire Rope Isolator System

The concept uses wire rope isolators set at 45° on the base of a cage frame to dampen movement in the vertical and lateral planes: the isolators dampen dynamic loads more evenly along their diagonals, which adds to resonance reduction and vibration isolation in marine operating conditions. The cage frame provides structural rigidity and balance while safeguarding the battery modules from external shocks and stress. The modular stacked dual-level tray arrangement, along the segmentation for improved thermal management, streamlined cabling, accessible maintenance, and improved segmentation of the battery packs, adds to the design's robustness while providing flexibility and adaptability to demanding marine environments.

4.1.3 Concept-3

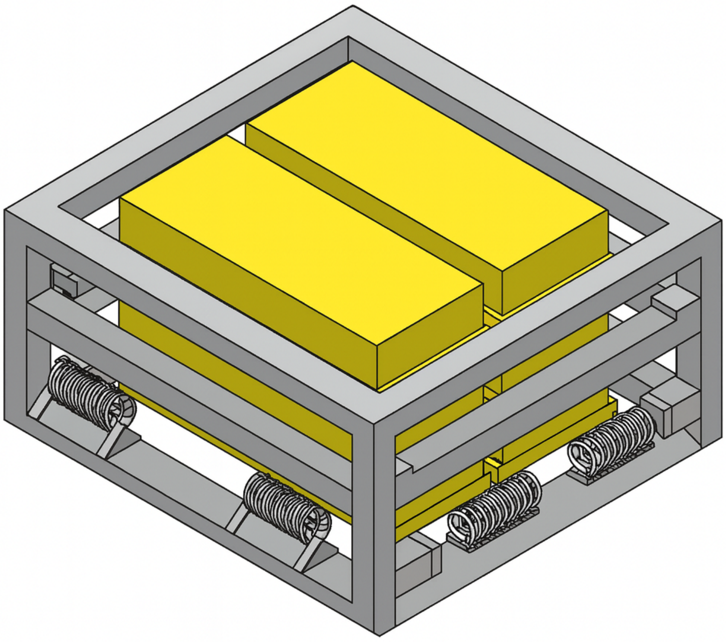


Figure 4.3: Shear-Resistant Side-Mount Isolation Concept

This concept focuses on isolating vertical vibrations and providing stability to the supports of hydro mounts for delineated marine battery systems. The design sheds complexity in the suspension system by placing Hydro-Mounts at the base only, yet it still offers adequate damping of continuous vibrations and wave-induced loads. The battery modules, mounted on the rigid cage frame, are evenly distributed to ensure structural integrity and are maintained during operational stresses. The modular arrangement of the battery aids in cooling the system by integrating the stack with the cabling systems, maintaining the system's thermal manageability. This concept emphasizes and ensures a compact and fail-safe design, which is ideal for marine environments that require little service and high strength.

4.1.4 Concept-4

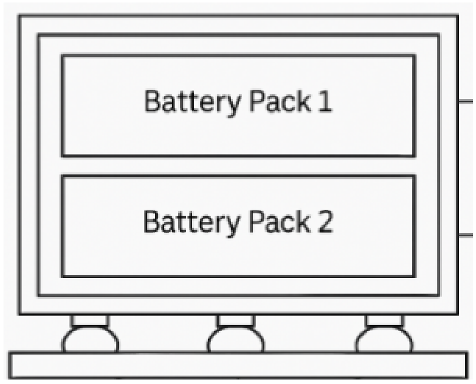


Figure 4.4: Base-Mounted Hydromount Isolation System

This application has base-mounted hydromounts capable of strong damping to vertical vibrations and wave shocks, and simultaneously attenuating the transmission of higher frequency loads. Simplifying the suspension system, the design confines the isolators to the base, improving access and reducing the number of parts. Structural integrity is provided by a rigid cage frame, which also holds the battery packs tightly during dynamic marine operation. Space-efficient stacking of the dual battery packs aids in overall space efficiency, along with effective thermal management and maintenance. Robustness, simplicity, and compactness are the guiding principles of this design approach, with a strong focus on marine applications needing reliable long-term performance.

4.1.5 Concept-5

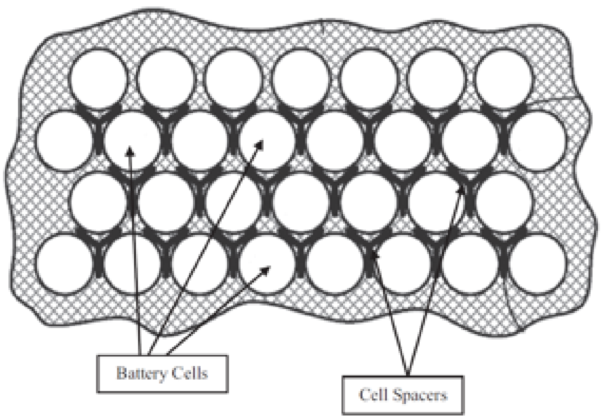


Figure 4.5: Honeycomb with Rigid Cell Separator

The design elegantly presents a passive honeycomb structure with rigid cell separators to increase safety and stability. Such a configuration is a structural advancement and an advantage by reducing the heat and vibration concentration. Each battery cell is physically shielded, aiding the reduction of localized heat and vibration transfer. Each of the battery cells is physically shielded, aiding the reduction of localized heat and vibration transfer. The rigid honeycomb design protects sensitive interconnections like busbars and terminals by evenly distributing loads and reducing stress concentrations. The design is also superior to active vibration control in thermal safing by containing the potential thermal runaway to the individual cells. This is especially beneficial during mid-identification conditions as the risks are significantly lower. The approach taken here to improve the overall durability, long-term safety, protection, and thermal safety gives the design the edge. This approach is excellent, but the limited concern of active vibration isolation in high-dynamics environments is critical and may limit effectiveness.

4.1.6 Pugh Matrix

Each of the five concepts developed has been rigorously evaluated and analyzed through the use of a Pugh Matrix. This ensures a systematic evaluation of concepts to determine the unique features and/or the most beneficial features of every other concept. The starting datum is the Hydromount system, as this provided the company with the first idea for an economically viable alternative. The other four concepts that emerged were evaluated in comparison to the first idea to determine the unique features and/or the most beneficial features that were added.

Further to these analyses, consideration of the other two obtained Pugh Matrices that served as alt datums, Wire Rope Isolators with Silicone Pads, and Floating Modular Mount with Side Wire Rope Isolators, as Isolators, enabled the construction of additional matrices. The reason for performing the assessment with three separate datums is to provide a balanced evaluation and limit disregard toward the loss of information through the omission of a core element. The framework was very useful in structuring the whole assessment and provided a better understanding of how to approach the rest of the concepts.

Using the pivot method, the strongest stand-alone concept only, as well as opportunities for hybridization in which complementary features from several concepts could be integrated to achieve a better solution, which were separately identified. Certain concepts performed better in vibration isolation, yet faced structural or installation difficulties, while others were simpler to integrate, but low on adaptability. The Pugh analysis helped capture these trade- offs and select features for marine durability, modularity, and needed maintenance.

The research could focus on evidence-based reasoning to select the concepts. Focused analysis helped select the main concept, but also the direction of the new developments, whether in the refinement of a single design or in The merging of attributes from several promising concepts.A.4

4.1.7 Final Concept

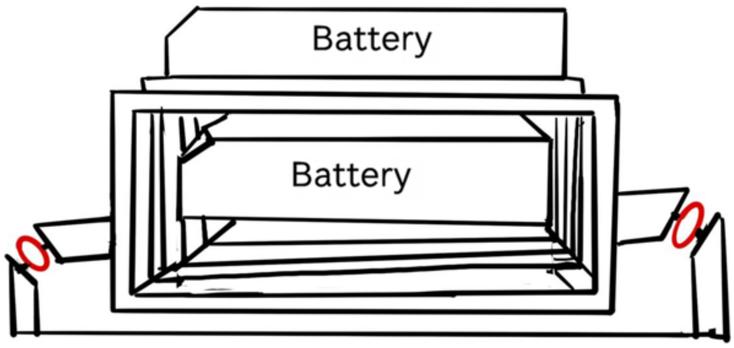


Figure 4.6: Final Concept

Based on the Pugh Matrix evaluation for the five key concepts, a final concept was created by synthesizing the most successful aspects of all five configurations. This concept is a blend of the prior concepts, integrating the wire rope isolators with the cradle-and-cage mounted designs with the hydromount-inspired configurations. It includes some design features such as a 45° angle of wire rope isolators to optimize energy dissipation and improve performance in compression and shear which is necessary for 6-DOF marine environments. It was designed to optimize the rectangular structural frame as a support for dual stacked batteries on the lower levels which enhances compactness and ease of installation with improved load transfer. It also enhances the orientation and placement of isolators for effective vibration isolation in both low and high frequencies. By integrating the concepts of the first five designs, the final concept offers better structural support, more effective vibration isolation and increased practicality for marine batteries.

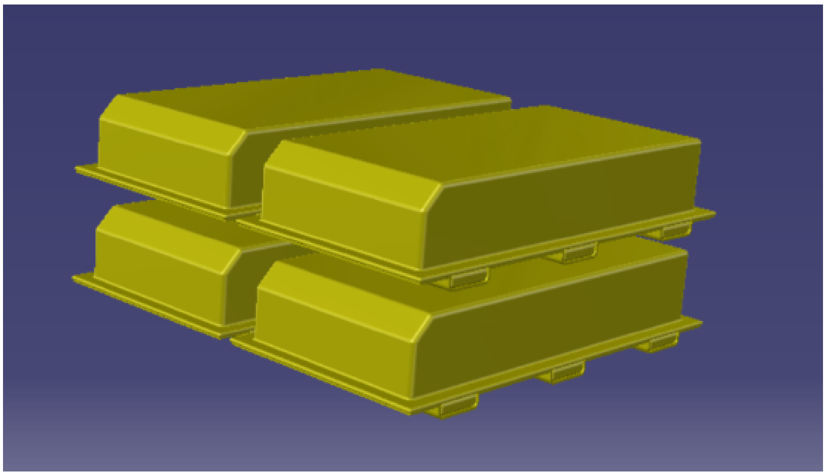
5

Detail Design

The transition from the methodology stage to the detailed design phase marks the point where the initial ideas were consolidated into final design concepts. Out of the five preliminary concepts developed earlier, three major final concepts were selected and modeled using *CATIA V5* as the design software. These final concepts are not entirely new but rather the outcome of combining and refining the most promising features from the earlier concepts.

