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Experimental Investigation into Slow Steaming Impacts on Hydrodynamic Journal Bearing for Sustainable Marine Propulsion

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Abstract

Slow steaming maneuverability is by all means one of the foremost operational techniques carried out for conquering the ship energy reduction ever-increasing demands. Inevitably necessitating reducing shaft speed, the recommended approach is unfortunately most likely to jeopardize hydrodynamic lubrication and hence intrinsic marine propulsion systems all alike. Committed by the criteria set by marine diesel engine loading program, the present experimental analysis has involved imposing variations in speed ranges and thus load impacts examining variable lubricant grades. Apparently, the prevalent transition was recorded from 93 down to 70 rpm, where maximum oil film pressure maintained permanent degradation tendency. Notably, lighter lubricant grades are more sensitive to the loss of speed induced entrainment, whereas elevated viscosity takes a considerable share in pressure preservation specifically at slow speed operating conditions. Further, slow steaming effective implementation ought to be assessed based on the performance of all intrinsic operational factors working together and not depending merely on speed as a sole evaluation reference. Considering tested conditions, the transition of 0W20 oil grade near 79 rpm sets test trial speed ranges from 93 down to 80 rpm as a conservative common hydrodynamic operating range and no merely a universal safety boundary. Technically speaking and given the actual operating conditions onboard ships, all potential influential operating and environmental impacts ought never to be taken for granted in case slow steaming evaluation is to be carried out both optimally and adequately.

***Keywords*:** Hydrodynamic lubrication; SEEMP; Ship energy efficiency; Maneuvering speed.

1. Introduction

Attaining tangible promotions regarding operational performance, working life and sustainability of the marine propulsion system onboard ships is largely dependent on maintaining the operational

integrity of marine journal bearing. Considering the beneficial regulatory criteria set by the International Safety Management Code (ISM), SOLAS Convention [1] and [2], enhancing the efficiency of such instrumental components is the sole guarantee for satisfying global objectives and addressing relevant concerns on the issue. Slow steaming technique, advocated by Ship Energy Efficiency Management Plan (SEEMP) related to MARPOL Convention, Annex VI [3], has of late been recommended for conquering the intricate concerns whose implications are permanently on the rise. Abiding by the proposed guidelines entails being committed to slow steaming operational maneuverability for cutting down fuel consumption and alleviating global warming emission expansion specifically that of Carbon Dioxide (CO_2), [4]. Based on all of the previously mentioned considerations, top priority ought to be given to promoting the performance of the foremost critical operational factors contributing to boosting hydrodynamic lubrication within journal bearing. Numerous research endeavors have over decades been devotedly concerned with promoting the performance of the most critical operational factors affecting the operational integrity and working life of such crucial mechanical components.

A considerable bulk of research investigations has essentially been focused on the mechanisms through which the hydrodynamic lubricating oil film sustains journal bearing, examining versatile geometrical and operational conditions and tracing the oil film pressure distribution as well as the load carrying capacity profiles. For instance, Patel et al. [5] intended to measure oil film pressure in a ferrofluid-based hydrodynamic journal bearing. Based on the conducted analysis, the adopted materials as well as the magnetic arrangement were asserted to have the potential to alter the developed profile. Comparably, Chen et al. [6] related and attributed the generated pressure field to the load carrying capacity of herringbone-grooved journal bearings. From another perspective, Goraj (2018) paid special attention to the equilibrium of an electromagnetically supported hydrodynamic bearing when liable to static loading. Further, investigating three dimensional CFD coupled with fluid-structure interaction, Dhande and Pande [7] emphasized that maximum oil-film pressure varied with changes made in journal shaft speed. Additionally, Loeffler et al. [8] addressed hydrodynamic pressure distribution relying on boundary-element radial-basis estimation, whereas Cui et al. [9] opted for partial wall slip under heavy load, demonstrating the potential of promoting the load carrying capacity and simultaneously curbing friction and temperature rise. Seeking to address another research arena, Zhou et al. [10] examined a finite element and mixed solution method. Employing the proposed approach, the study revealed the potential impacts of variations

made in lubricant viscosity and external load regarding journal bearing equilibrium position. Moreover, Tauviqirrahman et al. [11] derived CFD predictions concerning the critical operational factors of pressure and load carrying capacity. Also, the potential impacts resulting from the interaction among these intrinsic factors considering wall temperature and friction force were thoroughly examined. Comparably, Ganesha et al. [12] focused on deep-learning optimization concerning hydrodynamic pressure and load support observing multi-pad bidirectional adjustable bearings. Further, Santeramo et al. [13] proposed a viscohydrodynamic numerical approach regarding a polymer journal bearing. Remarkably enough, the full impacts triggered by the interaction among solid viscoelasticity, lubricant flow, hydrodynamic pressure generation and applied loading were elaborately accounted for. Also, examining versatile pad configurations, length-to-diameter ratios, speeds, slip intensities and applied loads, Shivani et al. [14] provided critical guidelines regarding the contribution of pressure distribution and load carrying capacity to the operational behavior of a multi-pad adjustable fluid-film bearing.

Besides, a remarkable number of research endeavors were chiefly concerned with tracing the impacts of variable rotational speeds and different applied loads on the sustainability of the lubricating oil film and the potential to be maintained durable and stable all through steady and transient operating conditions. Chatterton et al. [15] carried out severe condition test trials for tracing the impacts of rotational speed and static load on the oil film pressure distribution in a large scale 160 mm journal bearing. In comparison, Hemmati et al. [16] scrutinized the effects incurred by the critical operational factors of rotational speed and static load regarding short and long journal bearings considering laminar and turbulent regimes. In addition, Bhasker et al. [17] worked on a phosphor-bronze journal bearing operating between 1000 and 4000 rpm where variable loads and different oil grades were thoroughly examined. Optimized operating conditions were asserted to curb temperature rise and promote oil film pressure. In addition, Huang and Yan [18] pinpointed the impacts different speeds and lubricant viscosities regarding end leakage as well as friction losses. Increasing shaft speed was emphasized to exacerbate the likelihood and severity of friction losses and end leakage. Also, concerned with the detrimental consequences triggered by start-stop speed transitions, Santos et al. [19] launched an experimental investigation into the undesirable impacts that could extend to frictional demand as well as lubrication continuity. Further, Pokorny et al. [20] analyzed a high-speed tilting-pad journal bearing lubricated by concentrated hydrogen peroxide at 3000 and 18000 rpm and at lubricant flow rates from 100% down to 20% of nominal

flow rate. Notably, the study comprised wide range comparisons between pressure and temperature outcomes and their peers derived from a thermo-elasto-hydrodynamic model. Working on extending the scope of their experimental research program, Marey et al. [21] carried out numerous test trials involving miscellaneous speed and load conditions employing a circumferential grooved bearing model. Thermal deformation was concluded to enhance peak pressure and load carrying capacity, escalating the lubricating oil film temperature and friction simultaneously. Moreover, Cheng et al. [22] traced the effects of transient loading concerning main shaft sliding bearings. Transient load conditions were emphasized to incur tangible degradation regarding the operational performance of the lubricating oil film.

