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Vibration and Grease Condition Monitoring in Rotating Marine Mechanical Equipment: A Review

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Abstract
Rotating mechanical equipment forms the operational backbone of marine vessels and offshore installations. Main propulsion machinery, shaft lines, thrusters, deck cranes, winches, pumps, fans, and electric motors all depend on rolling element bearings, gears, and couplings that must survive sustained loading in one of the harshest industrial environments on earth. Unplanned failure of such equipment at sea carries consequences that extend far beyond repair cost, including loss of propulsion, grounding risk, environmental damage, and threats to crew safety. Condition monitoring has therefore become central to modern marine maintenance strategy, and two complementary technologies dominate the field: Vibration analysis, which interrogates the dynamic response of the machine, and grease or lubricant condition monitoring, which interrogates the health of the tribological interface itself. This review surveys the state of the art in both domains as applied to marine rotating machinery. Vibration monitoring is examined from sensing hardware through signal processing, covering time domain statistical indicators, spectral and envelope analysis, time frequency decomposition, and the rapid rise of machine learning and deep learning diagnostics. Grease condition monitoring is reviewed with attention to grease degradation mechanisms in the marine environment, offline laboratory techniques such as spectroscopic, rheological, and wear debris analysis, and emerging online sensing approaches including dielectric, ultrasonic, and acoustic emission methods. The complementary nature of the two technologies is emphasised, and the enabling infrastructure surrounding them, including sensing networks, data architectures, cybersecurity, maintenance logistics, safety management, and programme economics, is reviewed by drawing on developments in adjacent asset intensive industries. The review closes by identifying practical challenges specific to ships, including non stationary operating profiles, sensor survivability, limited crew expertise, and data transfer constraints, and outlines future research directions in sensor fusion, digital twins, and prognostics for remaining useful life estimation.

Keywords: Condition Monitoring, Vibration Analysis, Grease Degradation, Marine Machinery, Rolling Element Bearings, Predictive Maintenance, Wear Debris, Machine Learning, Prognostics

1. Introduction

Maritime transport carries roughly ninety percent of world trade by volume, and the reliability of the machinery installed on ships and offshore platforms is a direct determinant of the safety, economy, and environmental performance of the industry. A modern vessel is, in mechanical terms, a dense collection of rotating equipment: The main engine and its turbochargers, reduction gearboxes, shaft line bearings, stern tube arrangements, controllable pitch propeller mechanisms, bow and stern thrusters, steering gear, generators, purifiers, compressors, pumps of every description, ventilation fans, and deck machinery such as cranes, windlasses, and mooring winches. The overwhelming majority of these machines rely on rolling element or journal bearings, and a very large fraction of those bearings, particularly in deck machinery, thrusters, crane slew rings, and electric motors, are grease lubricated.

Historically, marine maintenance followed either a corrective philosophy, in which equipment was run until failure, or a preventive philosophy based on fixed calendar or running hour intervals. Both approaches are unsatisfactory for critical rotating machinery. Corrective maintenance exposes the vessel to catastrophic in service failures, while time based preventive maintenance frequently results in the replacement of healthy components and can introduce failures through maintenance induced defects such as bearing mounting damage or over greasing. The industrial literature documents a broad transition from reactive toward predictive maintenance philosophies in mechanical systems, in which sensing, smart fault detection in building services plant, thermodynamic efficiency control, and incident prevention practices are embedded directly into maintenance engineering, and in which plant uptime is understood to depend jointly on technical condition and on the readiness of the surrounding maintenance organisation (Sunday *et al*., 2020; Sunday & Omoegun, 2022; Sunday *et al*., 2019; Okonkwo *et al*., 2018b; Obogo *et al*., 2021b). Condition based maintenance, in which the actual health of the machine is measured and maintenance is scheduled only when degradation is detected, has been shown across many industries to reduce lifecycle cost while improving availability, and it is now embedded in the machinery survey schemes of the major classification societies (Jardine *et al*., 2006; Mobley, 2002).

This transition is part of a wider digital transformation of asset intensive industries, in which lifecycle performance management, asset registers with inventory visibility, geospatial asset management, and structured cloud migration strategies have reshaped how large equipment fleets are operated and maintained (Adelanwa *et al*., 2023a; Okonkwo *et al*., 2023b; Dagodzo & Ahiaeke Patrick, 2021a; Ladapo *et al*., 2022b; Sanni, 2023a). Two monitoring technologies are of particular importance for grease lubricated rotating marine equipment. The first is vibration monitoring, the most mature and widely deployed condition monitoring technology for rotating machinery in general (Randall, 2011). The second is grease condition monitoring, which is younger and less standardised, but which addresses a blunt statistical reality: A large share of rolling bearing failures are lubrication related, caused by lubricant starvation, ageing, contamination, or water ingress rather than by fatigue of properly lubricated surfaces (Lugt, 2009; Lugt, 2013). In the marine environment, with its salt laden humid atmosphere, wash down water, wide temperature excursions, and intermittent heavily loaded duty cycles, grease degradation is accelerated and lubrication related failure modes are especially prominent.

The scope of this review is deliberately practical. It covers rotating mechanical equipment installed on merchant vessels, naval vessels, and offshore units, with emphasis on grease lubricated bearings and gears, and it treats condition monitoring as an engineering system that spans transducer, signal path, analysis, decision, and maintenance action. Literature was drawn from the tribology, machine diagnostics, and marine engineering communities, supplemented by adjacent asset intensive sectors, power generation, process industry, construction, aviation, and enterprise information systems, wherever methods developed there transfer to the marine problem. Purely theoretical rotor dynamics, circulating oil systems for main engines, and structural health monitoring of the hull are touched on only where they intersect the two central themes. Throughout, the review distinguishes three questions that are often conflated in practice: Whether a fault exists (detection), what and where it is (diagnosis), and how long the machine can safely run (prognosis), because the two monitoring technologies contribute differently to each.

The purpose of this review is to bring these two threads together with a specifically marine focus, while also situating them within the enabling technological and organisational context, sensing networks, data platforms, cybersecurity, logistics, safety management, and economics, that determines whether monitoring programmes succeed in practice. The review is narrative in method: Literature was drawn from the tribology, machinery diagnostics, and marine engineering journals, from international standards, and from related and semi related work in adjacent asset intensive industries whose methods transfer to the marine monitoring problem, with coverage restricted to material published up to 2023. To the best of the authors' knowledge, no previous review has jointly treated vibration analysis and grease condition monitoring for marine rotating machinery together with the surrounding implementation context, and this integrated treatment constitutes the contribution of the paper. The contribution of the paper lies in this joint treatment: Whereas vibration diagnostics and grease analysis are usually reviewed as separate disciplines, they are examined here as complementary observations of a single tribological system, interpreted through the specific environmental, operational, and regulatory constraints of ships, and connected explicitly to the surrounding implementation infrastructure drawn from adjacent asset intensive industries. Section 2 characterises marine rotating equipment and its environment. Section 3 reviews vibration based condition monitoring. Section 4 reviews grease degradation and grease condition assessment. Section 5 discusses integration of the two data streams. Section 6 reviews the enabling infrastructure and management context. Section 7 discusses representative application cases together with open challenges and future research directions, and Section 8 concludes.