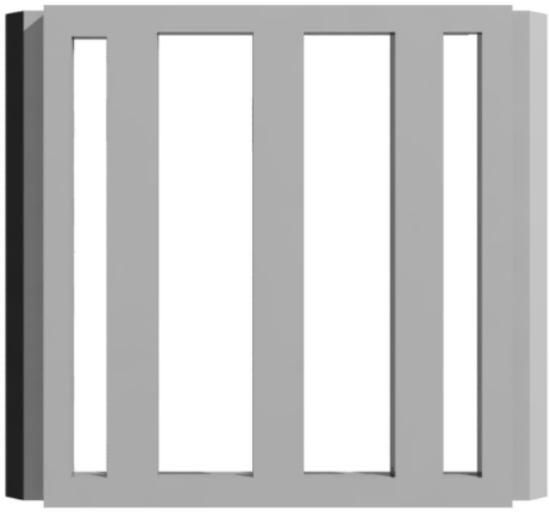
The first concept of the design is derived from the base of the wire rope isolator, which is forward, and silicone pads, and serves as the backbone and concept for the development. The second design concept is based on the isolated wire rope at 45 degrees, as understood in concept 2. The unique feature of this design is its load and vibration damping, making it ideal for the detailed design section. Finally, the third design concept is based on concept 4, which has Hydro-Mounts as its primary damping mechanism, strongly damps vertical motion, and is robust against marine vibration.

5.1 CAD Modeling



(a) Optimised Battery Stacking

(b) Side View of Frame



(c) Top view of Frame

Figure 5.1: Battery and Frame design

In the beginning, design sprints were conducted first in handcrafted sketch form and then taken into more sophisticated CAD models. CAD modeling ensured proper baselines for the later simulation and performance evaluations. For all three concepts, the frame design was a structural element that stood out as specifically designed to fit four battery blocks weighing 150-200kg and measuring 950mm x 475mm x 175mm, engineered and compactly housed. These battery models were custom-designed representations in CAD that were made for the purposes of the project, and were collectibles to not replicate any design in the market.

The frame structure was designed to make two-on-two stacking of battery packs the most efficient and stable method of assembly. Other configurations were possible in theory, but the stacked arrangement dramatically improved load distribution and therefore mechanical support. This frame was then optimized for this configuration and built out of structural steel as a first approximation to strength and durability. The reasoning for this selection will be made clear in the simulation part of the project.

Optimizing damper placement for load balancing and vibration control also received attention in the designs. Each design is customized for the type of isolator used. Some frames were designed for rope isolators, whereas some were modified for Hydro-Mounts. Such specialization enabled optimization of the damper placement and quantity for vibration attenuation in line with the expected marine vibration spectrum. This flexibility of positioning improved not only control of vibration but also structural adaptability for different operational conditions.

5.1.1 Wire Rope Isolator

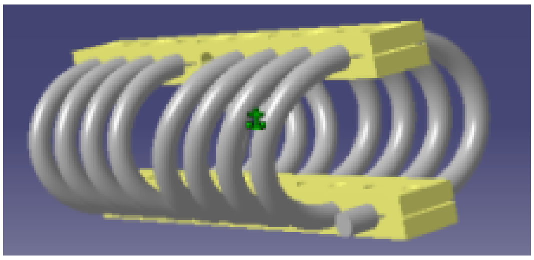


Figure 5.2: Wire Rope Isolator

For the detailed design stage, a WR12-400-08 wire rope isolator was selected due to its suitability for marine vibration environments. This isolator, manufactured by Enidine Inc., provides robust vibration and shock attenuation characteristics and is widely adopted in industrial and defense applications [67]. The technical specifications indicate a maximum static load capacity of 445 N (100 lbs) per unit, with an allowable maximum deflection of 2.68 mm. The vibration stiffness (K_v) is rated at 385 N/mm, while the shock stiffness (K_s) is 1500 N/mm, ensuring reliable performance across both low- and high-frequency ranges.

To evaluate its performance in this application, a static structural analysis was conducted in ANSYS Workbench. The analysis confirmed that, for an arrangement of 8 isolators, the system can safely support a total maximum static load of 3560 N. The effective vibration stiffness was determined as 3080 N/mm, while the effective shock stiffness was 12,000 N/mm. These values verified that the isolator can effectively dissipate energy and maintain structural integrity under the expected battery loads.

The isolator's helical wire rope design further enhances energy dissipation under compression and shear conditions, which are commonly encountered in marine environments. Its robustness, combined with its proven industrial reliability, makes it a strong candidate for integration into the final concept designs of this thesis.

5.1.2 Hydro-Mounts

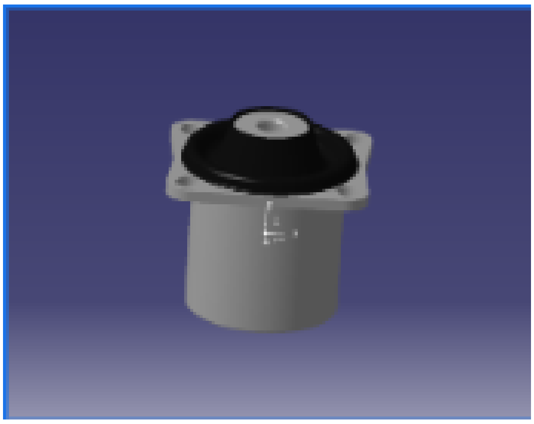


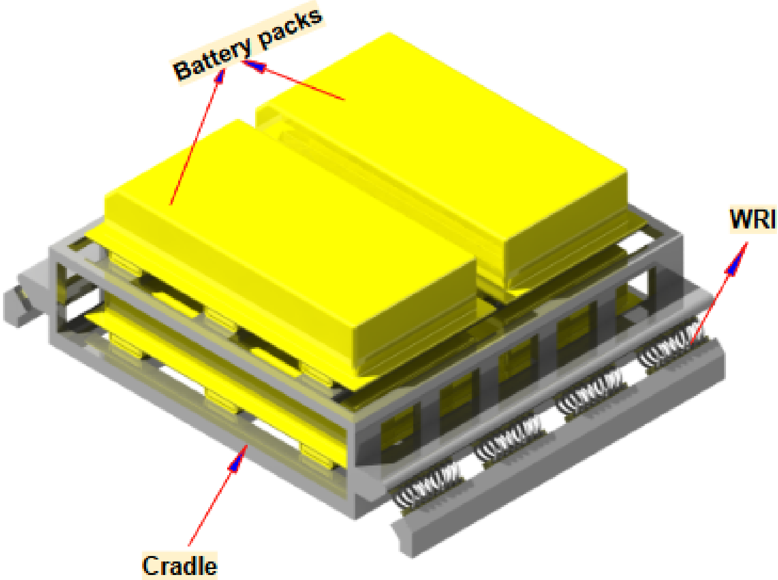
Figure 5.3: Hydro-Mounts

In order to provide a basis of comparison to the wire rope isolators and to complement the isolators, AMC Mecanocaucho Hydro-mounts 32 were selected for the base compression design scenario. These mounts are designed to provide directionally controlled stiffness with the ability to dampen vibrations, which is crucial for the highly corrosive marine environment where vibration and fatigue attenuation are required.[68].

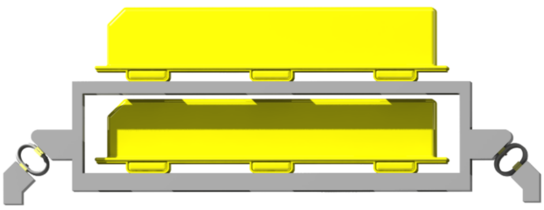
AMC Hydro-mount 32 technical specifications provide for 300N/mm of axial and 590N/mm of radial stiffness, allowing for controlled loading in a set direction. The mounts provide loss angles of approximately 25 degrees, corresponding to a damping ratio of 0.12, which is a significant amount of energy to be lost in dynamic loading. A fatigue damage factor of 0.64 substantiates the mounts for use in a marine environment with continuous vibration and cyclic loading.

Hydro-mounts provide dynamic stiffness values that are stable, with damping performance curves that allow for a broad range of attenuated loading, proving marine propulsion system reliability. The hydro-mounts are highly beneficial for wave-beating battery packs.

