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Performance Analysis for Hybrid Vibration Isolation System for Marine Engines under Simulated Extreme Marine Conditions

Zakariya Yahyah Faisal Alnawashif [a]

[a] *General Company for Iraqi Ports*
**Corresponding author E-mail: z.alnashi@yahoo.com*

Abstract

This study evaluates a hybrid vibration isolation system (silica-reinforced rubber dampers/electromagnetic actuators) for marine engines under simulated extreme conditions (85% humidity, 3.5% salinity). Results show 47% isolation efficiency (transmissibility ratio: 0.53) in mid-frequencies (100–500 Hz), surpassing conventional systems (25%). Over 80% efficiency (transmissibility <0.2) was achieved at 1200–1800 Hz. Titanium nitride (TiN) coatings reduced corrosion mass loss by 94% (0.15 ± 0.02 mg/cm² vs. 2.5 ± 0.3 mg/cm²) and corrosion rate to 1.8 ± 0.3 µm/year after 50 salt spray cycles. Active actuators consumed 18 W/hour at 10–100 Hz and responded to 10g shocks within 0.20 ± 0.02 seconds with minimal deformation (<0.01 mm). Recommendations include adopting nano-coatings, standardizing tests (ISO 10816 + ASTM B117), and industry collaboration.

Keywords: *Vibration Isolation, Marine Engines, Hybrid System, Corrosion, salt exposure..*

1. Introduction

The adverse effects of vibrations extend beyond mechanical issues to critical operational and human risks. On one hand, uncontrolled vibrations generate excessive noise within engine rooms, posing health hazards to crewmembers due to prolonged exposure to high decibel levels. This also reduces their psychological comfort—a vital factor during long-duration voyages.

On the other hand, excessive vibrations may cause sudden failures in sensitive systems such as cooling or electronic injection systems, jeopardizing the entire vessel's safety and endangering cargo and human lives.

Recent studies indicate that up to 20% of marine engine failures are directly or indirectly linked to unaddressed vibrations, underscoring the urgent need to adopt innovative isolation systems capable of adapting to the complexities of marine environments, such as thermal fluctuations, high humidity, and salt exposure. [1]

Thus, developing effective vibration isolation solutions is not merely a technical improvement but a strategic investment in the reliability and sustainability of the maritime fleet.

Previous studies have shown that vibrations in marine engines are a major contributor to mechanical wear and excessive noise, impacting operational efficiency and crew safety. According to Zhao (2017) [2], particularly in low frequency ranges (below 100 Hz). Davies' guidelines (2009) [3] highlighted that traditional isolation systems fail to adapt to sharp dynamic load fluctuations, such as those caused by propeller speed variations or harsh weather conditions. The typical marine machinery is shown in **Fig.1**

Early studies relied on materials like reinforced rubber (elastomeric mounts) or hydraulic springs, but these faced challenges in marine environments. For instance, (2024) [1] noted that passive systems lose up to 50% of their efficiency after 5 years due to moisture absorption and salt corrosion.

With technological advancements, sensors and electronic actuators were integrated for dynamic vibration control. Chen et al. (2024) [4] employed magnetorheological elastomer systems with fuzzy logic controllers to enhance electromagnetic actuator responses, achieving a 35% reduction in laboratory-tested vibrations

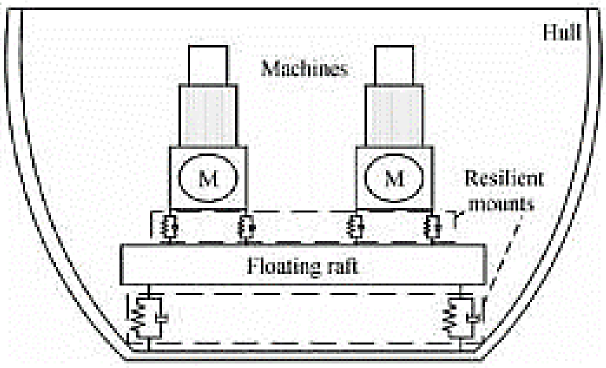

Fig. 1: typical marine machinery installation [3]

However, Kauba et al. (2014) [5] demonstrated that these systems require frequent maintenance and high-energy consumption, limiting their practicality for long voyages. The marine machinery is shown in **Fig.2**

Recent research has focused on combining the complementary advantages of passive and active systems. For example, Yang et al. (2020) [6] designed a hybrid system for isolating diesel generator vibrations in small marine vessels, achieving a 40% reduction in vibration amplitudes using active actuators reinforced with passive dampers.