More important still, a large portion of research efforts were basically intended to identify the operating conditions intensifying shear resistance as well as mechanical energy dissipation. To attain the aspired purposes, this bulk of research investigations have principally worked on the critical operational factors of friction coefficient, friction torque and frictional losses. For instance, Mansoor and Shayler [23] worked on the critical operational factor of friction torque employing controlled light loads. Oil feed condition was emphasized to exert a measurable impact regarding frictional response. Additionally, implementing uncertainty quantification with respect to journal bearing calculations, Griffini et al. [24] demonstrated considerable variations in as far as friction losses were concerned. Comparably, Vladescu et al. [25] examined journal bearing friction applying variable applied loads, rotational speed ranges as well as lubricant viscosities. Frictional behavior was concluded to be for the most part closely dependent on three critical operational factors. On the other hand, Van der Meer et al. [26] traced the critical operational factor of friction coefficient via comparing transition speed considering mixed and hydrodynamic lubrication for oil and magnetorheological fluid. Gosar et al. [27] elaborated on the impacts of experimental setup design as well as parasitic losses regarding journal-bearing friction measurement employing radial loads from 1000 to 4000 N and variable journal shaft speeds. Addressing another yet critical perspective, Dass et al. [28] introduced extensive analyses incorporating variable viscosity, couple stress lubricant behavior, magnetic fluid, slip velocity as well as sinusoidal surface texturing. Notably enough, considerable variations in pressure distribution, load carrying capacity as well as friction were reported.

Also, a remarkable number of investigations have addressed temperature distribution and thermo hydrodynamic behavior. The main objective of such a crucial bulk of research investigations was

to discern the reciprocal interaction among frictional heat generation, thermal expansion, lubricant viscosity as well as the lubricating oil film pressure. For instance, Li et al. [29] examined thermo-hydrodynamic behavior of a turbocharger rotor bearing system. In light of the derived outcomes, the importance of incorporating temperature, thermal expansion as well as viscosity variation into precise oil film predictions was emphasized. Further, Novotny et al. [30] traced the behavior of lubricant flow as well as shear related temperature variation during turbocharger run-up. In comparison, Visnadi and Castro [31] carried out a thorough investigation into oil temperature uncertainty and viscosity dependent impact in as far as journal bearing behavior was related. In addition, Zhu et al. [32] considered coupled thermal and lubrication equations, indicating the resulting variations concerning friction losses, pressure as well as temperature. In comparison, Kyrkou and Nikolakopoulos [33] conducted versatile test trials to examine a number of commercial oils of different performance. The study offered beneficial guidelines for obtaining distinctive thermo-hydrodynamic pressure and temperature profiles. Also, employing a full three-dimensional tilting-pad journal bearing, Soltani and Naderan [34] asserted the advantages of the proposed model to resolve oil film pressure and temperature fields compared with two dimensional formulations. On the other hand, Marey et.al [35] traced hydrothermal behavior employing marine slow speed diesel engine operating conditions. In comparison, Cartwright et al. [36] were essentially concerned with machine learning prediction regarding thermo-elasto-hydrodynamic pressure and temperature behavior examining variable speed ranges and load impacts.

In addition to that, a significant number of research efforts were basically keen on identifying the potential ways lubricant selection changes pressure generation, friction, temperature, and load support. To attain the intended purposes, special attention was particularly given to specific critical operational factors comprising different oil grades, viscosities, rheological models as well as alternative lubricant formulations. Among the foremost investigations pertaining to the current category was a study by Marey [37] comprising experimental comparisons of different oil grades. Lubricant selection was emphasized to play a critical role regarding hydrodynamic journal bearing operational performance and integrity. Also, Boubendir et al. [38] were specifically focused on a Rabinowitsch non-Newtonian lubricant. The potential of lubricant rheology to incur tangible variations in pressure generation and load response was asserted. Furthermore, Quinci et al. [39] compared conventional oil and magnetorheological fluid employing finite-element modeling as well as experimental test trials. Magnetorheological fluid was proved to generate thicker oil films

and a more favorable pressure distribution at low speed. Nevertheless, such very specific type of fluid had the disadvantage of incurring evidently higher friction losses. In addition, Awad et al. [40] negotiated titanium-dioxide nanoparticle lubricant additives, evaluating the impacts of such additives regarding load response, friction related performance as well as stability limits. Comparably, Hariharan et al. [41] conducted a thorough analysis into a titanium-dioxide nano-lubricated active journal bearing. Nanoparticle concentration and aggregate size were both ascribed to lubricant viscosity, pressure generation as well as load support. Further, Jabbar et al. [42] were primarily concerned with the thermohydrodynamic behavior of a CuO/SAE 30 Nano fluid-lubricated plain journal bearing. The study offered beneficial tips concerning the corresponding pressure, temperature and tribological characteristics.

Additionally, a significant share of research efforts was dedicated to promoting the reliability, prediction as well as control of intrinsic operational factors. For the purpose, integrated experimental, numerical and data-driven approaches were fostered. Interestingly, Marey. et .al, worked on promoting the validation of pressure, temperature, speed, load, and lubricant condition measurements concerning marine journal bearing applications. For instance, Marey and Ali [43] developed a measurement and control system for the Universal Journal Bearing Test Rig. The study provided beneficial recommendations for coordinating the acquisition and control of operational variables regarding marine journal bearing evaluation. More importantly, in order that the most prominent contributions towards optimal performance of the foremost operational factors could be recognized, a compact summary of the latest endeavors is systematically incorporated. The following Table 1, has deliberately been integrated for better understanding of the critical operational factors contributing majorly to the optimal performance of hydrodynamic lubrication within journal bearings. Further, research investigations have been divided into six major domains for more illustration and furnished understanding simultaneously.