2. Marine Rotating Equipment and Its Operating Environment

2.1 Equipment classes and typical failure modes

Marine rotating machinery may be broadly grouped into propulsion related equipment, auxiliary engine room equipment, and deck machinery. Propulsion equipment includes the main engine, reduction gearing, thrust and intermediate shaft bearings, stern tube bearings, and thrusters. Auxiliary equipment includes diesel generators, centrifugal and positive displacement pumps, compressors, separators, and ventilation fans. Deck machinery includes anchor windlasses, mooring winches, cargo and provision cranes, davits, and hatch cover drives. Grease lubrication dominates in deck machinery, crane slew bearings, open gears, wire rope sheaves, electric motor bearings, and many thruster and rudder components, because grease remains in place without circulating systems, seals the bearing against the environment, and tolerates the intermittent operation typical of these machines.

The dominant failure modes of this equipment population are bearing failures, gear tooth damage, misalignment and unbalance related failures, coupling wear, and structural looseness (Randall & Antoni, 2011). Rolling element bearing failures follow a well documented progression: Subsurface or surface initiated fatigue produces micro spalls that grow into macroscopic spalling of raceways and rolling elements, ultimately leading to cage failure and seizure. In marine service, however, a large proportion of bearings never reach their calculated fatigue life because lubrication failure, corrosion, false brinelling during transport or standby, and contaminant induced abrasive wear intervene first. Slow rotating, heavily loaded components such as crane slew rings and windlass bearings are especially problematic because their fault signatures are weak and their grease is highly loaded and infrequently replenished. The risk profile of this machinery is inseparable from how it is operated: Studies of heavy lifting and crane installation operations, risk pathway modelling for lifting and rigging, occupational safety management in oil and gas maintenance projects, and structured development and performance evaluation methodologies for process machinery all underline that mechanical integrity and operational practice must be assessed together (Obogo *et al*., 2020b; Arumosoye & Obriki, 2022; Obogo *et al*., 2020c; Bello *et al*., 2022a; Bello *et al*., 2022b).

2.2 Environmental and operational stressors

Several features of the marine environment shape both the degradation processes and the monitoring problem. First, the atmosphere is saline and humid, and deck equipment is exposed to green water, spray, and wash down. Water ingress into grease lubricated bearings promotes corrosion, degrades the grease thickener structure, reduces film forming capability, and can lead to hydrogen assisted rolling contact fatigue. Corrosion management is therefore a first class integrity concern for marine machinery and its supporting structures, and the adjacent engineering literature on corrosion inhibition, non destructive testing based integrity management, weld integrity evaluation, and welding inspection and quality assurance in large infrastructure provides directly transferable methods for shafts, foundations, crane pedestals, and pressure retaining components (Atta *et al*., 2018; Atta *et al*., 2020; Atta *et al*., 2021; Atta *et al*., 2022).

Second, temperatures vary widely, from arctic cold soak to engine room ambients exceeding fifty degrees Celsius, driving grease oxidation at the high end and stiffening or oil separation at the low end. Third, duty cycles are highly non stationary: A mooring winch may stand idle for weeks and then operate near maximum load, a shaft line experiences continuous slow speed torque with superimposed propeller induced fluctuations, and a thruster operates transiently during manoeuvring. Fourth, the vessel itself is a moving, flexing, vibrating platform, so machinery vibration measurements are contaminated by hull girder vibration, wave induced motion, adjacent machinery, and propeller excitation. Fifth, marine machinery operates under tightening environmental constraints: Lifecycle risk assessment for offshore produced water, integrated treatment strategies for oily waste streams, evolving fuel formulations, and circular economy expectations for chemical and lubricant waste all influence how greases, waste grease, and wash down effluent must be selected, handled, and disposed of (Falegan & Aniebonam, 2022; Falegan & Aniebonam, 2023; Bello *et al*., 2023b; Okojie & Abioye, 2020). Finally, ships operate far from laboratory support, with limited onboard expertise and constrained satellite bandwidth, which places a premium on robust, automated, low data rate monitoring solutions.

2.3 Classification society and regulatory framework

Condition monitoring on ships does not exist in a regulatory vacuum. The machinery of a classed vessel is subject to periodic survey, traditionally through open up inspection of bearings, gears, and shafting on a five year cycle. All major classification societies now operate planned maintenance scheme notations with condition monitoring credit, under which approved vibration and lubricant analysis programmes substitute for a substantial share of invasive surveys. To obtain and retain such notation, the operator must demonstrate documented measurement procedures, calibrated instrumentation, trained personnel, defined alert and alarm criteria, and a closed loop between condition findings and the planned maintenance system. Flag state and international requirements add further layers: The International Safety Management Code requires that critical equipment be identified and that measures be in place to ensure its reliability, which a documented condition monitoring programme directly satisfies, and cyber risk management requirements bring the monitoring infrastructure itself within the safety management system. For lifting appliances, crane certification regimes increasingly reference internal examination or grease sampling of slew bearings as a condition of continued certification. The practical consequence is that marine condition monitoring must be designed for auditability from the outset: Raw data retention, traceable analysis records, versioned alarm limits, and clear accountability for responses to alerts are as much a part of the system as the sensors themselves. Programmes that treat these obligations as an afterthought commonly fail their first notation audit even when their technical detection performance is good (Mobley, 2002; Jardine *et al*., 2006).

3. Vibration Based Condition Monitoring

3.1 Principles and measurement practice

Vibration monitoring rests on the principle that mechanical faults alter the dynamic forces within a machine and therefore alter the vibration measured on its structure. Each fault class has a characteristic signature. Unbalance produces vibration at the shaft rotational frequency; misalignment produces strong second harmonic content and axial vibration; gear damage modulates the gear mesh frequency, producing sidebands spaced at shaft speed; and rolling element bearing defects generate impulsive excitation at the bearing characteristic defect frequencies computable from bearing geometry and shaft speed (Randall & Antoni, 2011). The workhorse transducer is the piezoelectric accelerometer, valued for its wide frequency range, ruggedness, and stability. Measurement and evaluation practice is guided by international standards, notably the ISO 20816 series for broadband machine vibration and ISO 13373 for condition monitoring procedures (International Organization for Standardization, 2002, 2016), supplemented by classification society rules for machinery condition monitoring notation. Practical implementations increasingly rely on virtual instrumentation and modular data acquisition environments, and demonstrations of vibration based condition monitoring of rotating machinery built on platforms such as LabVIEW illustrate how flexible, low cost monitoring stations can be assembled for workshop and shipboard use (Omoegun *et al*., 2023).