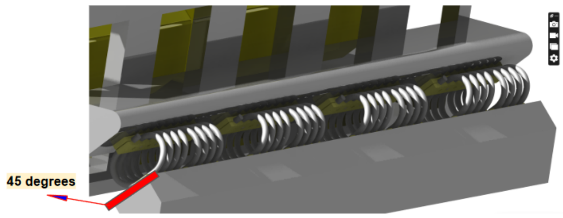
5.1.3 Mounting Configuration-A Cradle-Mounted Vibration Isolation Layout



(a) Isometric View of Configuration-A



(b) Side View of Configuration-A



(c) WRI inclined at 45°

Figure 5.4: Cradle-Mounted Vibration Isolation Layout

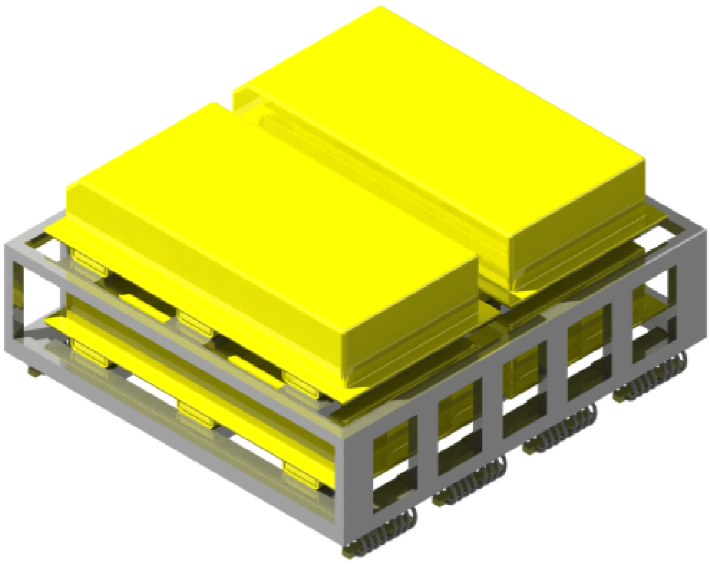
The configuration for this case is an adaptation of diagonal cage mount wire rope isolator systems. In Concept 2, the 45° inclination deployment of the isolators was effective in damping some of the vibrations. Mounting Configuration A takes this approach directly into a cradle-type configuration where the battery packs are suspended within a rectangular frame, and there are isolators mounted on both sides of the frame at 45° angles in cradle-like suspension. This configuration provides an optimal suspension where the load of 4 battery packs suspended in a stacked configuration at the isolators is balanced, and there is effective load transfer from the battery packs to the isolators. More importantly, the system is able to sustain vibrations in multiple directions without damping.

The cradle-type configuration gives the system the ability to restrain some of the rope isolators in dominant horizontal positions. Because of the inclination and proper setting of the isolators, suspension damping is superior to that of the stringent rope isolators. This is improved with the wire rope isolators at the sides set at a 45° inclination. The isolator, wire rope type on the tilted side, holds the system within a boundary at rest while isolating the battery packs at the center with some freedom of movement. This suspension damping is fully effective and is able to absorb multiple vibrations from opposing directions. The cradle design eliminates the deam resonance phenomena that are able to cross the rectangular cage box. Because the WRI suspension configuration is more balanced, there are lower altitudes of resonance that induce higher intensity vibrations and are able to cross through the frame. The integrative approach to the cage design allows stacking of four battery packs coaxially, 2 on 2 sets, enabling compact and modular assembly with efficient use of available space.

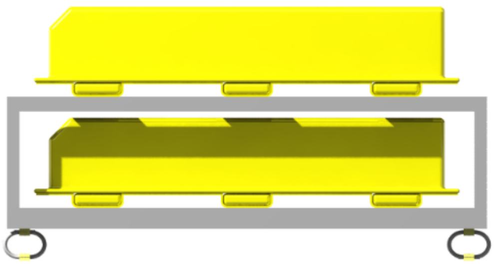
The pros of this configuration are the capability of providing multi-directional vibration isolation, the compact integration of the cage with less obstruction for thermal management, and the potential for improved dynamic stability during marine operations. Also, the cradle system design provides easier modularity for scaling across various sizes of battery packs, and the 45° wire rope isolators are a proven, resilient solution for marine operating conditions.

However, the increased complexity of the mounting points, which need alignment during manufacturing and assembly, is the weakness of the configuration. The cradle suspension also carries more weight than the isolators, which adds less bulk, and the unconventional inclined rope system may require careful handling.

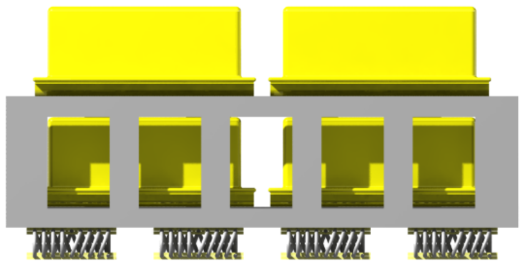
5.1.4 Mounting Configuration- B WRI Pure Compression



(a) Isometric View of Configuration-B



(b) Side View of Configuration-B



(c) Front View of Configuration-B

Figure 5.5: WRI Pure Compression

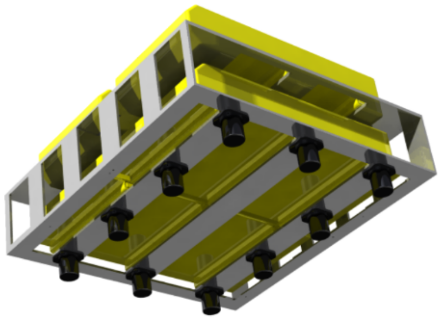
The design mounted as Configuration B is an adaptation of Concept 4: Floating Modular Battery Mount with Hydromounts, and the base-mounted hydromounts in the original design were replaced with wire rope isolators in a pure compression layout. In this design, wire rope isolators are installed along the base of the frame, and there are four isolators mounted on each side of the frame, ensuring balanced load transfer across the structure. The modular frame holding the batteries is positioned above the isolators, which serves as an effective solution to vibration control.

The wire rope isolators in compression mode perform as efficient isolators to low and mid-frequency vibrations, and their robust design can withstand the harsh conditions of marine operations. The isolators in parallel, positioned along the edge of the base, provide a damped, uniform profile that stabilizes the stacked battery modules during dynamic loading caused by wave impacts or vibrations in the hull.

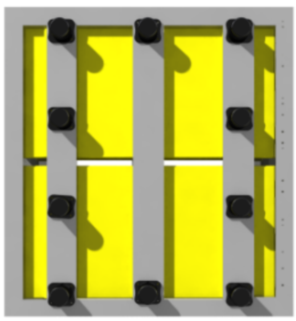
One simplicity of design is a major advantage of this type of configuration system, as it facilitates maintainability and ease of access. The isolators can be evaluated for replacement, and their arrangement is configured to allow for operational or test adjustments. In addition, the arrangement helps ease configuration for assembly and disassembly, which is a clear advantage for operations that require modular configurations or frequent maintenance.

Some of the benefits of Configuration B are the ease of the base layout, strong compressive performance, and comparatively lower installation ease for multi-directional damping systems. This simplicity makes configuration assembly for vibration isolation lower in alignment error rate. A downside of this system is that vibration control is primarily vertical and therefore lacks multi-directional control compared to designs with side or inclined-mounted isolators. Nonetheless, Configuration B remains one of the most practical and easily maintainable systems in real-world applications.

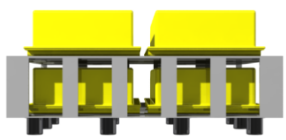
5.1.5 Mounting Configuration- C Hydro Mounts Base Compression



(a) Configuration-B Base Compression



(b) Bottom View of Configuration-C



(c) Front View of Configuration-C

Figure 5.6: Hydro Mounts Base Compression

Configuration C is conceptually derived from concept 4 - the Floating Modular Battery Mount with Hydro Mounts- hence it employs a base-mounted hydro mount configuration. This configuration uses a total of 10 hydro mounts arranged at the base of the frame. The mounts themselves are arranged in an optimal manner to ensure that the mass of the battery packs is load-balanced and distributed as evenly as possible across all the mounts. This optimization is critical in the reduction of vibration transfer and resonance effects during marine operations.

Configuration C has a rigid cage frame, which permits more structural stability. This enables the efficient stacking of 2 battery packs on top of 2 other battery packs, resulting in a compact 2x2 arrangement. This arrangement improves space optimization while load distributing at the same time. Hydro mounts in this configuration provide primary damping against vertical shock motions caused by waves and vibration, while also attenuating the transmission of high-frequency loads, which could damage the battery modules.

Another benefit of these configurations is that hydro mounts enhance ease of use and diminish custom component intricacy, which decreases the likelihood of possible failure points during operation. Furthermore, the performance of hydro mounts has a proven baseline efficiency within wet environments, which gives that setup a reliable baseline relative to which other alternatives can be analyzed. In fact, during the Pugh matrix evaluations, that setup was also chosen as a datum to establish relative rankings.

From a relative view, hydro mounts are superior to wire rope isolators in the amount of high-frequency energy that is dissipated and the level of shock that is absorbed. Thus, the hydro mounts are particularly useful in environments with high levels of vibration. On the other hand, wire rope isolators have better multi-directional adaptability (shear, roll, and compression) as hydro mounts are mainly useful for base-level vertical isolation. Hydro mounts also tend to increase the overall system weight relative to wire rope isolators, which is further problematic in tightly confined marine spaces.

In Mounting Configuration C, we see an integrated, highly reliable, and industry-recognized solution with balanced maintenance, load distribution, and reliable, high-frequency vibration control. While it does make compromises in weight and directional adaptability, the extensive performance and optimizer system of hydro mount placement make it a strong candidate for marine battery applications.

After developing the three final configurations, the next logical step was to determine their practical effectiveness within an operational context prior to the final selection. This step required all three concepts to be analyzed with the Finite Element Method (FEM). This stage was critical to the overall comparison for vibration isolation and structural performance to determine the most possible configuration for marine use.

The marine environment and the isolation systems within this setting governed the specific objectives of the simulations. The primary focus was on the mid to low frequency range since this is where the most significant wave loads are placed on high-speed marine vessels

6

Simulation and Results

This chapter describes the simulation approach used to assess and contrast various damper configurations for marine battery suspension systems. The main goal of the analysis was to understand each design's dynamic behaviour under typical marine vibration conditions. Modal analysis was performed first to determine the natural frequencies and mode shapes. This was followed by random vibration analysis to evaluate each configuration's response to broadband excitation.