Table 1 Towards optimized hydrodynamic lubrication performance for journal bearings

References	Research Scope	Obtained Results	Applied Approach	Operational Factors	Contribution
Research Domain		**Oil Film Pressure Distribution & Load Carrying Capacity**			
Patel et al. (2017), Chen et al. (2017), Goraj (2018), Dhande and Pande (2018), Marey, Aly, and Hegazy (2018), Loeffler et al. (2019), Cui et al. (2020), Zhou et al. (2022),	Assessment of oil film pressure generation, load support, wall slip impacts, bearing geometrical patterns and structural interaction under	Material & magnetic arrangements shaped oil film pressure profile. Shaft speed, viscosity and external load shifted maximum pressure. Partial wall slip promoted load	Oil film pressure profile measurement and numerical solution of the governing lubrication equations employing FEM, BEM, CFD-FSI, mixed methods and	Oil film pressure distribution & load carrying capacity, with shaft speed, applied load, variable viscosities, geometry as well as deformation	Proposing key mechanisms shaping hydrodynamic pressure and load support. Improving numerical,

Tauviqirrahman et al. (2023), Ganesha et al. (2024), Santeramo et al. (2025), Shivani et al. (2026)	variable loads and speeds, oil grades and surface conditions.	carrying capacity while decreasing friction and temperature.	viscohydrodynamic models. Optimization via deep learning and adjustable multi pad evaluation.	maintained as the controlling variables.	experimental and data generated tools regarding bearing geometry and performance optimization.
Research Domain	**Different Shaft Speeds, Applied Loads & Transient Operational Conditions**				
Chatterton et al. (2017), Hemmati et al. (2017), B et al. (2020), Huang and Yan (2020), Santos et al. (2020), Wodtke and Litwin (2021), Pokorny et al. (2023), Marey et al. (2024), Cheng et al. (2025)	Evaluating steady, start-stop, run-up and transient bearing performance examining different shaft speeds, dynamic applied loads. Misalignment decreased lubricant flow and severity of operating conditions.	Critical operational factors have a vast impact on pressure, temperature, friction and lubrication integrity. Optimal operating conditions enhanced pressure and curbed temperature rise. Start-stop motion decreased flow whereas transient loading negatively affected oil film performance and exacerbated the hazard of boundary lubrication.	Controlled test trials and dynamic simulations integrating predetermined rotational speed ranges, static and transient loads. Start-stop operation decreased flow conditions and extreme operation. Optimization relying on Taguchi-fuzzy and thermos elasto-hydrodynamic measures.	Different rotational speeds and applied loads, comprising start-stop transition, run-up, transient loading, lubricant flow reduction, misalignment as well as vibration impacts.	Pinpointed the operational boundaries concerning hydrodynamic oil film continuity and yielded proof regarding speed-load control, transient-hazard management and sustainable bearing operation.
Research Domain	**Friction Coefficient, Friction Torque & Mechanical Losses**				
Mansoor and Shayler (2018), Griffini et al. (2018), Vladescu et al. (2019), Van der Meer et al. (2023), Gosar et al. (2024), Dass et al. (2024)	Prediction of friction torque & coefficient, friction losses and shear generated energy dissipation at fluctuating supply pressure, load, speed, viscosity, surface texture as well as magnetic lubricant conditions.	Oil supply pressure, radial load, shaft speed, oil viscosity and surface texture have a large impact on friction. Magnetorheological fluids shaped transition speed and friction coefficient, whereas setup relevant friction losses affected friction values.	Extensive friction torque and friction coefficient measurements, uncertainty analysis, mixed to hydrodynamic transition examination, friction loss correction and modelling of textured, slip and magnetic oil lubrication.	Friction coefficient, friction torque and mechanical losses, with oil supply pressure, radial load, shaft speed, viscosity, surface texture, slip and oil grade involved.	Enhanced measurement reliability of frictional behavior and facilitated identifying methods to reduce mechanical losses of journal bearings.
Research Domain	**Oil Film Temperature Distribution & Thermo-Hydrodynamic Performance**				
Li et al. (2017), Novotny et al. (2018), Visnadi and de Castro (2019), Zhu et al. (2020), Kyrkou and Nikolakopoulos (2020), Soltani and Naderan (2021), Marey (2023), Marey, El, and Fayed (2023), Cartwright et al. (2024)	Tracing oil film temperature distributions, frictional heat, thermal profile, turbulence, misalignment, oil supply pressure and temperature generated viscosity with respect to journal bearing.	Lubricant temperature, thermal expansion and viscosity variation were asserted to be essential for oil film pressure prediction and stability assessment. Starting up, turbulence, misalignment, oil properties and oil supply pressure affected thermal fields. Comparably, machine learning models boosted pressure and temperature prediction.	Empirical pressure and temperature oil film measurement integrated with coupled thermal lubrication equations, transient and turbulent simulation, uncertainty analysis as well as machine learning prediction.	Oil film temperature distribution and thermo-hydrodynamic response, incorporating frictional heat, thermal expansion, viscosity temperature variation, turbulence, misalignment as well as oil supply pressure.	Asserted the importance of thermo-hydrodynamic coupling and the vitality of thermal monitoring, stability assessment and predictive modelling regarding journal bearing operational performance.
Research Domain			**Oil Grades, & Alternative Lubricants**		
Marey (2019), Boubendir et al. (2019), Quinci et al. (2021), Awad et al. (2023),	Comparing a wide-range of conventional oil grades, non-Newtonian and	Oil grade and viscosity affected oil film pressure distribution and load profile. Nanoparticle	Comparison-based test rig experiments and numerical modelling including conventional lubricants,	Different oil grades and lubricant viscosities integrating base oil, magnetorheological fluid, TiO2 additives,	Confirmed the importance of lubricant selection as a key design and

Hariharan et al. (2026), Jabbar et al. (2026)	magnetorheological fluids, titanium-dioxide additives as well as CuO/SAE 30 nanofluids concerning oil viscosity, oil film formation, pressure, load support, friction, temperature and stability.	concentration and total size shaped oil viscosity, pressure, load support, temperature and tribological performance.	Rabinowitsch fluids and nanofluids applying viscosity, stability and thermo-hydrodynamic formulations.	CuO/SAE 30 nanofluid, concentration and total size.	operational decision. Asserted the potential of alternative and nano-lubricants to furnish oil film formation as well as load support.
Research Domain		**Measurement, Control & Data Referenced Assessment**			
Marey, et al. (2023)	Promoting an integrated measurement and control experimental test rig for marine journal bearing performance, examining oil film pressure, temperature, rotational speed as well as applied load.	Identifying the key hydrodynamic lubrication variables, sustaining accurate assessment of marine journal bearing operational performance under selected operating conditions.	Integrated UJBTR instrumentation, sensor calibration, synchronized data acquisition and closed loop control regarding oil film pressure, temperature, rotational speed, applied loads as well as lubricant condition variables.	The critical operational factors comprising the oil film pressure, temperature profile, shaft speed, applied loads and lubricant condition combined together.	Introduced the experimental infrastructure essential for tracing the impact of key operational factors involving oil film pressure, temperature, speed, load and lubricant data simultaneously and for validating numerical and data grounded bearing models.