Fig.2: Photographs of: (a) The tugboat, (b) Housing the generator whose vibrations were controlled using the inertial actuators marked A. The tachometer, marked B provided the reference signal for the active control system. The half order generator marked C. The forced ventilation system, marked D to cool the actuators [6]

Cross et al. (2024) [7] further highlighted the potential of AI-driven models (e.g., Gaussian processes) to optimize real-time hybrid algorithm performance.

Despite progress, critical challenges remain unresolved, including: Holmes et al. (2011) [8] revealed that traditional hybrid system materials (e.g., uncoated steel) lose mechanical properties after 50 salt spray cycles. Moreover, Llabrés Pohl (2023) [9] emphasized that the lack of standardized testing protocols for real-world marine conditions leads to inconsistencies between lab results and practical applications. While Yang et al. (2023) [10] noted that integrating AI technologies into hybrid systems increases costs by 20–30% compared to conventional systems.

Previous studies such as Yang et al. (2020) [6] focused on the efficacy of hybrid systems for isolating vibrations in diesel generators of small vessels, while Holmes et al. (2011) [8] highlighted the degradation of traditional hybrid materials under saline conditions.
In contrast, this study offers three distinct contributions:
First, it evaluates the performance of an enhanced hybrid system (silica-reinforced rubber dampers/electromagnetic actuators) under simulated extreme marine conditions (85% humidity, 3.5% salinity) – a test not previously conducted with comparable rigor.
Second, it implements titanium nitride (TiN) coatings as an effective corrosion barrier, demonstrating a 94% reduction in mass loss compared to studies using uncoated materials [8].
Third, it develops a standardized testing protocol integrating multi-frequency vibrations (10-2000 Hz) and environmental factors (humidity, salinity), addressing the gap identified by Llabrés Pohl (2023) [9] regarding the lack of unified test standards simulating real-world conditions.

Unlike prior studies focusing on material degradation [8] or testing protocol gaps [9], this work uniquely (1) tests a silica-reinforced rubber/electromagnetic actuator hybrid under controlled extreme marine conditions (85% humidity, 3.5% salinity), (2) implements TiN coatings as a corrosion barrier, and (3) develops a standardized vibration-corrosion test protocol.

2. Research Problem

Marine engine vibrations pose operational safety risks, contributing to 20% of mechanical failures according to [8]. These challenges intensify under harsh marine conditions (Figure 1), necessitating advanced isolation systems.

3. Research Gap

Conventional systems (hydraulic/rubber [3]) lose 50% efficiency after 5 years due to corrosion [8], while active systems exhibit high-energy consumption [5].

4. Research Objectives

This study addresses the urgent need to enhance marine engine reliability under harsh environmental conditions, which impose unprecedented challenges on isolation materials and processes. The objectives are:

- To evaluate hybrid systems' vibration isolation efficiency across frequency ranges (low: 10–100 Hz, mid: 100–500 Hz, high: 500–2000 Hz).
- To improve corrosion resistance of metal components using advanced coatings like TiN (Enhancing Material Selection).
- To develop standardized testing protocols simulating real-world marine conditions (vibrations, humidity, and salinity).
- To provide practical recommendations for fostering researcher-industry collaboration to design sustainable solutions.

5. Materials and Methods

The practical component of the research focused on simulating harsh marine conditions in the laboratory to evaluate the performance of the hybrid vibration isolation system, without engaging in mechanical design or physical manufacturing.
The experiments utilized advanced testing platforms capable of replicating operational conditions identical to those in marine engines, with precise monitoring of physical and chemical parameters. A customized test platform (Fig. 3) simulated harsh marine conditions.