3.2 Time domain analysis

Time domain indicators are computed directly from the raw waveform and remain valuable because they are simple, computable on inexpensive embedded hardware, and effective for trending. Root mean square value tracks overall vibratory energy and responds to unbalance, misalignment, and advanced degradation. Peak value and crest factor respond to impulsiveness and therefore to early bearing and gear surface damage. Kurtosis rises markedly when localised bearing defects appear and can fall again as damage becomes distributed, which motivates its use in combination with energy measures rather than alone (Rai & Upadhyay, 2016). For gears, time synchronous averaging suppresses non synchronous content and isolates the vibration of an individual gear, enabling residual and difference signal metrics that are sensitive to localised tooth damage.

3.3 Frequency domain and envelope analysis

Spectral analysis via the fast Fourier transform is the foundation of vibration diagnostics, mapping measured energy onto the characteristic frequencies of specific components. For rolling bearings, the direct spectrum is often uninformative in early damage stages because defect impulses are weak, broadband, and buried beneath gear mesh and shaft harmonics. The established solution is envelope analysis: Defect impacts excite structural resonances in the kilohertz range, and band pass filtering around such a resonance followed by demodulation yields an envelope spectrum that displays the bearing defect frequency and its harmonics with high clarity (Randall & Antoni, 2011). The selection of the demodulation band was historically a matter of experience, but spectral kurtosis and the fast kurtogram provided a principled, automated means of locating the most impulsive frequency band (Antoni, 2006; Antoni & Randall, 2006). Cepstrum analysis complements envelope methods by detecting families of harmonics and sidebands, which is particularly useful in geared marine drives where sideband spacing identifies the faulty shaft.

3.4 Time frequency and non stationary methods

Marine machinery frequently operates under varying speed and load, during manoeuvring, in heavy weather, or in the inherently transient duty of cranes and winches. Under such conditions the stationarity assumption behind conventional spectral analysis fails. Time frequency methods resolve signal energy jointly in time and frequency: The short time Fourier transform offers simplicity at fixed resolution, the continuous wavelet transform provides multi resolution analysis well suited to short transients, and adaptive decompositions such as empirical mode decomposition and variational mode decomposition separate the signal into oscillatory modes from which fault features are extracted (Rai & Upadhyay, 2016). Order tracking, in which the vibration signal is resampled against measured shaft angle, is essential for machinery with significant speed variation and is standard practice for propulsion shaft line analysis. Cyclostationary analysis, which exploits the hidden periodicity of modulated bearing and gear signals, has proven especially powerful for weak fault detection in noisy multi source environments such as engine rooms (Randall, 2011).

3.5 Machine learning and deep learning diagnostics

The last decade has seen an explosion of data driven approaches to vibration diagnostics. Classical machine learning pipelines combine engineered features with classifiers such as support vector machines, random forests, and shallow neural networks, while deep learning removes manual feature design entirely: Convolutional networks operating on raw waveforms or spectrograms, recurrent architectures capturing temporal degradation dynamics, and autoencoder based anomaly detectors trained only on healthy data have all been demonstrated with strong results (Lei *et al*., 2020; Zhang *et al*., 2020). The methodological toolkit underpinning these diagnostics is shared with a much wider analytics literature: Systematic reviews of machine learning for fraud and anomaly detection, anomaly detection in time series data, natural language processing for surveillance applications, predictive analytics for institutional risk, and artificial intelligence techniques for automated software testing all rehearse the same core problems of feature learning, imbalanced classes, drift, and validation that condition monitoring must solve (Atakpa & Abetoh, 2022; Atakpa, 2021; Atakpa & Fobellah, 2023; Atakpa & Abolaji, 2023; Aliliele & Mbonu, 2023c; Borah *et al*., 2022; Mbonu *et al*., 2021b).

For the marine sector specifically, data driven condition monitoring of naval propulsion plants has been demonstrated using machine learning on shipboard automation data (Cipollini *et al*., 2018), and anomaly detection approaches that require only healthy baseline data are attractive because labelled failure data from ships are scarce. The principal open issues are domain shift between operating conditions and between sister vessels, class imbalance, and the interpretability demanded by surveyors and superintendents. Work on hybrid deep learning forecasting, on the fairness and equity consequences of accurate but unevenly performing predictive models, on interpretable machine learning for early failure prediction in distributed assets, and on human in the loop machine learning provides directly relevant guidance for building diagnostic models that engineers can question, correct, and trust (Komi, 2021a; Komi, 2023; Komi, 2021b; Ladapo *et al*., 2022a). More broadly, the maturing practice of applied forecasting and predictive cost modelling in operations, including demand forecasting algorithms, predictive cash flow and simulation based process optimisation, geospatial predictive methods, and quantitative asset valuation frameworks, offers transferable lessons on model lifecycle management, backtesting discipline, and the coupling of predictions to decisions (Tonoyan *et al*., 2021a; Tonoyan *et al*., 2021b; Tonoyan *et al*., 2022b; Tonoyan *et al*., 2022c; Tonoyan *et al*., 2022a; Tonoyan *et al*., 2023).

3.6 Monitoring of marine electric machines and low speed machinery

Electric motors drive most auxiliary and deck machinery on modern vessels, and the electrification of propulsion increases their criticality. Motor condition assessment couples vibration analysis with electrical signature analysis, and rests on a modelling literature for machine parameter identification and optimisation, including multi objective optimisation of single phase induction machine loss and weight functions, voltage control in networks with distributed generation, power electronic efficiency in modern power systems, and the engineering of reliable telecommunication links that carry monitoring data (Amayo, 2017; Amayo & Popoola, 2017a; Amayo & Popoola, 2017b; Amayo & Ubeku, 2015; Oshevire & Eyenubo, 2017; Adenuga, 2023). Slow rotating equipment, including crane slew bearings, windlass shafts, and stern tube arrangements, poses a distinct challenge because defect impact energy scales with speed, and at a few revolutions per minute conventional accelerometer signals may show no measurable fault content. Approaches that have shown promise include acoustic emission monitoring, which detects the high frequency stress waves released by crack growth and asperity contact and remains sensitive at very low speeds (Mba & Rao, 2006), high resolution long duration envelope analysis, and stress wave or shock pulse methods.