Collectively, just a quick scan over the illustrated research efforts will definitely reveal that the full impacts resulting from slow steaming technique regarding marine journal bearing operational sustainability and integrity have evidently not been given the due investigations these by all means deserve. Consequently, the research endeavor at hand is basically intended to carry out a thorough analysis aiming at tracing the repercussions triggered by slow steaming maneuverability operating conditions regarding ship propulsion systems. Considering the major share critical operational factors take in such very specific phases, the current effort is essentially intended to examine the impacts such factors could exert on the overall performance of the lubricating oil film within marine journal bearing. These factors mainly comprise the oil film pressure and temperature distributions, the different lubricant viscosities, the variable applied loads, the different speed ranges applied as well as the critical factor of friction coefficient. Additionally, for envisaging the consequences such critical operating conditions could have on the operational performance, all of the involved factors will together be experimentally traced to acquire the credible combined effects and not in any way individually-derived implications.

2. Emission Reduction adopting Slow Steaming Maneuverability

A remarkable bulk of research investigations has recommended resorting to slow steaming technique as a practical approach for alleviating fuel consumption and hence emissions incurred by marine diesel propulsion systems. Corbett et al. [44] asserted that tangible speed reduction could minimize fuel depletion and CO_2 emissions by roughly 70%, while Cariou [45] confirmed the potential of obtaining reductions exceeding 11% provided slow steaming maneuverability is widely adopted. Parallel to that, Lindstad et al. [46] asserted the potential of achieving emission reductions ranging from 19% to 28% via applying minimized operating speeds. Chang and Wang [47] achieved CO_2 reductions in the average of 34.9% to 80.3% attributing such a crucial outcome to the decrease of propulsion power and fuel demand with ship speed. Another portion of no less significance research efforts have addressed the wider perspective of different marine diesel propulsion arrangements. For instance, Taskar and Andersen [48] succeeded in realizing fuel savings ranging from 2% to 45% through applying ship speed reduction by 30%. Additionally, Degiuli et al. [49] emphasized the fact that imposing a 13.6% reduction in service speed could reduce CO_2 emissions by roughly 31%. Further, Farkas et al. [50] assured that the reduction in propulsion power employing slow steaming could largely facilitate containership adherence to EEXI obligations. Comparably, Pelić et al. [51] were mainly concerned with slow speed as well as medium speed marine diesel engines. Based on the conducted analysis, substantial fuel consumption reductions of 72.36% to 76.25% at 12 knots and tangible degradation in CO_2 emissions amounting to one quarter of those at 23 knots were all adequately demonstrated. Farkas et al. [52] pinpointed the tight interdependent relation between minimized sailing speed, lower propulsion power, decreased fuel consumption and degrading CO_2emissions. Collectively, slow steaming is by all means as an effective measure for cutting down emissions from marine diesel engines. Nevertheless, the effectiveness of such a critical maneuverability ought to be assessed observing engine loading, specific fuel consumption as well as the configuration and safe low load potential of the marine propulsion system.

Considering the significance of slow steaming technique, the present investigation is basically dedicated for investigating the optimal methods of implementation observing SEEMP criteria. Slow steaming involves imposing gradual reductions in voyage speed ranges. Yet, such critical and inevitable measures could in most cases pose a real threat to the lubricating oil film within marine

journal bearing. Lubrication process may turn from hydrodynamic region into the detrimental boundary one, seriously jeopardizing the propulsion system and leading ultimately to unsafe navigation. Hence, Figure 1 provides a Flowchart that is meaningfully integrated for discerning the optimal way of implementing slow steaming technique. The proposed approach could ensure attaining conformity between SEEMP-based implementation considerations and excluding any likelihood concerning marine journal bearing deterioration and ultimate failure simultaneously.