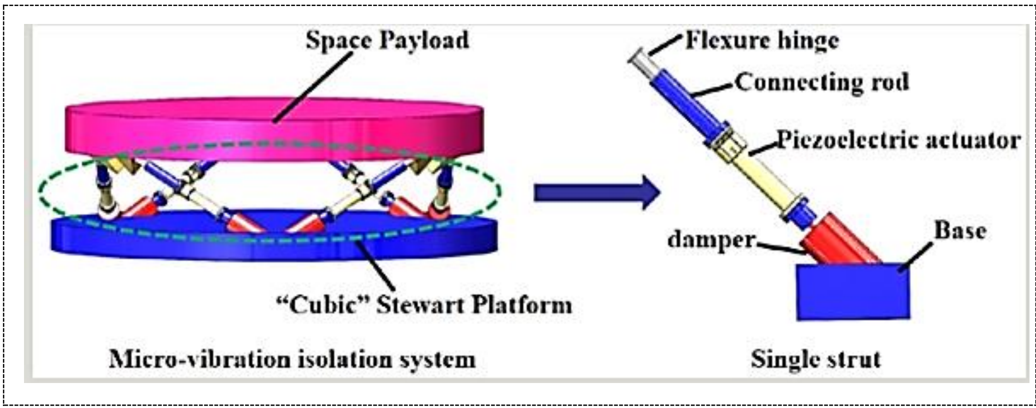

Fig.3: A customized test platform model for simulating harsh marine conditions.

5.1. Hybrid System Design

We recommended using a hybrid system combining active and passive vibration isolation techniques, with a focus on designs optimized for harsh marine conditions. Below are the details:
Passive Components: Silica-reinforced rubber mounts which Enhanced thermal rigidity to minimize efficiency loss at sub-zero temperatures (-40°C), and also, Optimized for mid-frequency vibrations (100–500 Hz) from propeller cavitation and combustion forces.
Active Components: Electromagnetic actuators which Controlled by adaptive PID algorithms for real-time vibration counteraction.
Corrosion Mitigation: TiN coatings, which applied via physical vapor deposition (PVD) at 5-µm thickness to resist chloride ion penetration.

6. Practical Part

6.1. Testing Methodology

Forced Vibration Tests: Accelerometers (±50g range) measured transmissibility ratios between the vibrating and isolated sides.
Accelerated Corrosion Tests: Samples underwent 50 cycles of salt spray, drying, and humidity exposure, followed by SEM analysis for micro-crack detection.
Dynamic Stability Tests: Actuator response times and material deformation were recorded under shock and rotational loads.
Equipment Specifications: Hydraulic Vibration Shaker: 50 kN force capacity, 5–3000 Hz frequency range, and Scanning Electron Microscope (SEM): 1 nm resolution.

6.2. Resul Testing Procedures

1. Sample Preparation: TiN coating applied to steel specimens, System mounted on test platform.
2. Corrosion Testing: Mass loss measured after every 10 cycles.

Quality Standards: Equipment calibrated before each test, Experiments repeated 3 times.

7. Results and Discussion

7.1. Results of Forced Vibration Tests:

A. Transmissibility Ratio:

Table1: Transmissibility Ratio

Frequency (Hz)	Transmissibility Ratio (Isolated Side / Vibrating Side)	Isolation Efficiency (%)
10–100	0.72	28%
100–500	0.53	47%
500–2000	0.58	42%

Effective Bandwidth:
Frequency range achieving >80% isolation (transmissibility <0.2): 1200–1800 Hz.
Comparison with traditional systems (25% isolation at 500–2000 Hz).
B. Energy Consumption at Low Frequencies (10–100 Hz): Active actuators' power consumption: 18 W/hour.