3.7 Practical implementation of shipboard vibration programmes

Translating the techniques of the preceding subsections into a working shipboard programme raises implementation questions that the research literature often leaves implicit. The first is measurement point selection and repeatability. Diagnostic sensitivity depends on a short, stiff transmission path from the bearing to the transducer, so measurement points must be defined on bearing housings rather than casings or guards, marked permanently, and measured in consistent directions; on route based programmes, magnet mounted accelerometers demand flat, clean, painted free spot faces if high frequency content is to be preserved. The second is operating condition control. Because vibration amplitudes vary strongly with load and speed, readings must be taken under defined reference conditions, for pumps at a defined valve position, for generators at a defined load band, and for shaft lines at defined shaft speeds, or must be normalised afterwards using recorded process parameters. The third is alarm philosophy. Absolute limits drawn from ISO 20816 zones serve as a coarse safety net, but experience across fleets shows that statistical baseline limits, set per machine and per measurement point from the machine's own healthy history, detect developing faults far earlier; a common scheme sets alert at the baseline mean plus two to three standard deviations with alarm at a larger multiple, refreshed as the baseline matures (International Organization for Standardization, 2016).

The fourth question is periodicity. Monthly route based measurement suits most auxiliary machinery, whose failure development times span months, but is inadequate for machinery with fast failure progression or intermittent operation; deck cranes are best measured during planned load tests, and thrusters during scheduled manoeuvring trials, so that comparable operating states recur. The fifth is data management discipline: Measurements are only as useful as their metadata, and programmes fail quietly when machine identities, measurement point codes, or operating conditions are recorded inconsistently across crew changes. Finally, severity assessment must feed a decision, not merely a report. Mature programmes define, in advance, the maintenance response attached to each alarm class, from increased measurement frequency, through lubricant sampling and thermographic confirmation, to planned component replacement at the next port with suitable crane and spares availability. This pre agreed escalation ladder is what converts a monitoring technology into a maintenance strategy, and it is the element most frequently missing when programmes are audited after an unexpected failure (Mobley, 2002).

4. Grease Condition Monitoring

4.1 Grease function and degradation mechanisms

Lubricating grease is a semi solid dispersion of a thickener, most commonly a metallic soap such as lithium or lithium complex, in a base oil, with an additive package providing oxidation inhibition, corrosion protection, and extreme pressure or anti wear performance. In a rolling bearing the grease acts as an oil reservoir: After an initial churning phase the grease is pushed aside into the covers and cage pockets, and lubrication proceeds by slow bleed of base oil into the contact tracks (Lugt, 2009; Lugt, 2013). Grease life, rather than material fatigue, therefore limits the life of many sealed and deck mounted marine bearings.

Grease degrades through interacting mechanical, chemical, and physical mechanisms. Mechanical working shears and breaks down the thickener fibre structure, softening the grease and reducing its ability to hold oil in place. Chemical ageing proceeds mainly through oxidation of the base oil and thickener, accelerated exponentially with temperature, producing acids, sludge, and varnish, consuming antioxidant additives, and eventually hardening the grease and destroying its bleed capability (Rezasoltani & Khonsari, 2016). Physical degradation includes base oil evaporation and oil separation, after which the grease can no longer replenish the contact. Superimposed on these intrinsic mechanisms are contamination processes that dominate in marine service: Ingress of sea water and fresh water, which emulsifies into the grease, hydrolyses additives, corrodes surfaces, and collapses film thickness; ingress of hard particles such as grit, cargo dust, and rust; and cross contamination with incompatible greases during maintenance. The grease in a failing bearing also accumulates wear debris from the bearing itself, which makes the grease a valuable diagnostic medium, a carrier of the physical evidence of wear.

4.2 Offline laboratory analysis of grease

In service grease analysis is less standardised than oil analysis, in part because sampling is intrusive and the tiny quantities recoverable from a bearing are difficult to handle, but a mature toolbox now exists. Consistency and rheological measurements track thickener breakdown and hardening. Fourier transform infrared spectroscopy quantifies oxidation, additive depletion, water content, and product identity, and is among the most information rich small sample techniques. Oil bleed tests measure the remaining capacity of the grease to release lubricating oil. Water content can be measured by Karl Fischer titration or estimated spectroscopically. Elemental analysis quantifies wear metals such as iron, copper, and chromium, contaminants such as silicon and sodium, and additive elements such as zinc and phosphorus, with sodium serving as a tell tale marker of sea water ingress. Ferrography and particle counting characterise wear debris morphology and severity, and linear sweep voltammetry can measure remaining antioxidant content (Rezasoltani & Khonsari, 2016). Taken together, a small set of measurements, consistency, oxidation, water, ferrous debris, and elemental fingerprint, provides a practical grease health assessment for marine equipment.

The quality of these results depends on the quality of the laboratories that produce them. Fleet scale grease and oil analysis programmes rely on networks of shore laboratories whose siting, spatial planning, regulatory compliant design, sustainable materials and energy strategies, and risk managed construction and delivery determine turnaround time, analytical accuracy, and cost per sample; the substantial literature on developing and delivering diagnostic laboratory infrastructure in demanding and resource constrained settings therefore carries direct lessons for the marine lubricant analysis supply chain (Aminu-Ibrahim *et al*., 2018; Aminu-Ibrahim *et al*., 2019; Aminu-Ibrahim *et al*., 2020; Ogbete *et al*., 2018; Ogbete *et al*., 2019). Equally relevant are lifecycle performance evaluation of purpose built laboratories, design standards for scalable sample collection and logistics networks, and evidence that well planned diagnostic infrastructure measurably expands access to testing services (Ogbete *et al*., 2020; Ogbete *et al*., 2021; Ogbete *et al*., 2022; Ogbete *et al*., 2023; Aminu-Ibrahim & Ogbete, 2023).

4.3 Online and in situ grease condition sensing

The logistics of grease sampling from ships, and the desire for continuous protection of critical bearings, motivate online grease condition sensing. Several modalities have been demonstrated. Dielectric and impedance sensors track the permittivity and conductivity of grease, which change with water content, oxidation products, metallic debris, and thickener degradation. Ultrasonic methods measure the reflection coefficient at the raceway and can infer lubricant film thickness in situ, directly detecting starvation. Acoustic emission sensing detects the asperity contact activity that rises when the lubricant film collapses, making it an indirect but sensitive online indicator of lubrication quality (Mba & Rao, 2006). Optical and infrared photometric sensors track darkening and oxidation of grease in feed lines, temperature remains the simplest though latest indicator, and inductive debris sensors have been adapted to centralised greasing systems. No single online sensor yet captures grease health completely, and the consensus of the literature is that combinations of modalities provide far more reliable assessments than any modality alone.