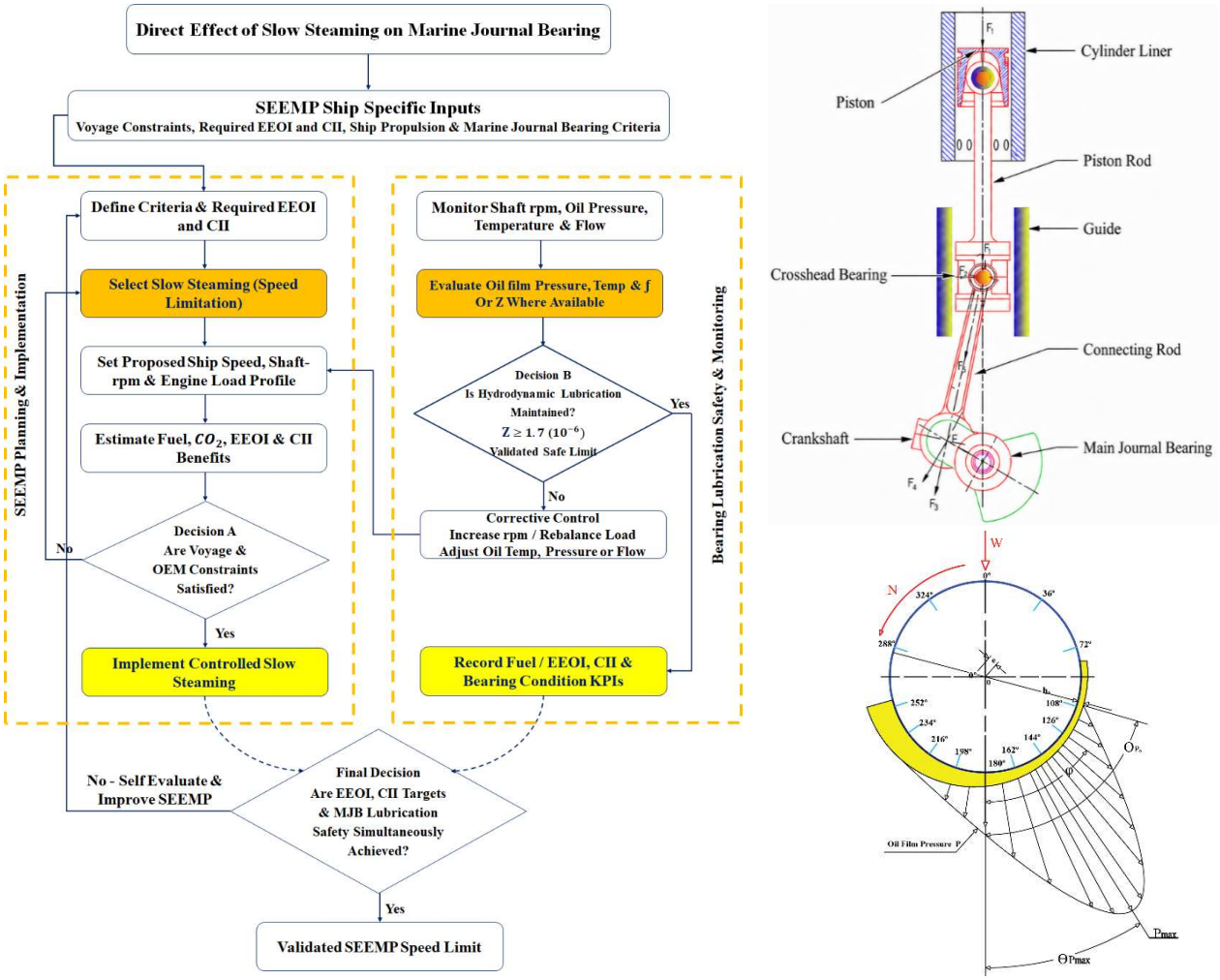


Fig. 1 SEEMP workflow for ships integrating slow steaming with marine journal bearing lubrication safety

3. Experimental Test Rig Setup

Essential for the precision and credibility of intended test trial outcomes is to carry out the relevant procedures employing a fully controlled and thoroughly monitored experimental discipline. Such a prerequisite could not only ensure obtaining firmly-grounded readings and analysis, but it will

also facilitate referring to the provided data for reference and repeatability for all those working on the crucial investigation perspective currently addressed. Consequently, all the experimental test trials have been conducted utilizing the Universal Journal Bearing Test Rig (UJBTR) involved in the Marine Experimental Electromechanical Lab (MEEL), Arab Academy for Science, Technology and Maritime Transport (AASTMT).

UJBTR, Figure 2, is a multifunction, multi-system experimental platform mainly constructed for tracing the tribological and thermohydrodynamic characteristics of hydrodynamic journal bearings. Also, it allows for full monitoring and control of the most critical operating conditions, typical of marine propulsion shafting systems as well as marine diesel engines. It is marked by the potential to both adjust and trace the most influential operational factors put together including journal speed, externally applied loads, lubricant grade, oil supply pressure as well as oil supply temperature. Additionally, UJBTR, whose technical data are elaborately provided in Table 2, makes it possible to obtain accurate measurements regarding the circumferential distributions of oil film pressure and temperature. Provided by a distinguished modular arrangement, UJBTR has the advantage of changing the test bearing as well as the operating programs without the need to modify the principal drive, lubrication, loading or control system. More importantly, shaft shear and bending stresses, frame stiffness, alignment precision, component availability, maintainability, measurement integrity and the potential to repeat the intended operating conditions have all been among the foremost considerations closely observed in the design and component selection processes.

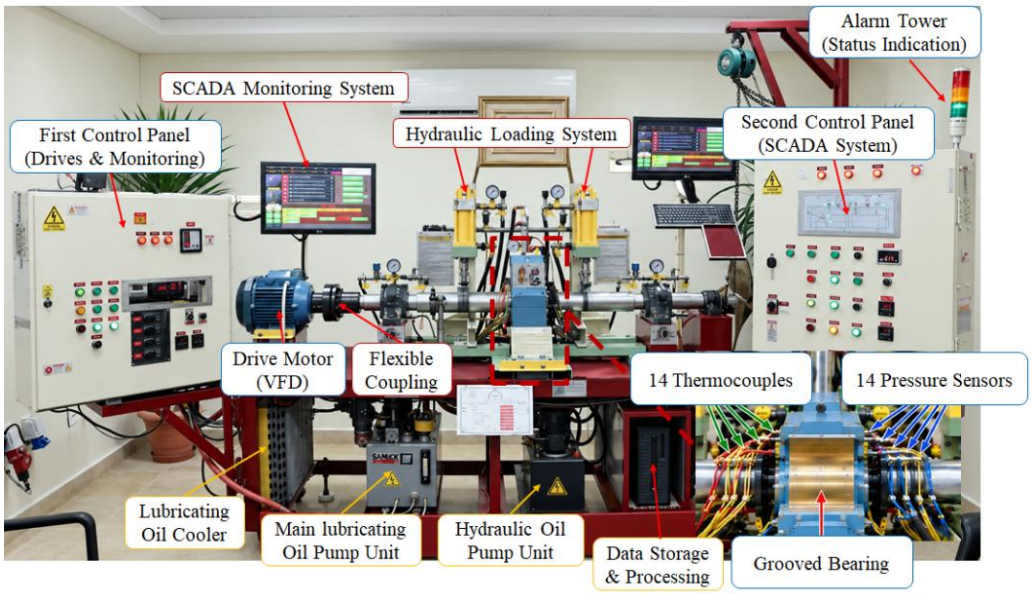


Fig. 2 UJBTR experimental platform integrating intrinsic systems

Table 2 Technical data for UJBTR.

Parameters	Value	Pressure Sensors	Value
D, Shaft Diameter	104.97 mm	**Measuring range**	0 … 40 bar
R, Radius Journal Shaft	52.425 mm	**Output signal**	4 - 20 mA, 2-wire
L, Bearing Length	58.00 mm	**Power supply**	8 … 30 V DC
d, CGB Inner Diameter	105.05 mm	**Non-linearity**	0.5% BFSL
C_0, Total Clearance	0.104 mm	**Measuring deviation of zero signal**	$\leq \pm 0.3\%$ of span
C, Radial Clearance	0.052 mm	**Permissible medium temperature**	0 … +80 ℃

The multi-purpose experimental platform of UJBTR incorporates a number of 4 intrinsic interdependent and interrelated subsystems. These mainly comprise the shafting system, the lubricating oil system, the hydraulic loading system, as well as the Supervisory Control and Data Acquisition System, Figure 3. Noteworthy that the individual systems offer and maintain the privilege of distinct functional boundaries and these also facilitate and ensure smooth and coherent operation via under full control, monitoring and well-manipulated operating conditions.