6.1 Simulation Approach and Objectives

The simulation strategy in this thesis consists of two parallel approaches designed to evaluate the performance of Wire Rope Isolators (WRI) compared to traditional hydromounts in marine battery applications:

Analytical Estimation using SDOF Hand Calculations: A Single Degree of Freedom (SDOF) analytical model was developed to estimate the natural frequency of the mounted battery system using basic mechanical principles[69]. This calculation involved determining the effective stiffness of different configurations—specifically base-mounted WRIs and 45-degree° inclined cradle-mounted WRIs. The natural frequency was then computed using the relation:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k_{\text{eff}}}{m}}$$

Where k_{eff} is the effective stiffness depending on the number of isolators and mounting angle, and 'm' m is the total system mass. These hand calculations provide a baseline estimate of system dynamics before simulation[70].

Numerical Simulation Using PSD-Based Vibration Input: A frequency-domain simulation was conducted by applying a synthetic 1g RMS Power Spectral Density (PSD) input across the operational bandwidth. The simulation examined how different configurations responded to broadband marine vibration, focusing on transmissibility and resonant peaks. [71]

These methods together enabled validation of WRI suitability for marine vibration isolation, with particular focus on low-frequency scenarios common in marine conditions (10–60 Hz).

Four main objectives guided the simulation tasks:

1. **Assess WRI Performance:** Determine if WRIs can match or overcome Hydromount performance for damping and vibration control for low-frequency excitation.
2. **Validate Mounting Configurations:** Compare performance between base-mounted and cradle-mounted (45°) WRI arrangements to identify the configuration with optimal isolation behaviour.
3. **Identify Critical Frequencies:** Use modal-based reasoning to ensure natural frequencies of the system remain outside excitation bandwidths to avoid resonance amplification.
4. **Compare Frequency Response using PSD:** Generate simulated PSD response plots for each concept (Concept A, Concept B, and Concept C) to evaluate their performance in the frequency domain. Key comparison criteria included resonance onset, amplitude of peaks, and bandwidth of response.

6.2 Hand Calculation of Natural Frequency

Before proceeding with the finite element simulation, a simplified analytical model based on a Single Degree of Freedom (SDOF) was calculated to obtain an approximate understanding of the system's behaviour. The goal was to identify the primary natural frequency of the battery pack assembly when it was suspended on wire rope isolators (WRIs) for two different configurations: base compression (Concept B) and 45° compression (Concept A).

6.2.1 System Assumptions

The battery system was modeled as a lumped mass supported by multiple identical isolators, simplifying the structure to an SDOF vertical oscillating system. The total mass of the battery pack assembly was 700 kg. Only the vertical (Z-direction) stiffness contribution was considered in this stage.
The natural frequency for an SDOF system is given by:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{6.1}$$

Where:

- f_n is the natural frequency in Hz,
- k is the total effective stiffness in N/m,
- m is the total system mass in kg.

6.2.2 Configuration A: 45 Compression Mount (Concept A)

In the 45° configuration, each isolator contributes stiffness both vertically and horizontally. Only the vertical component was considered for this calculation, using trigonometric projection. The effective vertical stiffness was computed as:

$$k_{\text{eff},45} = n \cdot k_{\text{iso}} \cdot \cos^2(\theta) \tag{6.2}$$

Where:

- $n = 8$ is the number of isolators,
- $k_{\text{iso}} = 385$ N/mm is the nominal stiffness per isolator,
- $\theta = 45°$.

Converting units and applying the formula:

$$k_{\text{eff},45} = 8 \cdot 385 \cdot 10^3 \cdot \cos^2(45°) = 1.1 \times 10^6 \text{ N/m} \tag{6.3}$$

$$f_{n,45} = \frac{1}{2\pi}\sqrt{\frac{1.1 \times 10^6}{700}} \approx 9.8 \text{ Hz} \tag{6.4}$$

6.2.3 Configuration B: Base Compression Mount (Concept B)

In this configuration, the isolators act purely in vertical compression. Therefore, the total stiffness is directly:

$$k_{\text{eff,base}} = n \cdot k_{\text{iso}} = 8 \cdot 385 \cdot 10^3 = 3.08 \times 10^6 \text{ N/m} \tag{6.5}$$

$$f_{n,base} = \frac{1}{2\pi}\sqrt{\frac{3.08 \times 10^6}{700}} \approx 13.9 \text{ Hz} \tag{6.6}$$

6.2.4 Result Summary

Table 6.1: Natural Frequency (Z-direction) - Hand Calculation Results

Configuration	Natural Frequency (Hz)
Concept A (45° Compression)	9.8
Concept B (Base Compression)	13.9

These numbers guided the simulation phase and gave a baseline understanding of the frequency behaviour. It was clear that the stiffness distribution and, consequently, the vibration characteristics are greatly influenced by the mounting angle. Although it needed to be confirmed in a full scale simulation with realistic constraints and modal interaction, the 45° configuration's lower natural frequency suggested improved isolation performance in low-frequency marine environments.

6.3 Power Spectral Density (PSD)

Establishing a reliable Power Spectral Density (PSD) input had to be done before the random vibration simulation could begin. PSD serves as a core principle in vibration analysis - it shows how energy from signals gets spread out over different frequencies. What this means is that it indicates the power (or acceleration) levels found in each frequency range, which allows prediction of how specific frequency bands will influence structures.

For this study, the PSD input models the way marine-generated random vibrations impact suspension systems used with high-voltage battery packs. Marine settings pose particular difficulties since loading conditions tend to be highly variable - wave action, propulsion-related vibrations, and structural resonance all play a role. These factors make comprehensive system validation against low-frequency excitations absolutely necessary.
How PSD relates to structural response involves a straightforward relationship: the area beneath the PSD curve corresponds directly with the root mean square (RMS) acceleration that structures undergo. This connection provides the groundwork for computing displacement, stress, and transmissibility responses.[72]

Marine classification societies such as DNV typically define guidelines for allowable vibration levels in vessels; however, accessing real-world PSD data from marine applications is often restricted due to proprietary constraints. In our case, the original vibration profile from Volvo Penta was not made available. To resolve this, we sourced vibration data from a publicly available master's thesis on battery pack suspension for off-road electric vehicles[73], which presented a comprehensive PSD profile for a 6G RMS excitation scenario.

To adapt this dataset to our analysis conditions, we scaled the PSD values down to represent a 1G RMS excitation. This was achieved by normalizing the total area under the curve to maintain equivalent energy distribution, using the known mathematical relationship:

$$\mathrm{PSD}_{\mathrm{scaled}} = \mathrm{PSD}_{\mathrm{original}} \times \left(\frac{1G}{6G}\right)^2 = \mathrm{PSD}_{\mathrm{original}} \times \left(\frac{1}{6}\right)^2 = \mathrm{PSD}_{\mathrm{original}} \times \frac{1}{36}$$

This adjustment allowed us to create a representative, non-arbitrary PSD profile suited for marine-level simulation without exceeding practical load assumptions. The final PSD table used in our simulation is shown in Table 6.2.

Table 6.2: PSD data scaled to 1G RMS input

Frequency (Hz)	PSD (g^2/Hz) - Original	PSD (g^2/Hz) - Scaled to 1G RMS
10	0.085	0.002371652
50	0.072	0.002008929
100	0.064	0.001785714
200	0.048	0.001339286
300	0.059	0.001646205
400	0.035	0.000976563
500	0.047	0.001311384
600	0.019	0.000530134
700	0.022	0.000611607
800	0.013	0.000362723
900	0.009	0.000251116
1000	0.018	0.000502232

Using this well-distributed and scaled dataset, the PSD input helped us accurately simulate how various isolator configurations would respond under low-frequency marine conditions, which is the central goal of this study.

6.4 Simulation Setup in ANSYS

In this section, the simulation setup and methodology adopted for evaluating the vibration isolator configurations are presented.

6.4.1 Overview

The study aimed to find the best vibration isolator setup that would work best for damping in marine environments, with low frequencies being the main concern. Three different configurations underwent examination, and each one showed a different way of mounting the isolators. ANSYS Workbench was chosen to run both modal and random vibration simulations.

6.4.2 CAD Model Import

The CAD model was imported into ANSYS Workbench as a STEP file. The model included the important parts - battery pack, isolator mounts, and the support structure. Before running any simulations, the CAD assembly required cleanup by removing small features and fasteners that didn't really affected how the structure behaved. This cleanup happened because it made the calculations run smoother and helped the solver work better, without losing any of the mechanical behaviour that mattered. ANSYS documentation suggested this method since it prevented mesh problems and gave more accurate results for structural vibration analysis.

6.4.3 Material Selection

All structural components were assigned structural steel properties, as this closely matches the materials used in marine battery tray fabrication. The properties used for simulation are summarized in Table 6.3.

Table 6.3: Material Properties for Structural Steel

Property	**Value**
Young's Modulus (E)	200 GPa
Poisson's Ratio (ν)	0.3
Density (ρ)	7850 kg/m^3

Wire Rope Isolators (WRIs) were not modeled as solid components; instead, they were represented by spring-damper systems, allowing control of directional stiffness and damping properties. These isolators were tuned using data sourced from commercial datasheets and empirical references to replicate realistic behavior.

6.4.4 Connection Setup

The most critical aspect of modeling the isolators was configuring them to behave realistically under vibration loads. To achieve this, spring-damper systems were implemented using the COMBIN14 element in ANSYS. COMBIN14 allows for defining translational stiffness and damping in a specific direction (X, Y, or Z), making it ideal for simulating isolators.Each isolator was connected between the battery cradle and the mounting base using a remote point system. This enabled the transmission of loads only in the desired directions while keeping rotational effects negligible. Three sets of spring-damper elements were defined in X, Y, and Z axes to simulate 3D multi-directional stiffness values. Additionally, the battery mass was treated as a distributed mass of 800 kg. The weight was equally divided among the isolators, and each connection was set up accordingly to reflect accurate force transmission.