4.4 Grease monitoring in marine practice

In current marine practice, grease condition monitoring is applied most systematically to high value, high consequence components: Crane and davit slew bearings, thruster gears and bearings, controllable pitch propeller mechanisms, stern rollers, and windlass bearings. Classification societies and crane certification bodies increasingly recommend periodic grease sampling of slew bearings, because slew ring failure modes develop internally with little external sign and can be catastrophic. Published experience shows that trending ferrous debris and elemental wear metals in slew bearing grease reliably identifies raceway degradation years before functional failure, allowing planned replacement. The chief practical difficulties are obtaining representative samples from large slow bearings, the absence of universally accepted condemnation limits, and the need for grease specific baselines. Grease selection, replenishment, and disposal also increasingly sit inside environmental, social, and governance reporting obligations: Automated ESG reporting for energy assets, integration of artificial intelligence with ESG metrics in infrastructure auditing, predictive monitoring of emissions and infrastructure risk, and green procurement strategies that weigh cost against long term environmental responsibility all shape how shipowners must document lubricant stewardship (Abioye *et al*., 2023; Okojie *et al*., 2023a; Okojie *et al*., 2023b; Akin-Oluyomi *et al*., 2023a).

4.5 Sampling practice, trending, and condemnation limits

The value of a grease analysis programme is decided at the sampling point and in the trending discipline that follows. Grease does not mix, so a sample represents only its location; good practice fixes, per machine, a consistent sampling port, method, and point in the operating cycle, discards the first purge volume, samples large slew bearings at multiple points around the circumference, and records machine, port, running hours, and regreasing history, since regreasing resets every trend. Interpretation is comparative rather than absolute: Fresh grease of the same product is retained as reference, ferrous debris density is trended as the most decision relevant trace, and elemental ratios separate mechanisms, iron with chromium indicating raceway material, copper indicating cage or bushing wear, silicon with aluminium indicating ingested dust, and sodium with magnesium indicating sea water. Water, oxidation, and consistency results then contextualise the debris: Heavy debris in dry fresh grease suggests a mechanical or alignment problem, while modest debris in wet, oxidised, hardened grease points to lubrication failure and to relubrication or seal repair as the first action. These procedural disciplines determine whether the techniques of Sections 4.2 and 4.3 deliver usable conclusions.

Interpretation rests on trending rather than absolute values. Because grease chemistry, thickener type, and additive fingerprint differ between products, a result is meaningful only against a baseline of the same grease in the same duty, and the essential discipline is therefore to archive a reference sample of every new grease introduced to the fleet and to resample monitored points at fixed intervals. Within a trended series, three patterns carry most of the diagnostic weight: A rising ferrous debris density with increasingly severe particle morphology indicates active wear of the monitored component; rising sodium, chlorine, or water content indicates seal failure and sea water ingress and calls for regreasing and seal renewal before surface damage begins; and rising oxidation together with falling bleed capability indicates that the grease has reached the end of its service life regardless of bearing condition, so the relubrication interval, not the bearing, is the problem. Published condemnation thresholds should be treated as starting points to be tightened or relaxed against fleet experience, and any severe or anomalous result should trigger a confirmatory resample before major intervention, since a single contaminated sample is the most common cause of false alarms in grease programmes (Rezasoltani & Khonsari, 2016; Lugt, 2009).

5. Integrating Vibration and Grease Monitoring

5.1 Complementarity of the two technologies

Vibration and grease analysis observe the same tribological system from different vantage points and at different stages of the failure timeline. Grease condition indicators respond to root causes: Water ingress, contamination, additive depletion, oxidation, and starvation all measurably alter the grease before any surface damage exists. Wear debris in grease then responds to the earliest material loss, often while vibration signatures are still marginal, particularly at low speeds. Vibration analysis, conversely, excels at localising the damage and at tracking the growth of spalls through the final stages toward functional failure (Randall & Antoni, 2011). A widely used conceptual framework places the technologies along the potential failure to functional failure interval: Lubricant condition monitoring provides the longest warning horizon for lubrication driven failures, wear debris analysis detects damage initiation, and vibration analysis detects, localises, and stages established damage. On slow speed marine equipment the case for grease based monitoring is especially strong because the vibration horizon is compressed.

5.2 Data fusion and health assessment

Formal fusion of vibration and lubricant condition information has been pursued at the data, feature, and decision levels, using multivariate methods, health indices, Bayesian networks, and evidence theory, and studies consistently report that fused indicators reduce both missed detections and false alarms relative to either source alone (Jardine *et al*., 2006). Fused health indices feed remaining useful life models ranging from physics based spall propagation and grease life models through statistical degradation models to data driven recurrent predictors (Lei *et al*., 2020). Presenting fused condition information to decision makers is itself a design problem, and the broader literature on real time risk assessment dashboards driven by machine learning, business intelligence dashboards for executive visibility, data visualisation for strategic decision making, spreadsheet and visual analytics for operational profitability, big data driven business intelligence for operational optimisation, and predictive analytics for risk detection in large administrative systems offers well tested patterns for turning multi source health data into defensible maintenance decisions (Filani *et al*., 2022; Sanni & Atima, 2021b; Babatope *et al*., 2023; Akin-Oluyomi *et al*., 2020; Akinleye *et al*., 2023; Adelanwa *et al*., 2023b).

5.3 Shipboard system architectures

Practical shipboard implementations range from portable route based programmes, in which crew or riding teams collect monthly vibration readings and periodic grease samples that are analysed ashore, to permanently installed online systems on critical machinery integrated with the vessel automation and alarm system. Modern architectures increasingly adopt an edge computing model: Local processing units compute condition indicators onboard, raise alerts against approved limits, and transmit only compact indicator trends over satellite links to shore based fleet monitoring centres. This mirrors architectural developments in other distributed energy and infrastructure systems, where tiered digital twins bring predictive diagnostics to resource constrained assets, edge intelligence supports resilient control of remote microgrids, and hierarchical, decentralised, and hybrid control architectures, smart grid designs, battery storage integration in hot and weak grid regions, compact power electronic converters, hybrid solar installations and programmatic renewable integration in constrained settings, and community scale co optimisation of technical and economic performance have been systematically compared (Komi & Adeniji, 2023; Komi & Ganiu, 2023; Komi, 2022; Adenuga, 2022; Komi & Ganiu, 2022; Tackie *et al*., 2023; Komi & Adeniji, 2020; Sunday & Omoegun, 2018; Sunday & Omoegun, 2019; Yeboah & Ike, 2020). The parallel is direct: A vessel is, in monitoring terms, a bandwidth constrained remote microgrid of machines, and the same tiered edge to cloud design principles apply.

5.4 Prognostics and remaining useful life estimation

Detection and diagnosis answer whether and where a fault exists; prognostics answers the question the superintendent actually asks, which is whether the machine will survive until the next scheduled port stay. Remaining useful life estimation for grease lubricated marine bearings draws on three model families. Physics based approaches propagate a damage state through a degradation law, spall growth models for rolling contact fatigue, or grease life models of the Arrhenius type in which life halves for roughly every fifteen degree rise in operating temperature, and they extrapolate well beyond observed data but require parameters that are rarely known precisely for aged, contaminated, in service greases. Statistical degradation models, including gamma and Wiener process formulations fitted to a trended health index, capture unit to unit variability and deliver a full probability distribution of failure time, which is exactly the form a voyage risk decision requires. Data driven predictors, most prominently recurrent neural networks trained on run to failure histories, can capture complex nonlinear degradation but are constrained at sea by the scarcity of complete failure trajectories, since well run fleets intervene before functional failure and thereby censor their own data (Lei *et al*., 2020; Jardine *et al*., 2006).