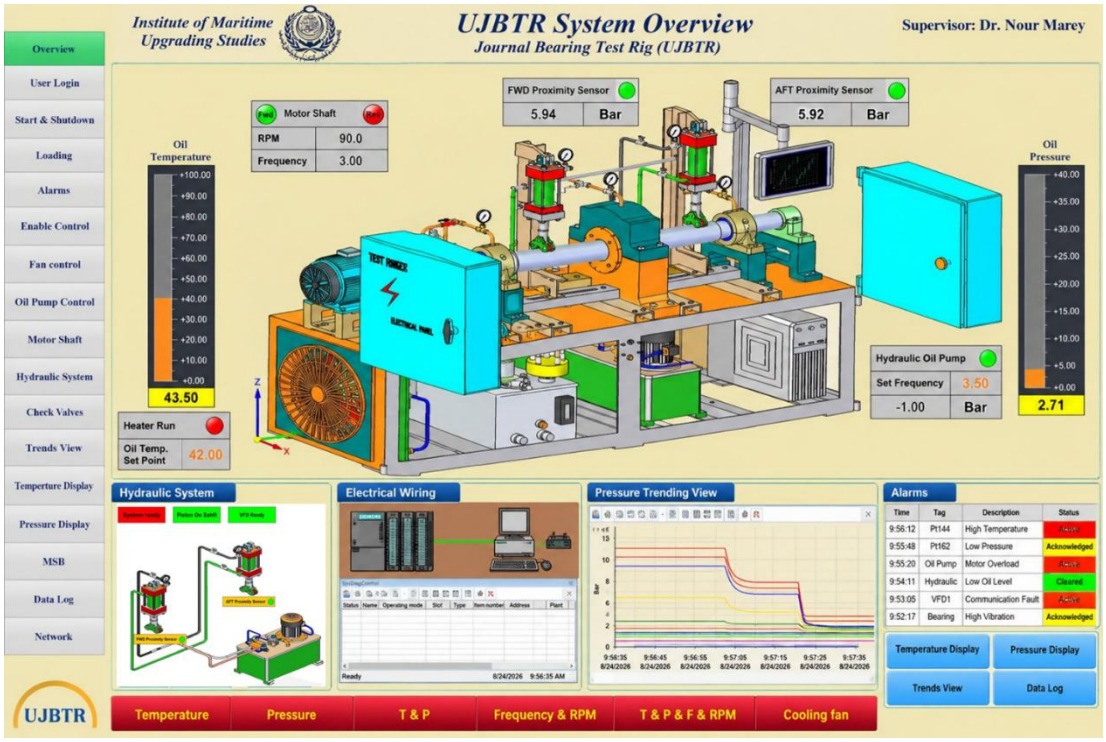


Fig. 2 A schematic illustrating SCADA manipulating system

4. Experimental Test Trial Procedures

In order that slow steaming technique impacts could sufficiently be examined, an extensive experimental test trial program has been carried out employing Universal Journal Bearing Test Rig (UJBTR). The assigned operating conditions of the MAN B&W 6S60MC-C slow speed marine diesel engine were experimentally simulated to represent the selected journal shaft speeds of UJBTR. Shaft speed was controlled via drive motor and VFD, while the applied loads were independently exerted utilizing hydraulic loading system, Marey et al. [43]. In such a way, the impacts of shaft speed variations and variable loads on the hydrodynamic oil film pressure and temperature distributions within Circumferential Grooved Bearing (CGB) could adequately be investigated ensuring controlled conditions Marey et al. [43] and [53]. For more illustration, the experimental operating program is involved in Table 3, integrating load percentages representing the selected operating conditions of the MAN B&W 6S60MC-C. It should also be noted that such percentages are by no means representative of these of UJBTR drive motor power. Additionally, the assigned shaft speeds were directly reproduced on the experimental platform, whereas the hydraulic loading system had the function of manipulating the variable bearing loads independently.

Table 3 Experimental loading program applied on UJBTR to represent operating conditions of MAN B&W 6S60MC-C marine diesel engine

Load	Shaft Speed	Maneuvering Speed
25%	28 rpm	Dead Slow Maneuvering Conditions
50%	45 rpm	Slow Speed at (Part Load) Maneuvering Conditions
75%	70 rpm	Half at (Part Load) Maneuvering Conditions
85%	93 rpm	Full Speed at (Normal Continuous Rate “NCR”)
100%	105 rpm	Full Navigation at (Maximum Continuous Rate “MCR”)

Additionally, the scope of the present analysis has deliberately been extended to cover the impacts that variations in lubricant grade viscosities could have on the total operational behavior of marine diesel engines in real operating conditions. Hence, experimental procedures have involved the application of four oil grades of individual and distinct viscosities, Table 4. Notably, among the employed four oil grades was the crucial lubricant grade oil of 20W50 due to being commonly utilized in such types of marine diesel engines.

Table 4 Oil grade properties

Typical Characteristics	Oil Grade Properties			
	0W20	**0W30**	**5W40**	**20W50**
Density at 15°C	0.843 g/ml	0.838 g/ml	0.85 g/ml	0.88 g/ml
Kinematic Viscosity at 100°C	8.2 mm^2/s	11.8 mm^2/s	14 mm^2/s	19 mm^2/s
Kinematic Viscosity at 40°C	44.8 mm^2/s	61.0 mm^2/s	84.7 mm^2/s	161 mm^2/s
Viscosity Index	161	193	171	136
Flash Point (°C)	222	217	236	260
Pour Point (°C)	-41	-42	-36	-24

Test trial procedures were instigated at the shaft speed limit of 105 rpm representing full navigation at (Maximum Continuous Rate "MCR"). Additionally, gradual reductions regarding tested speed variations have been carried out observing the loading program for MAN B&W 6S60MC-C slow-speed two stroke diesel engine. Further, test trial results have specifically been recorded regarding the most influential operational impacts comprising the oil film pressure and temperature distribution values along the circumferential marine grooved bearing