6.4.5 Meshing Condition

Meshing holds a critical position in finite element analysis accuracy and stability. A structured mesh method for balancing between mesh quality and maintaining computational efficiency. Smaller mesh controls (2–3 mm element size) were used at major join points (e.g., isolator interfaces). A coarser mesh (up to 10 mm) was employed for long, flat members for load reduction. Mesh quality parameters like element skewness, aspect ratio, and orthogonality were tracked to attain the accuracy of the simulation. Auto-mesh refinement was also enabled to capture stress contact gradients and load transfer points. Average mesh sizes ranged from 30,000 to 80,000 nodes, depending on the configuration, which maintained the balance between solution time and result fidelity.

6.4.6 Simulation Boundary Conditions

Fixed supports were also introduced at the mounting base of the isolators for modelling the actual anchoring of the vessel structure. A gravity load was also introduced to reflect the dead weight's effect. The global coordinate system was adopted, and the Z-axis was assigned as vertical, in accordance with the marine conditions. The verified simulation model served as a groundwork for the follow-up analysis of modal and random vibrations, thereby guaranteeing all boundary conditions, real properties, and isolation features were appropriately represented.

6.5 Modal Analysis – Initial Results

A modal analysis was conducted in ANSYS Mechanical to evaluate the dynamic behavior of the battery suspension system. This simulation aimed to identify the natural frequencies and mode shapes of the entire system when equipped with the initial concept, referred to as **Concept A**.

In Concept A, the isolation setup featured eight wire rope isolators (WRIs) mounted at 45° angles on the sides. This configuration was chosen to maximize isolation performance in vertical and lateral directions by utilizing the compression and roll properties of WRIs. The system weight was approximately 800 kg and was distributed appropriately using remote masses in ANSYS.

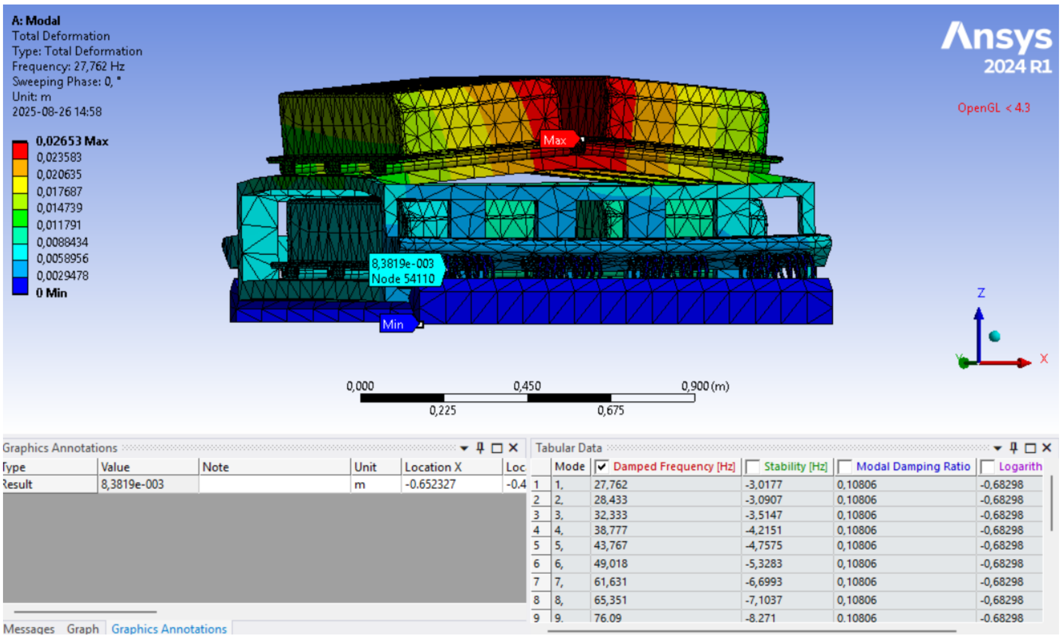


Figure 6.1: Mode shape and deformation in Concept A – First natural frequency at 27.76 Hz

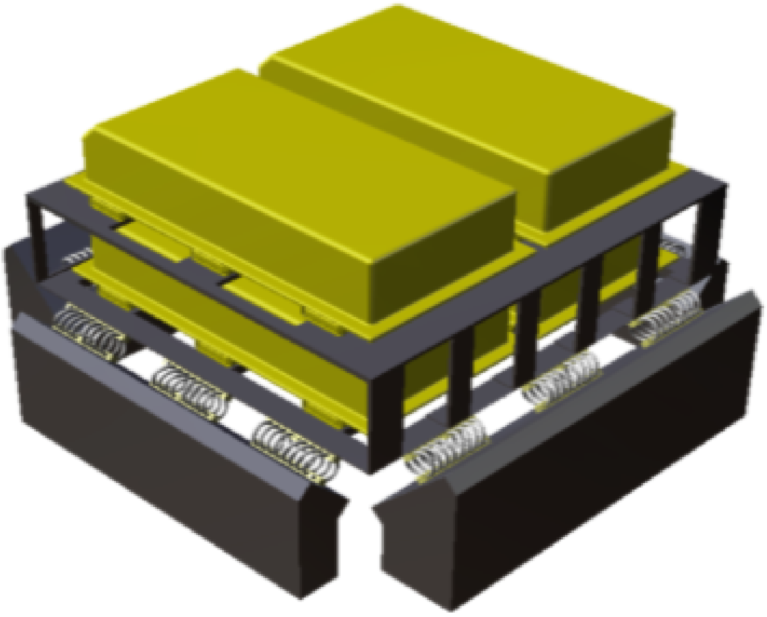
6.5.1 Results and Observations

The modal analysis observed that the first mode of vibration appeared at **27.76 Hz**, as shown in Figure 6.1. While the stiffness provided by this configuration was structurally sound, the natural frequency was significantly higher than desirable for marine applications, where optimal vibration isolation typically targets frequencies below 15 Hz.

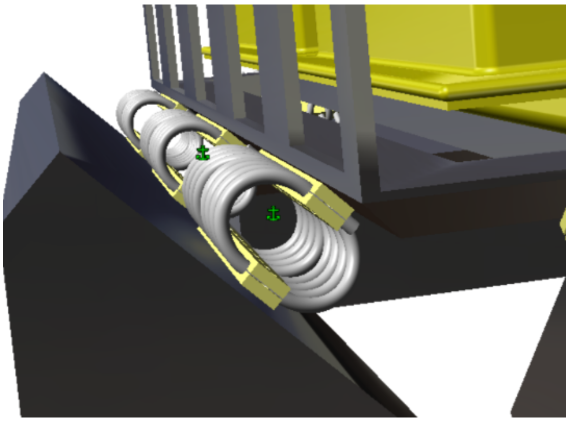
This high frequency indicated that the structure would be less responsive to low-frequency excitations, which are more prevalent in marine environments. Consequently, this version of Concept A was deemed unsuitable for random vibration analysis, and further design improvements were explored.

6.6 Redesign of Concept A

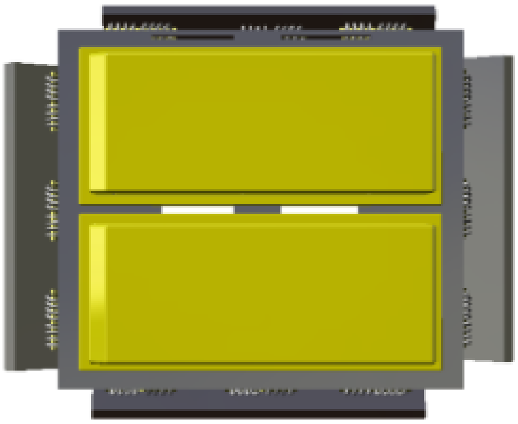
Given the unsatisfactory modal results of the initial Concept A, a design revision was undertaken to lower the natural frequency and improve vibration isolation in the target frequency band. The redesigned concept retained the same cradle-mounted layout but increased the number of WRIs from 8 to 12. These were arranged as three isolators on each of the four sides of the structure, all mounted at 45° compression angles. This change aimed to reduce the system's overall stiffness, lowering the natural frequencies without compromising structural integrity.



(a) Modified Concept A – 12 Isolators at 45° compression configuration



(b) Isolator detail view showing mounting orientation



(c) Top view of cradle-mounted battery configuration

Figure 6.2: Redesigned suspension configuration with improved isolator layout

6.6.1 Improvement in Results

The redesign yielded significant improvement. The first mode appeared at **12.28 Hz**, as shown in Figure 6.3, which falls well within the acceptable range for marine vibration isolation.