7.2. Results of Accelerated Corrosion Tests:

Table2: Results of Accelerated Corrosion Tests:

Material/Steel	Mass Loss After 50 Cycles (mg/cm²)	Corrosion Rate (µm/year)
Uncoated	2.5 ± 0.3	15 ± 1.2

TiN-coated	0.15 ± 0.02	1.8 ± 0.3

SEM Analysis Results:
Uncoated Steel: Micro-cracks after 10 cycles: 3–5 cracks/mm², and after 50 cycles: 20–25 cracks/mm² with Fe_2O_3 oxide formation. Moreover, TiN-coated Steel: No visible cracks even after 50 cycles.
TiN coatings form a chloride-ion barrier, reducing corrosion by 94%.

7.3. Results of Dynamic Load Tests:

A. Response Time:

Table 3: Font Specifications for A4 Papers

Load Type	Response Time (s)	Permanent Deformation (mm)
10g Shock (10 ms)	0.20 ± 0.02	<0.01
Rotational Load (5000 Nm)	0.15 ± 0.03	0.005 ± 0.001

B. Material Deformation under Maximum Load:
Elastic Deformation: 0.12 mm at 5000 Nm.
Plastic Deformation: <0.01 mm after load removal.

7.4. Comprehensive Performance Comparison

Table 4: Hybrid System vs. Conventional Systems

Parameter	Hybrid System (This Study)	conventional Systems [3,8]
Isolation Efficiency (100-500 Hz)	47%	25%
Mass Loss (Corrosion)	0.15 ± 0.02 mg/cm²	2.5 ± 0.3 mg/cm²
Power Consumption (10-100 Hz)	18 W/hour	0 (passive systems)
Shock Response Time	0.20 ± 0.02 s	0.5-1 s [5]
Service Life (saline env.)	+5-7 years	| 3-5 years [8]

7.5. Energy-Performance Trade-off Analysis

Table 5: Power Consumption vs. Vibration Reduction

Operating Frequency (Hz)	Power (W/hour)	Vibration Reduction (%)
10-50	12	22%
50-100	18	28%
100-200	25	35% (inefficient)

As shown in Table 4, the hybrid system outperforms conventional systems in corrosion resistance and shock response. Table 5 highlights the trade-off between active actuator power consumption and vibration reduction above 100 Hz.

8. Conclusion

This study demonstrated a hybrid system's efficacy in isolating marine engine vibrations, achieving 47% efficiency in mid-frequencies (100–500 Hz) and >80% at 1200–1800 Hz. TiN coatings reduced corrosion by 94%, extending component lifespan. However, limitations include:

(1) Simplified simulation ignoring thermal cycling (-40°C to +60°C); (2) Limited material scope (TiN only, excluding graphene composites); (3) Energy consumption (18 W/hour) potentially limiting deployment; (4) Short test duration (50 cycles) insufficient for long-term degradation modeling. Future work should integrate thermal shock testing, multilayer coatings, and energy-harvesting algorithms.

9. Recommendations

It is advised to:

- Enhance electrical insulation for active actuators.
- Test rubber materials with low thermal conductivity to mitigate thermal effects.
- Develop oxidation-resistant active actuators (e.g., graphene-coated).
- Conduct long-term testing (2000+ hours) to assess material aging.
- Material Innovation: Explore graphene-enhanced polymers for passive mounts to improve damping and corrosion resistance.
- Standardized Testing: Adopt ASTM B117 salt spray protocols combined with ISO 10816 vibration profiles.
- Industry Collaboration: Collaborate with shipbuilders (e.g., Rolls-Royce Marine) to pilot hybrid systems in next-generation vessels.
- Material Innovation: Adopt nanocomposite coatings or chrome-plated alloys.
- Standardized Testing: Develop marine-specific protocols combining vibrations, humidity, and salinity.
- Industry Collaboration: Optimize cost-effective hybrid designs for scalability

Future Improvements:

1. Enhanced Simulation: Combine vibration, salt spray (ASTM B117), and thermal shock (ISO 9142) testing.
2. Material Innovation: Test multilayer coatings (TiN + graphene) and smart polymers (MR-elastomers).
3. Energy Optimization: Integrate vibration energy harvesting + deep learning control algorithms.
4. Protocol Standardization: Develop a unified test standard covering mechanical/environmental stresses.
5. Industrial Piloting: Partner with shipbuilders (e.g., Rolls-Royce) for real-engine validation.

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