For marine practice, three pragmatic points stand out. First, prognostic horizon should be matched to the decision it serves: A horizon of weeks to the next port call is operationally sufficient and far easier to achieve reliably than a horizon to end of life. Second, fused indicators improve prognostic stability, because grease derived indicators typically degrade monotonically while vibration indicators can plateau or dip as spalls smooth over, and a health index built from both is less likely to mislead the extrapolation. Third, every remaining useful life statement should carry an explicit confidence bound and an explicit validity condition, the operating profile assumed, because a prediction made for steady steaming is invalidated by a week of heavy weather thruster use; presenting prognoses without these qualifiers has repeatedly damaged the credibility of monitoring programmes with sceptical chief engineers (Cipollini *et al*., 2018).

6. Enabling Infrastructure and Management Context

6.1 Sensing networks, wireless systems, and remote inspection

Dense, affordable sensing is the raw material of condition monitoring, and marine deployments push sensor engineering to its limits. Radio frequency energy harvesting and the pursuit of maintenance free wireless infrastructure directly address the cost of cabling and battery replacement on steel vessels, while security of IoT driven critical infrastructure must be designed in from the start (Asiedu, 2023a; Asiedu, 2023b; Jimoh *et al*., 2023a). Remote and autonomous inspection technologies developed for land infrastructure corridors also transfer naturally to marine assets: UAV integration into grid inspection programmes, UAV applications for transmission line and pipeline corridor monitoring, and integrated UAV, LiDAR, and GIS frameworks demonstrate how visual and geometric inspection can complement fixed sensing (Dagodzo, 2018a; Dagodzo, 2018b; Dagodzo & Ahiaeke Patrick, 2020; Dagodzo & Ahiaeke Patrick, 2021b), and further work on geospatial encroachment detection, enterprise GIS integration of drone operations, UAV regulatory frameworks in developing economies, and deep learning classification of corridor imagery maps out the operational and regulatory scaffolding such programmes require (Dagodzo & Ahiaeke Patrick, 2022a; Dagodzo & Ahiaeke Patrick, 2023a; Dagodzo & Ahiaeke Patrick, 2023b; Dagodzo & Ahiaeke Patrick, 2022b). For ships, comparable techniques support hull, crane boom, and mast inspection, and for ports and terminals they support monitoring of shore side rotating equipment.

6.2 Data architecture, analytics platforms, and automation

Condition monitoring produces continuous streams of measurements that must be stored, governed, and served to analytics. The enterprise IT literature provides mature guidance: Comparative frameworks for DevOps tooling, lessons from offline assessment of security critical systems, structured analyses of directory service attacks and deployments, and IT service management reviews describe the platform disciplines a fleet monitoring centre must adopt (Badmus *et al*., 2020; Ladapo *et al*., 2018; Ladapo *et al*., 2023a; Ladapo *et al*., 2023b), while implementation studies of enterprise directory services, service management platforms, and access control policy reviews address day to day administration of monitoring infrastructure (Ladapo *et al*., 2019; Ladapo *et al*., 2023c; Ladapo *et al*., 2023d). Because condition data increasingly crosses organisational and national boundaries, data governance matters: Legal and ethical risk modelling for enterprise data protection, comparative data protection regulation and secure cloud implementation, data protection impact assessment in multi cloud systems, and privacy preserving architectures for regulated industry analytics frame the compliance obligations of fleet data platforms (Mbonu *et al*., 2018; Mbonu *et al*., 2019a; Mbonu *et al*., 2022b; Atakpa & Abolaji, 2022), and continuous cloud misconfiguration monitoring, infrastructure as code governance, cloud identity and access governance, and identity and access management integration provide the operational controls (Aliliele & Mbonu, 2023a; Mbonu *et al*., 2020c; Mbonu *et al*., 2022c; Mbonu *et al*., 2020a).

On top of governed data, analytic platforms deliver value. Risk based business intelligence architectures, integrated data management for forecasting accuracy, enterprise log analytics with automated incident response, forensic analytics of communication streams, AI enabled general controls and audit automation, and API governance and risk prioritisation together describe the machinery of a modern analytics stack (Mbonu *et al*., 2021a; Agu & Akomolafe, 2023b; Mbonu *et al*., 2019b; Mbonu *et al*., 2021c; Mbonu *et al*., 2022a; Aliliele & Mbonu, 2023b). The automation of analytic pipelines themselves has advanced furthest in marketing and customer analytics, where lifecycle aware automation with federated learning, adaptive control of automated decision systems in compliance constrained environments, telemetry driven value realisation, machine learning for behavioural prediction, AI assisted content optimisation, and predictive segmentation have been reduced to routine engineering practice (Sanni *et al*., 2023; Sanni *et al*., 2022; Ogundairo & Ayivi-Donkor, 2023b; Ogundairo & Ayivi-Donkor, 2023a; Sanni, 2023b; Atima & Sanni, 2022); attribution modelling, return on investment measurement, data driven positioning, analytics driven go to market design, and structured market research in regulated industries complete a template for the closed loop, measurable automation that condition monitoring programmes aspire to (Sanni & Atima, 2022; Sanni *et al*., 2020a; Sanni *et al*., 2020b; Sanni & Atima, 2021a; Sanni, 2023c; Sanni *et al*., 2020c). Real time streaming analytics and audience level forecasting demonstrated on large media platforms further illustrate the engineering of always on monitoring pipelines (Basnet *et al*., 2021; Basnet *et al*., 2023).

6.3 Cybersecurity of shipboard monitoring systems

Networked condition monitoring converts machinery health data into an attack surface, and shipboard systems are operational technology in the full sense. The critical infrastructure security literature is directly applicable: Securing operational technology networks under regulatory regimes, security architectures for IT and OT convergence, threat detection for industrial control and SCADA networks, zero trust architectures for operational technology, adversarial machine learning threats against infrastructure analytics, and AI augmented threat detection in industrial control systems define the threat model and the defensive architecture for vessel monitoring networks (Adegbite *et al*., 2020; Adegbite *et al*., 2022; Adegbite *et al*., 2023; Ahmed & Adegbite, 2021; Adebayo *et al*., 2022; Adebayo *et al*., 2023). At the enterprise level, security audit and risk assessment frameworks, intrusion detection and prevention, incident response and digital forensics, threat intelligence integration, threat actor analysis, and cybersecurity governance frameworks describe the organisational capabilities a shipping company must maintain around its fleet data (Dosunmu & Ogundele, 2019; Dosunmu & Ogundele, 2020; Dosunmu & Ogundele, 2021; Dosunmu & Ogundele, 2022; Dosunmu & Ogundele, 2023; Jimoh *et al*., 2023b), while identity centric zero trust designs, privacy centric security engineering, and predictive capacity planning for shared service platforms address the secure operation of the shore side analytics estate (Ogbole *et al*., 2021; Okoruwa *et al*., 2020; Edivri, 2022). The International Maritime Organization now requires cyber risk to be addressed within safety management systems, which makes these capabilities a condition of trading rather than an optional refinement.