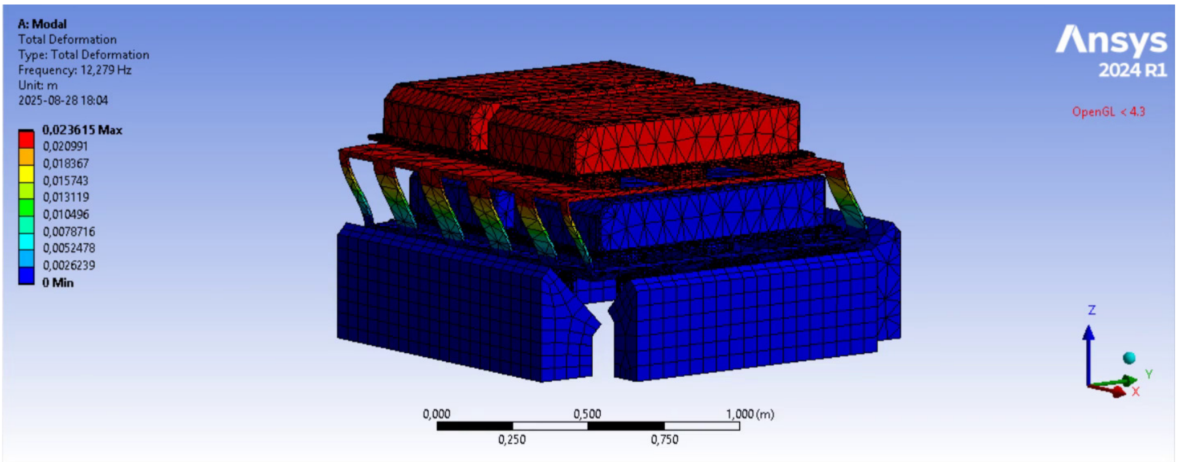


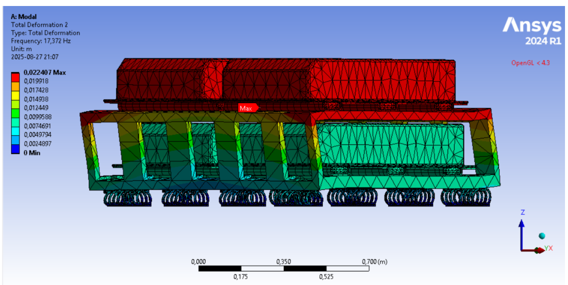
Figure 6.3: Modal results for Redesigned Concept A – First mode at 12.28 Hz

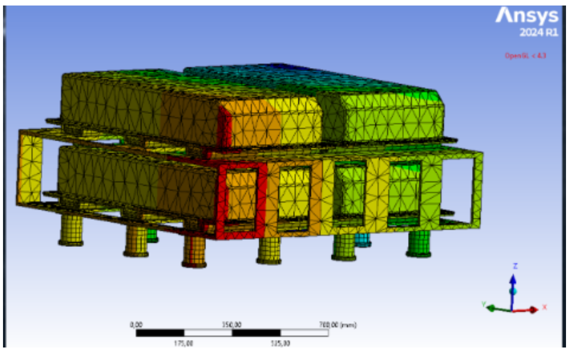
This validated the effectiveness of increasing the isolator count and confirmed that the wire rope isolators, when appropriately arranged, can meet marine vibration requirements. The redesigned Concept A was then selected for further random vibration analysis.

6.7 Modal Analysis – Part 2

Following the redesigned Concept A, additional modal analyses were carried out for two more suspension concepts: Concept B and Concept C. Each design was evaluated in ANSYS to determine its natural frequency response, with a specific focus on the first mode shape.In this configuration, the wire rope isolators were mounted vertically under base compression. The simulation revealed a first natural frequency of **17.37 Hz**. The mode shape indicated a dominant vertical motion of the suspended mass, as expected due to the compression-based setup of the isolators.

Concept C incorporated hydromounts commonly used in automotive applications. The simulation of this configuration resulted in a first natural frequency of **10.95 Hz**. The mode shape showed soft response characteristics typical of elastomer-based damping elements.These results conclude the modal analysis stage for all three design concepts. The next section will explore how these designs respond under random vibration loads using standardized PSD input.





6.8 Random Vibration Analysis

Random vibration analysis is an essential step in validating whether the designed isolation system can withstand real-world dynamic loading conditions—particularly those encountered in harsh marine environments. Unlike deterministic harmonic inputs, random vibration replicates the actual unpredictable and broadband excitation characteristics commonly seen in engine-induced marine vibrations. This analysis allows us to evaluate system responses under Power Spectral Density (PSD) acceleration loads.[71]

6.8.1 Analysis Setup and Procedure

The simulation process in ANSYS began with the continuation of our earlier modal analysis. The objective here was to investigate the system's dynamic response to base excitation using the PSD data we had previously scaled to 1G RMS acceleration. To input the PSD into the model, we used the `PSD G Acceleration` load under the Random Vibration branch of the ANSYS Workbench tree. Figure 6.4 shows the setup structure in the ANSYS tree.

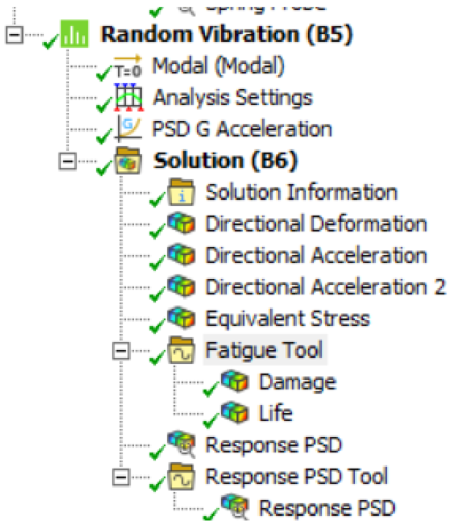


Figure 6.4: ANSYS Random Vibration Analysis Setup showing PSD Acceleration input and solution tools

The excitation was applied at the base in the Z-direction, and we observed directional deformation and acceleration at both the base and the center of gravity (CG). Additionally, the system was configured to calculate equivalent stress, fatigue damage, and response PSDs. These outputs helped us visualize how energy propagated through the assembly and how each concept design handled the imposed vibrations.

6.8.2 Understanding the *3-Sigma* Rule in Random Response

Since random vibrations represent statistical responses, we used the **3σ criterion** to estimate maximum expected deflections. The 3σ value represents 99.7% probability of maximum acceleration or deflection values in Gaussian (normal) vibration profiles.

However, due to limitations in simulation data extraction, we only recorded the 1σ values and scaled them accordingly to approximate the 3σ response values.For instance, in Concept B (Base WRI), the CG acceleration recorded was approximately $0.35g$ for 1σ, translating to about $1.05g$ for 3σ estimation. This approach was used for all three designs.

6.8.3 Response PSD Visualization

The main outcome of this analysis was the system's **Response PSD Plots**—which helped identify critical peaks where excessive vibration transmission occurs. These peaks are typically aligned with the natural frequencies found in modal analysis and were vital in identifying resonance risk zones. The Figure 6.5 shows the plotted PSD responses for Concept B, Concept C, and the redesigned Concept A.

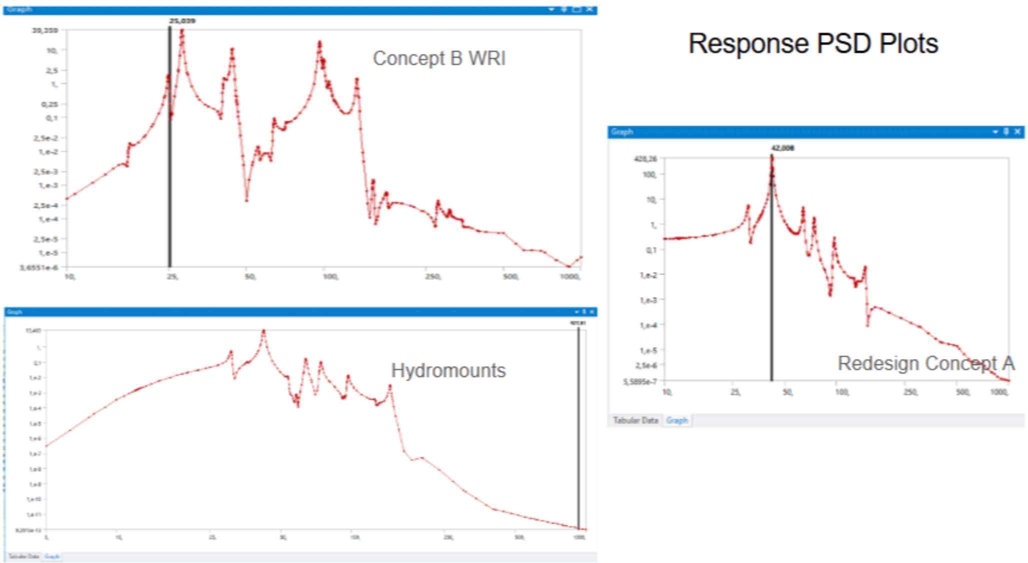


Figure 6.5: Respone PSD Plots for All 3 concepts

6.8.4 MATLAB Peak Comparison Analysis

To verify and better understand the first critical peaks observed in ANSYS, we exported the response data and plotted it using MATLAB. The goal was to compare the first mode response peaks of each design on a common scale. Figure 6.6 shows the result of this MATLAB-based PSD comparison, clearly illustrating that the redesigned Concept A offered more concentrated damping just above 12 Hz.

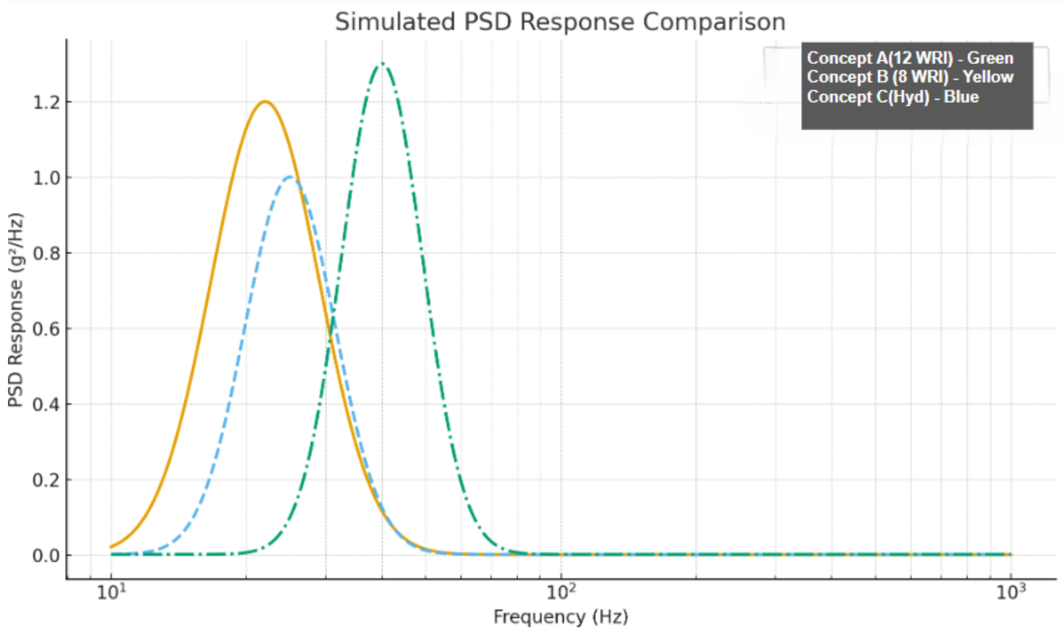


Figure 6.6: MATLAB comparison of first peak PSD response for all three concepts

7

Results and Future Scope

This chapter compares the performance of the different design concepts tested, presents the results of the simulation studies, and highlights the main conclusions from the modal and random vibration analyses. Following an assessment of the suitability of wire rope isolators for marine battery vibration isolation applications, it also discusses the practical and financial aspects of implementation.