5. Results and Discussion

As clearly illustrated by Figure 3, experimental test trials were purposely instigated at 105 rpm, which is the speed limitation typical of Full Navigation at Maximum Continuous Rate (MCR). Journal shaft speed was then degraded observing the adopted Marine Diesel Engine "MAN B&W 6S60MC-C" loading program. The maintained downward trend involved 93 rpm (Full Speed "NCR"), 70 rpm (Half, "Part Load Maneuvering"), 45 rpm (Slow Speed, "Part Load Maneuvering") and 28 rpm (Dead Slow Maneuvering) respectively. Noteworthy that the key analysis is meant to trace variations featured in the value of P_{max} regarding the oil film at both angles of 198° and 216°, located in lower shell of grooved bearing. In such a way, each lubricant grade was examined considering the corresponding load criteria set by the loading reference program. Clearly enough, the measured response is characterized by being collectively derived regarding the most influential operational impacts. Considering the initial speed range being examined, 105 rpm, the lower and medium viscosity lubricants were evident to feature strong hydrodynamic pressure generation under the highest exerted loads. To illustrate, it is specifically at 105 rpm that 0W20 and 0W30 tolerating 6180 N and 6082 N have produced P_{max} values of 5.66 and 5.90 bar, whereas 5W40 recorded 6.22 bar under 5396 N. Also, compared to the oil grade of

20W50 at load 3483 N and assuming the P_{max} value of 4.34 bar, the 0W20 and 0W30 liable to the higher load impacts of 77.43% and 74.62%, P_{max} values were clear to rise by 30.41% and 35.94%, respectively. Based on the acquired outcomes, sufficiently accelerated shaft speed, lubricant entrainment can support a tight converging wedge even if relatively minimized viscosity lubricants were employed.

Throughout the conducted test trials, it is observed that the most elevated value recorded for P_{max} occurred at 93 rpm for 0W30, yielding 6.64 bar at 198° under 5886 N. Remarkably, the P_{max} increase from 5.90 bar at 105 rpm should not be ascribed to improved lubrication resulting from shaft speed reduction solely. Rather, the shift of P_{max} peak from 216° at 105 rpm to 198° at 93 rpm is an irrefutable indication of redistribution as well as rotation of hydrodynamic pressure incurred by variations in journal eccentricity and attitude angle. Nevertheless, the most clear-cut slow steaming impact turns up as speed is further decreased. Imposing speed degradation from 93 rpm to 70 rpm, P_{max} is obvious to plummet from 5.22 bar to 3.38 bar for 0W20 (-35.25%), from 6.64 bar to 4.56 bar for 0W30 (-31.33%), and from 5.93 bar to 4.54 bar for 5W40 (-23.44%). Comparably and employing the same operating conditions, 20W50 the corresponding P_{max} value is noted to drop from 4.12 bar to only 3.83 bar (-7.04%). Interestingly enough however, the ranking at Dead Slow at 28 rpm is observed to be reversed, where 20W50 assumed 4.05 bar, compared to solely 2.40 bar, 1.76 bar and 0.81 bar for 5W40, 0W30 and 0W20, consecutively. Evidently, such an outcome could be considered as the most logical tribological evidence of the test trials considering loading program.

Further, the less shaft speed gets, the weaker the entrainment term in charge of drawing lubricant into the converging clearance becomes. Therefore, elevated viscosity could safely be concluded to take a considerable share in maintaining pressure generation as well as oil film stiffness. Additionally, the comparatively stable pressure of 20W50 across the speed range is a confirmed indication of build-up resistance of the pressure field to the deterioration incurred by slow speed. Notwithstanding, the different applied loads imposed undermine the potential of ascribing such behavior to viscosity as an isolated impact. Collectively, it is inferred that the central bearing reliability implication is not that one oil grade is universally superior, but that safe operation necessitates sufficient compatibility and interaction among the critical impacts of shaft speed, applied loads as well as oil viscosity. This is definitely the sole guarantee for maintaining sufficient oil film pressure and minimum film thickness as shaft speed is reduced.