6.4 Maintenance logistics, spares, and procurement

A diagnosis is only useful if the resulting maintenance action can be executed, which couples condition monitoring to spares logistics and procurement. Conceptual models linking materials readiness to maintenance driven supply chain performance, demurrage elimination and port logistics efficiency, strategic procurement optimisation in energy operations, contract negotiation and vendor governance, supply chain risk management for engineering projects, and resilience frameworks for critical infrastructure supply chains describe the logistics system into which condition based work orders must flow (Okonkwo *et al*., 2021a; Okonkwo *et al*., 2020; Okonkwo *et al*., 2018a; Okonkwo *et* *al*., 2019; Agbabiaka *et al*., 2019; Ogunwole *et al*., 2021). Digitalisation of that system is well documented: GIS enabled procurement processes, data driven vendor evaluation and bid selection, integration of IT systems engineering with supply chain operations, agile supply chain digital transformation with embedded IT risk controls, regulatory compliant procurement in high risk environments, process automation for procurement transparency, negotiation optimisation, and supplier relationship management frameworks collectively map the procurement machinery of a condition based maintenance regime (Ahiaeke Patrick *et al*., 2020; Ahiaeke Patrick *et al*., 2021; Okonkwo *et al*., 2023a; Okonkwo *et al*., 2021b; Mbonu *et al*., 2020b; Akinleye, 2021; Akinleye, 2022a; Akinleye, 2022b).

Supplier relationships and forecasting close the loop between predicted failures and available parts. Supplier relationship management for innovation and resilience, lean supply chain practice, end to end visibility frameworks, predictive analytics for demand forecasting, and resilient logistics frameworks integrating predictive analytics show how failure predictions become inventory positions (Ike *et al*., 2021; Ike *et al*., 2022; Nnabueze *et al*., 2021; Aifuwa *et al*., 2020; Anene, 2022), while supplier risk and compliance assessment, e-commerce grade demand forecasting, supplier sustainability metrics, data driven operations management, sustainable procurement in local manufacturing, lean supply chain optimisation, and post pandemic supply chain resilience indices extend the picture to sustainability and shock resistance (Akin-Oluyomi *et al*., 2023b; Akin-Oluyomi *et al*., 2023c; Akin-Oluyomi *et al*., 2023d; Efobi & Akinleye, 2021; Efobi & Akinleye, 2022a; Efobi & Akinleye, 2022b; Efobi & Akinleye, 2023). At the workshop level, lean and small business process improvement research, including Lean Six Sigma adaptations for small enterprises, standard operating procedures as strategic assets, cycle time reduction projects, change management and user acceptance testing in small organisation technology deployment, regulatory workflow translation, and multi stakeholder governance alignment, speaks directly to the realities of implementing monitoring routines within small ship management offices and onboard crews (Ambali *et al*., 2021; Eyetsemitan *et al*., 2022; Oyeleye *et al*., 2022; Eyetsemitan *et al*., 2023a; Eyetsemitan *et al*., 2023b; Eyetsemitan *et al*., 2021; Eyetsemitan *et al*., 2020). Where monitoring programmes are rolled out across multinational fleets, project governance research on multinational infrastructure programmes, compliance frameworks, and the performance effects of diverse project teams is likewise relevant (Amayo *et al*., 2023a; Amayo *et al*., 2023b; Amayo *et al*., 2023c).

6.5 Safety management and human factors

Condition monitoring is ultimately a safety technology, and it operates inside a safety management system. The construction and process industry safety literature offers a rich, transferable evidence base: Heat stress risk modelling for work in extreme environments, systematic use of near miss and hazard observation data, data driven occupational safety risk control, the effect of management safety walkthroughs on culture, hazard identification and risk control practice, and multi contractor safety risk governance all translate to shipboard and shipyard maintenance work (Arumosoye & Obriki, 2018; Arumosoye & Obriki, 2019; Obriki & Arumosoye, 2018; Obriki & Arumosoye, 2019; Obogo *et al*., 2019c; Obogo *et al*., 2019b). Organisational studies of contractor safety performance governance, safety maturity models based on organisational learning, leadership driven culture transformation, leadership models for safety culture development, institutionalisation of life preserving practices, facility scale safety governance, and contractor compliance systems describe how monitoring findings become sustained behavioural change (Arumosoye & Obriki, 2020; Arumosoye & Obriki, 2021; Obogo *et al*., 2019a; Obogo *et al*., 2023; Obriki & Arumosoye, 2021; Obogo *et al*., 2022; Obogo *et al*., 2021c). Human error causation frameworks, recurrence mechanisms of unsafe behaviour, proactive hazard recognition and near miss reporting, digital safety data streams for proactive hazard identification, continuous hazard monitoring systems, and behavioural safety programmes connect the sensing layer of this review to the human layer that acts on it (Obriki & Arumosoye, 2020; Obriki & Arumosoye, 2022; Obogo *et al*., 2021a; Obriki & Arumosoye, 2023; Obriki *et al*., 2023a; Obriki *et al*., 2023b), while workforce safety training models, emergency preparedness and evacuation systems, emergency response readiness in energy and process facilities, and internal QHSE audit systems complete the management system view (Obriki *et al*., 2022a; Obriki *et al*., 2022b; Arumosoye & Obriki, 2023; Obogo *et al*., 2020a). Regulated transport sectors show what mature oversight looks like: Predictive compliance monitoring for systemic safety risk, adaptive safety management system implementation, AI driven risk quantification, encroachment management around safety critical infrastructure, risk tiered oversight of unmanned operations, benchmarking of certification compliance, and regulatory evidence frameworks in aviation provide a template for how classification societies and flag states may evolve condition monitoring oversight for ships (Adeyelu, 2018; Adeyelu, 2019; Adeyelu, 2020; Adeyelu, 2021; Adeyelu, 2023; Adeyelu, 2022b; Adeyelu, 2022a).