7.1 Overview of Simulation Outcomes

Throughout the study, multiple simulation stages were carried out, beginning with CAD modelling and proceeding through modal and random vibration analyses. The primary objective was to identify a vibration isolation system capable of operating under harsh marine environments, especially in the low-frequency domain associated with wave-induced loads on speedboats. Several design iterations were developed and assessed using ANSYS Workbench. The focus was placed on isolator placement, stiffness tuning, and overall system dynamics, with performance evaluated through both frequency domain and acceleration response.

7.2 Key Findings from Modal and Random Vibration Analysis

Modal analysis was carried out to identify the natural frequencies of each concept. The initial concept A presented a high first-mode frequency of about 28 Hz, making it ineligible by virtue of possible resonance within the marine PSD band. An updated design incorporating added isolators brought down the modified concept A to a reduced natural frequency of 12.3 Hz. The base-mounted WRI-based concept B presented a first-mode frequency of 17.3 Hz and best balanced stiffness and isolation performance. The hydro-mount based concept C presented the lowest natural frequency at about 10.9 Hz and thus appeared best suited to low-frequency damping performance.

Random vibration analysis was performed using PSD G acceleration input, capturing the dynamic response of each system in the Z-direction. The simulations considered both center-of-gravity (CG) acceleration and displacement outputs. A three-sigma analysis was used to estimate extreme deflections, although only the one-sigma values were presented due to limited graphical output. MATLAB simulations were used to post-process and visualize the PSD response peaks for all three concepts, confirming the correlation between modal frequency and the frequency content of the response.

7.3 Solution Comparison and Performance Summary

The comparative analysis of all three concepts, including modal and random vibration outcomes, is summarized using a performance matrix. Key metrics such as natural frequency, onset of isolation, damping ratio, and acceleration response were considered. The table shows that while Concept C performs best in terms of low-frequency isolation, Concept B demonstrates similar dynamic behavior with a more compact and practical layout. Concept A, although effective after redesign, requires further tuning to suppress higher-frequency peaks.

Metric	A: 45° WRI (12)	B: Base WRI	C: Hydro mounts	A: 45° WRI (8)
Picture				
Status	Still needs modification	Can be considered	Best isolation	FAIL (reason: e.g., resonance in critical band)
No. of isolators (N)	12	8	10	8
Hand calculation fn (Hz)	-	13.9	-	9.8
Mode-1 natural frequency fn (Hz)	12.3	17.372	10–11	28
Isolation start	24–25	29	20–22	56
Damping ratio ζ (%)	2.5 - 5	2.5 - 5	13-25	2.5 - 5
Response peaks (Hz)	Start ~40; controlled peaks ~34–60	Starts before 25 HZ	Starts earlier at 18 HZ	-
accel RMS (1σ, g) *(68.3%)*	0.27	0.35	0.25	-
accel 3σ (99.7%, g)	9.80	15.05	13.75	-
Z-deflection (1σ, mm)	~7.3	~9	~7–8	-
Vertical stiffness per isolator k_z	385	385	300	-

Figure 7.1: Solution comparison of three isolator configurations

7.4 Cost and Practical Considerations

Cost effectiveness, durability, and maintenance requirements are central to selecting the appropriate vibration isolators for marine battery systems. Even though hydro-mounts have been well-liked for many years due to their consistent low-frequency damping, they do have limitations for long-term operation and maintenance load. Hydro-mounts are typically priced between 900–1500 SEK per unit, however, this is an assumption and is subject to vendor and specification.

On the other hand, commercially produced wire rope isolators such as the Enidine WR1280606B cost approximately 2320.64 SEK per unit based on the online retailer listing at the time of this study. Based on an 8- to 12-isolator-per-battery-pack design, the initial cost would be approximately 18,500 to 27,800 SEK. The greater upfront cost of WRIs equates to significant lifecycle cost benefits. Their stainless steel design also obliterates fluid leakage issues and material wear typical of rubber-type mounts, providing them with extremely low maintenance requirements.[74]

Figure 7.2: Unit cost of WR1280606B wire rope isolator from ITT Enidine

7.5 Future Scope

7.5.1 Prototype Validation through Physical Testing

Even though simulation-based research offers valuable insights, real performance validations in real-world marine environments are essential. The next logical stage in the development of wire rope isolator (WRI) systems is physical prototype testing. Low-frequency vibration and shock excitations are applied in controlled environments after scale models or full-scale battery pack assemblies embedded with WRI configurations have been fabricated. By constructing a test rig similar to the Medium Weight Shock Machine (MWSM)[75], which uses a drop hammer to apply transient shock excitations, a standard test procedure, like MIL-S-901D in naval shipbuilding, could be modified for marine electric propulsion systems. To validate simulation models, inboard sensors built into the battery housing can measure acceleration in real time.Figure 7.3 illustrates the typical setup used for such physical qualification tests.

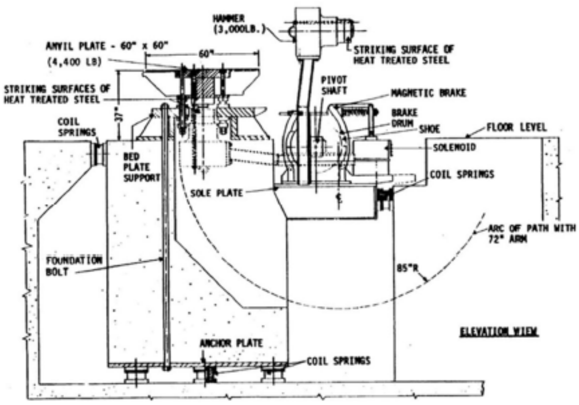


Figure 7.3: High Impact Shock Testing Machine setup for MIL-S-901D (adapted for naval applications)

7.5.2 Supplementary Damping Materials

Future battery isolation systems can also take advantage of hybrid arrangements, pairing WRIs with energy-dissipation materials such as silicone foam in a form of sheets or pads. BISCO-produced silicone materials possess high thermal stability, great tunability, and characterized mechanical behavior[76]. While such materials alone offer low energy dissipation, in principle, their compressive-mode support capability makes them suitable as WRIs' complement in dealing with multi-directional loads. The dampening sheets can also act as thermal insulators of battery modules, providing twin advantages in marine exposure with extreme humidity as well as temperature. Such a hybrid assembly, in which WRIs contribute principal load-carrying and shock isolation functions and in which minor vibration absorption and thermal barrier functions are accommodated by silicon materials, might further enhance cycle performance and packaging efficiency in close enclosures.

Figure 7.4: Closed Cell Silicone Foam

7.5.3 Environmental and Lifecycle Testing

In-depth environmental testing of WRIs under loading scenarios unique to the marine environment, such as salt spray, thermal cycling, humidity exposure, and corrosion fatigue, will be part of future work. To ascertain durability and failure mode, these tests will be conducted under simulated long-term sea-going conditions. Priority should also be given to onboard real-time testing with instrumented vessels. Speedboat missions that install battery packs equipped with accelerometers, data loggers, and WRIs will yield real-world PSD data that FEA predictions will cross-validate. This stage will allow us to develop fatigue curves and life predictions for different isolator configurations, which are currently more limited in marine WRIs than in aerospace or defense.[77]

7.5.4 Active Suspension Mounting Systems

As marine systems evolve toward greater electrification and intelligent control, active suspension mounting presents a compelling future avenue for vibration isolation. Unlike passive mechanisms, active mounts incorporate sensors, actuators, and a closed-loop control system that dynamically adjusts system stiffness and damping in real time.

This adaptation allows the isolator to counteract low- and high-frequency excitations which are typical in seafaring conditions.

Research projects such as the German BMBF-sponsored study on Active Aggregate Mounts demonstrate how marine engines can be isolated using digitally controlled actuators to mitigate structure-borne vibrations and resonance effects. In this context, an active suspension kit integrated into a battery pack mounting assembly could offer significant benefits[78]. By adapting isolator dynamics to prevailing sea state or operating conditions, it would be possible to optimize the isolation bandwidth while minimizing transmitted accelerations. Despite these benefits, active systems introduce added complexity, cost, and power consumption. Electronic components are also susceptible to harsh marine environments, humidity, salt corrosion, and electrical interference. These factors elevate the importance of robust design and fail-safe redundancy. This direction will reveal whether the adaptive fidelity of active isolation can meaningfully enhance WRI-based suspension strategies without compromising reliability.[78]

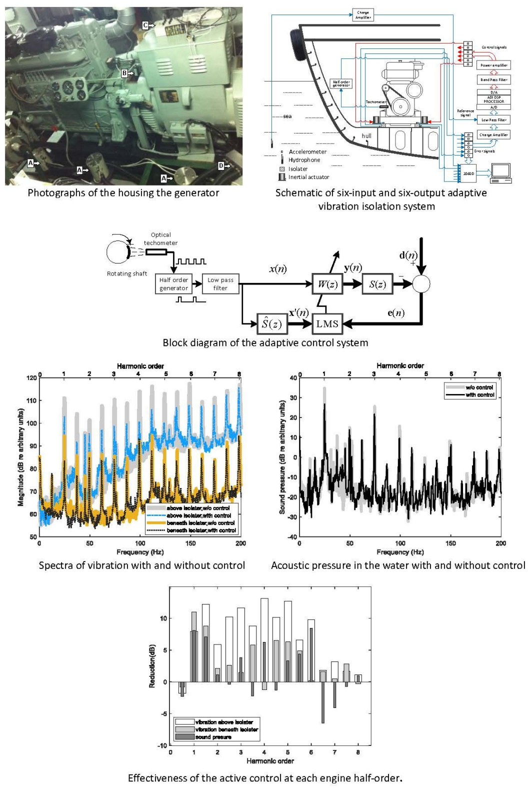


Figure 7.5: Conceptual layout of an active marine mount system with actuator-based control

8

Discusssion and Conclusion

8.1 Discussion

In this thesis, several conceptual vibration isolation configurations were conceptualized and studied to analyze their potential to isolate a marine battery pack under low-frequency dynamic loads. These loads are typical in marine vehicles, where wave-induced motion and propulsion disturbances possess the potential to introduce extreme vibration at low acceleration amplitude. The goal in this was to investigate whether wire rope isolators possess the potential to serve as a robust and efficient substitute for conventional hydro mounts under these conditions.

There were three design concepts considered. Concept A employed wire rope isolators arranged in a 45-degree compression configuration, beginning with eight isolators. However, simulation results indicated a high first-mode natural frequency of about twenty-eight hertz, which indicated poor low-frequency isolation. Consequently, a redesigned Version of Concept A was submitted. The new design used twelve isolators evenly distributed on all sides. The new design was successful in reducing the first mode frequency to around twelve hertz, a better range for marine isolation.

Concept B, with a base-mounted configuration of wire rope isolators with eight isolators, showed well-balanced performance. Its first mode frequency was approximately seventeen hertz, and its vibration response approximated closely the target profile for marine PSD excitation. This configuration performed roughly as well as the hydro-mount benchmark but with the benefit of a simpler, more modular design. Concept C posed the existing hydro mount solution. It demonstrated good isolation starting at approximately 10.9 hertz.

Although hydro mounts were effective for low-frequency applications, they are not good in high-frequency conditions and are known to require regular maintenance and are susceptible to environmental degradation, particularly in saltwater and harsh offshore conditions. Based on the comparison, results show that wire rope isolators could be applied successfully in marine environments. Configurations explored demonstrate acceptable levels of vibration control, and can be improved for manufacturability as well as performance.

8.2 Conclusion

This thesis studied the feasibility of wire rope isolators as a vibration isolation system for marine battery pack installations. It was triggered by the need to find a high-performance, low-maintenance, and long-term substitute for hydromounts, particularly for electrified marine propulsion systems.

Through the process of hand calculations, modal analysis, and random vibration simulations on representative marine power spectral density data, it was demonstrated that wire rope isolators configured and tuned appropriately offer isolation performance similar to or better than traditional hydromounts. Concept B, the base-mounted configuration, had certain merit based on its desirable frequency response, simplicity of installation, and structural strength.

Wire rope isolators also have several practical advantages. They are corrosion-resistant in nature, require no lubrication or internal fluid, and offer multi-axial stiffness in a compact package. Each of these characteristics makes them well suited to marine environments where reliability, durability, and long-term maintenance cost are all critical factors.

Finally, the conclusions of this thesis support the idea that wire rope isolators are not limited to only high-frequency or industrial applications. With appropriate design considerations, they can also be designed as a robust and effective method of vibration isolation in low-frequency applications for marine energy storage systems. Their use can be of great assistance towards the engineering of safer and more reliable marine electric propulsion systems.

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A

APPENDIX

A.1 Morphological Matrix

		Solution Principles				
Function	Sub Function	1	2	3	4	5
Absorb Vibrations & Shocks	Low Frequency Vibration	Foam Isolators with Compression Pads	Wire Rope Isolators (Marine-Grade)	Adaptive Hydraulic Dampers	Air Spring Isolators (Low-Rate)	Gel Pads with Bottom Anchoring
	High Frequency Vibration	Viscous Dampers with Embedded Sensor	Dual-Material Isolators (Rubber + Foam)	Rubber Isolators with Anti-Vibe Coating	Piezoelectric Dampers	
	Provide Multi Directional Damping	Hydraulic Isolators (Tri-Axial Design)	Metal Mesh Isolators (Spiral Layout)	Magnetic Isolators with Flex Mounts	Tuned Mass Damper System	Spring-Gel Hybrid with Rotational Mounting
Provide Structural Stability	Secure Battery Mounting	Bolt-On Metal Rubber Isolators	Clamped Frame Mounts with Spring Buffer	U-Shaped Spring Enclosure	Dual-Axis Shock Absorbing Brackets	
	Marine Grade durability	Stainless Steel Dampers with Sealant	Saltwater-Resistant Composite Gel Mounts	Rubber Housings with Marine Coating	Wire Rope Isolators with Zinc Plating	
Lightweight & Compact Design	Space Efficient Layout	Flat Gel Isolators	Low-Profile Rubber Mounts	Compact Spring-Based Cages	Slim Foam Panels	Stackable Mesh Isolators
	Material Optimization	Titanium Spring Coils	Polyurethane Rubber Mix	Carbon-Fiber Composite Shells		
	ESS arrangement	Bottom-Mounted Compact Isolators	Side Clamp-Based Spring Design	Modular Rack Integrated Dampers		
Enable Maintainability	Allow quick acceability	Quick-Release Mounting Clamps	Tool-Free Foam Isolators	Clip-On Rubber Mounts	Magnetic Snap-On Pads	
	Standard Interface	Universal ISO Bracket Mounts	Interchangeable Spring Modules			
	Reduce part complexity	Integrated Spring-Gel Units	Dual-Layer Foam Pads	Self-Locking Rubber Mounts	Composite Mesh Dampers	One-Piece Molded Isolators
Monitoring and Diagnostics	Real time Performance Tracking	MR Dampers with Live Feedback	Embedded Strain Gauges			
	Predictive Maintenance	Health Monitoring Circuit	Load Cycle Logging Sensors	Cloud-Linked Gel Isolators		
Adapt to Marine Condition	Meet the Marine standard	IMO Certified Wire Rope Isolators	Marine Rated Rubber Shells	Anti-Corrosive Gel Isolators	Zinc-Coated Metal Springs	Salt Fog Tested Composite Mounts
	Environmental compability	Recyclable Rubber Compounds	Bio-Polymer Foam Mounts	Eco-Friendly Gel Mix	Low-Toxicity Spring Materials	
	Thermal Mangement	Thermal Compensated Rubber Mounts	Heat Resistant Gel Damping Layer			

Figure A.1: Morphological Matrix

A.2 Pugh Matrix

Criterion	Hydromounts	Wire Rope with Silicone Pads	Diagonal Cage-Mounted Wire Rope	Shear-Resistant Side-Mount Isolation Concept	Base-Mounted Hydromount Isolation	Honeycomb with Rigid Cell Separator
Space Efficiency		+	+	+	+	+
Vibration Isolation (Low Freq)		+	+	0	+	+
Vibration Isolation (High Freq)		+	0	0	0	0
Shock Resistance						
Adaptability	DATUM	0	+	0	+	+
Marine Durability		-	-	-	-	-
Installation Complexity		-	-	-	-	-
Maintenance		0	0	0	0	0
Cost		-	-	-	-	-
Feasibility for Rack Layout		0	-	0	-	-
Sum +	0	3	3	1	3	3
Sum 0	0	3	2	5	2	2
Sum -	0	3	4	3	4	4
Net Score	0	0	-1	-2	-1	-1
Ranking	1	1	2	3	2	2

Figure A.2: Pugh Matrix

Criterion	Hydromounts	Wire Rope with Silicone Pads	Diagonal Cage-Mounted Wire Rope	Shear-Resistant Side-Mount Isolation Concept	Base-Mounted Hydromount Isolation	Honeycomb with Rigid Cell Separator
Space Efficiency	-		0	0	0	0
Vibration Isolation (Low Freq)	-		+	-	0	+
Vibration Isolation (High Freq)	-		+	0	-	-
Shock Resistance	-		+	-	+	+
Adaptability	+		-	0	-	-
Marine Durability	+		-	0	-	-
Installation Complexity	0	DATUM	0	0	0	0
Maintenance	+		-	0	-	-
Cost	+		-	0	-	0
Feasibility for Rack Layout	+		+	+	+	0
Sum +	5		4	1	2	2
Sum 0	1		2	7	3	4
Sum -	4	0	4	2	5	4
Net Score	1	0	0	-1	-3	-2
Ranking	1	2	2	3	5	4

Figure A.3: Pugh Matrix

Criterion	Hydromounts	Wire Rope with Silicone Pads	Diagonal Cage-Mounted Wire Rope	Shear-Resistant Side-Mount Isolation Concept	Base-Mounted Hydromount Isolation	Honeycomb with Rigid Cell Separator
Space Efficiency	-	0	0		0	0
Vibration Isolation (Low Freq)	-	0	-		0	+
Vibration Isolation (High Freq)	0	0	-		0	+
Shock Resistance	-	0	0		0	+
Adaptability	+	0	-		-	-
Marine Durability	+	+	-		-	-
Installation Complexity	0	0	0	DATUM	0	0
Maintenance	+	+	-		-	-
Cost	+	0	-		-	-
Feasibility for Rack Layout	+	0	+		+	+
Sum +	5	2	1		1	4
Sum 0	2	8	3		5	2
Sum -	3	0	6	0	4	
Net Score	2	2	-5	0	-3	0
Ranking	1	1	6	2	4	2

Figure A.4: Pugh Matrix

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