6.6 Economics, audit, and governance of monitoring programmes

Condition monitoring programmes compete for capital and must demonstrate return, and their outputs increasingly feed formal assurance processes. The internal audit and risk governance literature, covering technology enabled audit quality, risk based internal control models, integrated governance and compliance strategies, risk based auditing in strategic financial management, quantitative compliance risk assessment, cross border compliance frameworks, data driven procurement risk management, and portfolio risk optimisation, maps directly onto the auditing of planned maintenance systems and survey credit schemes (Akomolafe & Agu, 2018; Akomolafe & Agu, 2019a; Akomolafe & Agu, 2019b; Akomolafe & Agu, 2019c; Akomolafe & Agu, 2023a; Akomolafe & Agu, 2023b; Agu & Akomolafe, 2023a; Bello *et al*., 2023a; Eboh, 2023). On the investment side, financial analytics research on enterprise value creation, tax and cross border compliance analytics, transfer pricing risk, data driven executive decision systems, capital allocation decision models, and the alignment of planning analytics with corporate strategy frames how fleet monitoring investments should be appraised (Lawal & Oduleye, 2018a; Lawal & Oduleye, 2018b; Lawal & Oduleye, 2019a; Lawal & Oduleye, 2019b; Lawal &

Oduleye, 2021a; Lawal & Oduleye, 2021b), while decision analytics for sustainable profitability, behavioural financial analytics, financial reporting models for compliance, financial planning for sustainable profitability, and predictive cash flow and working capital optimisation supply the quantitative apparatus for valuing avoided downtime and deferred overhauls (Lawal & Oduleye, 2023a; Lawal & Oduleye, 2023b; Medon & Oduleye, 2022; Medon & Oduleye, 2023; Oduleye & Medon, 2023a; Oduleye & Medon, 2023b).

7. Discussion

The findings of this review are best interpreted against concrete machinery. The general methods reviewed above land differently on different machines, and four representative cases, spanning the speed, criticality, and accessibility range of grease lubricated marine equipment, illustrate how vibration and grease information are weighted in practice before the open challenges are drawn together.

A deck crane slew ring is the canonical case for grease led monitoring: It rotates at a few revolutions per minute through partial arcs under eccentric intermittent load, and vibration monitoring is nearly blind because defect impact energy at slewing speed is minimal and every luffing motion excites the structure. Grease analysis inverts the picture, since purge grease has traversed the raceways and carries their debris; trending ferrous density and wear metals from consistent purge points, sector by sector, gives years of warning of raceway spalling, corroborated by rocking clearance measurements and acoustic emission sweeps where warranted. Because slew ring renewal needs heavy lift support and long lead time, the programme's whole value lies in converting sudden failure into planned replacement at a convenient port call.

The shaft line combines very high criticality with continuous slow speed operation. Order tracked vibration analysis separates shaft rate, blade rate, and gear orders, but the dominant practical signals are temperature trends, lubricant condition, and wear metals, because film failure in heavily loaded slowly turning bearings announces itself chemically and thermally before it does dynamically. Water content is the sentinel parameter, since aft seal degradation admits sea water long before bearing distress, and a rising water trend with stable metals is a seal work order rather than a bearing alarm; the case shows the timeline complementarity of Section 5.1 in its purest form.

Azimuth thrusters and podded drives concentrate gears, bearings, and seals in a submerged, largely inaccessible housing, making them the strongest candidates for permanent online monitoring and the hardest environment for it, since repair access requires dry docking. Practice combines permanently installed accelerometers with continuous lubricant monitoring, water in oil sensing, inductive debris counting, periodic laboratory analysis, and grease sampling on shaft seals and steering components. Because load follows dynamic positioning and manoeuvring demand, condition indicators are computed with operating state gating that retains only defined load and speed windows; the thruster thus demonstrates the edge processing, state aware extraction, and vibration to lubricant fusion architecture of Section 5.3 in miniature.

Mooring machinery represents the large population of low cost, intermittently used, weather exposed deck machines for which permanent instrumentation is rarely justified, yet whose failure at the wrong moment has outsized consequences. The realistic regime is periodic and simple: Scheduled grease sampling during planned maintenance, onboard ferrous debris screening with laboratory follow up on exceptions, thermographic checks, and opportunistic vibration or acoustic emission measurements while the machine runs under load during actual mooring evolutions. Success depends on sampling discipline across crew turnover, unambiguous procedures, and visible feedback to crews, exactly the standard operating procedure, training, and culture mechanisms of Sections 6.4 and 6.5; for most machines on most ships, condition monitoring is less a signal processing problem than a management system problem.

Drawing these threads together, and despite substantial maturity, several challenges specific to the marine context remain open. First, non stationarity and platform noise: Manoeuvring transients, sea state dependent hull excitation, and dense multi machine environments degrade methods developed under laboratory conditions, and robust operating condition normalisation remains an active research need. Second, slow speed and intermittent machinery continues to strain vibration methods, sustaining interest in acoustic emission, ultrasonic film sensing, and grease debris based approaches. Third, grease condition monitoring lacks the standardised sampling procedures, condemnation limits, and interlaboratory consistency that oil analysis enjoys; grease specific standards and reference degradation datasets would materially advance the field. Fourth, sensor survivability and installation cost in exposed marine locations remain barriers, motivating self powered wireless nodes, energy harvesting, and corrosion tolerant packaging. Fifth, data scarcity for failures limits supervised learning; transfer learning between vessels, simulation based training data from digital twins, and semi supervised anomaly detection are promising responses. Sixth, interpretability and certification: For condition monitoring to displace invasive surveys, its outputs must be explainable and auditable to surveyors, favouring hybrid physics informed models. Seventh, the cybersecurity, data governance, and organisational capabilities reviewed in Section 6 must mature in step with the sensing and analytics, since a technically excellent monitoring system embedded in a weak management system delivers little. Finally, integration trends point toward digital twin frameworks in which physics based models of shafting, bearings, and lubrication are continuously updated with measured vibration and grease condition data to deliver diagnosis and remaining useful life prediction at fleet scale, supporting the autonomous and lean crewed vessels now under development.

8. Conclusion

Vibration analysis and grease condition monitoring are complementary pillars of condition based maintenance for rotating marine mechanical equipment. Vibration technology is mature, standardised, and unmatched for detecting, localising, and staging mechanical damage in medium and high speed machinery, and its diagnostic power continues to grow through advanced signal processing for non stationary conditions and through machine learning. Grease condition monitoring directly addresses the lubrication related failure mechanisms that dominate in the saline, wet, and thermally demanding marine environment, offering the earliest available warning of water ingress, contamination, lubricant ageing, and incipient wear, and it is uniquely valuable for the slow speed, heavily loaded deck machinery where vibration methods are weakest. The literature strongly supports combining the two: Fused vibration and grease indicators improve detection reliability, extend warning horizons, and clarify root causes. Realising this potential fleet wide will require progress not only in sensing and analytics but in the surrounding infrastructure surveyed here, wireless and remote sensing, governed data platforms, cybersecurity, maintenance logistics and procurement, safety management, and programme economics. As the industry moves toward reduced crewing, autonomous operation, and tighter environmental and safety expectations, integrated vibration and grease condition monitoring will shift from a cost saving option to an enabling technology for safe and efficient marine operations.

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