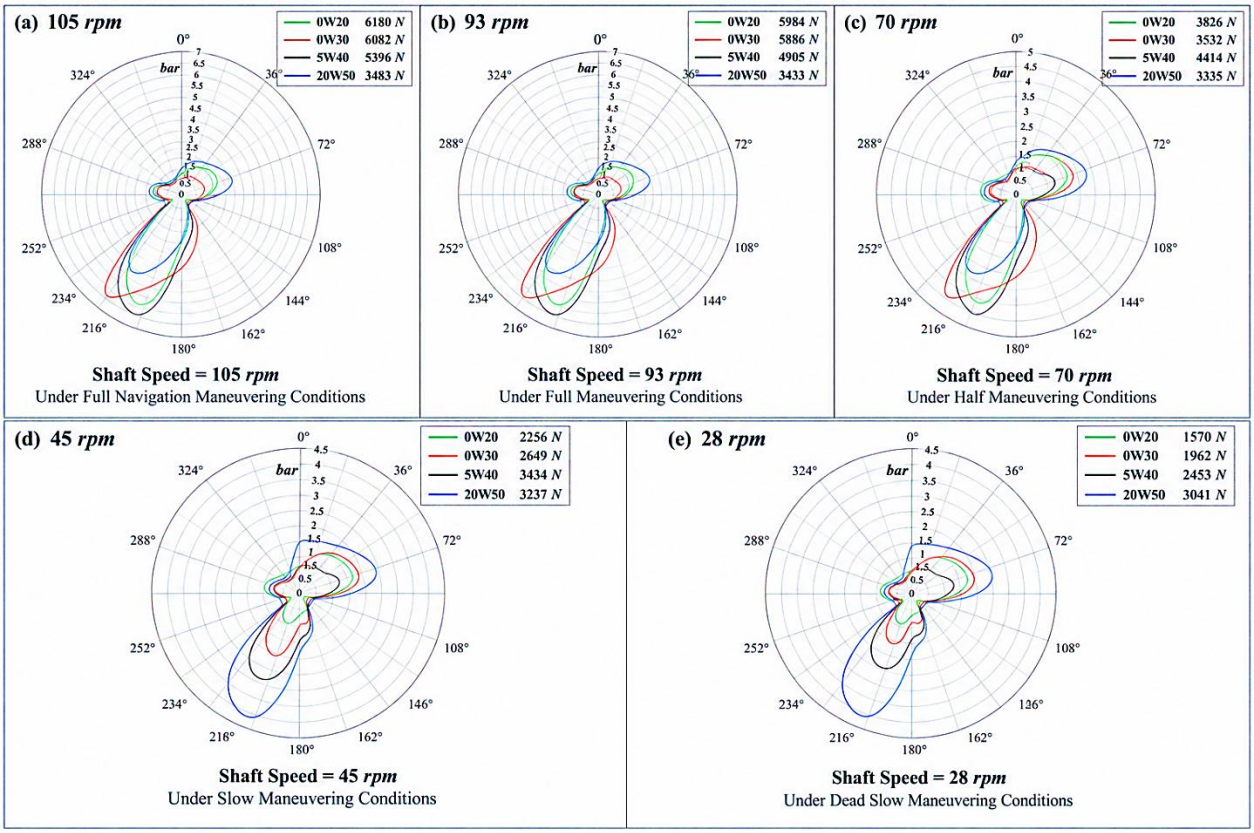


Fig. 3 Oil film pressure distribution corresponding to reference loading program

Examining the combined impact involving oil film temperature distribution together with bearing characteristic "Z" Figure 4 and friction coefficient "f", Figure 5, another bulk of no less importance tribological outcomes could be derived. For all examined oil grades, the measured oil film temperature, Z and f are evident to maintain consistent trends, with 20W50 featuring the most remarkable overall response. The main reason for such apparent consistency could be attributed to the fact that Z and f are governed by the common hydrodynamic operating condition $\mu N/P$. Hence, the acquired variations could safely be ascribed to the coupled impacts comprising dynamic viscosity (μ), shaft speed (N), nominal pressure (P) as well as oil film temperature, rather than the culmination of an outright temperature influence. Temperature is the major contributor to viscosity variations, whereas speed and load are essentially in charge of the operating position of journal bearing within the hydrodynamic lubrication region. Noteworthy that the proposed analysis is basically meant to incorporate oil film temperature, $\mu N/P$ and f with the measured oil film pressure distribution results. The adopted approach consolidates the interpretation of the experimental loading program by integrating the thermal, frictional and hydrodynamic responses into consistent speed, load and viscosity operating conditions.

Carrying out slow steaming procedures, the degradation in shaft speed weakens lubricant entrainment as well as the hydrodynamic wedge. Nevertheless, the resulting temperature reduction leads to increased oil viscosity, and such thermal viscous compensation is not adequate to prevent the deterioration previously identified in the pressure field and Z at the slower speed conditions. Comparably, the evident slow speed response of 20W50 is compatible with a greater viscous contribution with respect to lubricating oil film support. Thus, Temperature, Z and f ought to be employed as a supporting consistency evaluation of the key pressure and speed-load outcomes. That is, this could by no means be regarded as independent validation, as Z and f share the same μN/P dependence. Given the aforementioned analysis, the current endeavor could be said to lay firm grounds for identifying the tribological boundaries concerning journal bearing operation considering the critical operating moments of slow steaming maneuverability.

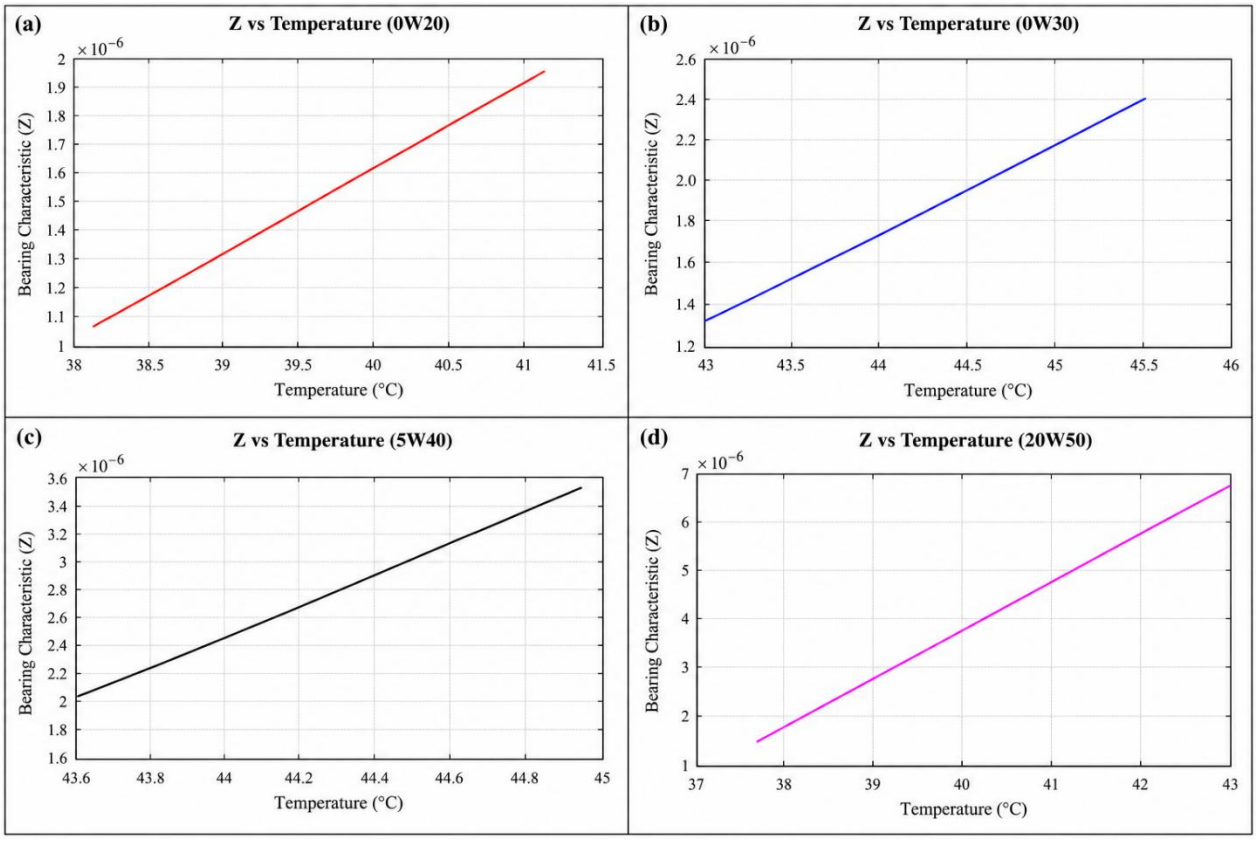


Fig. 4 Sensitivity of bearing characteristic (Z) to oil film temperature variations for different lubricant grades

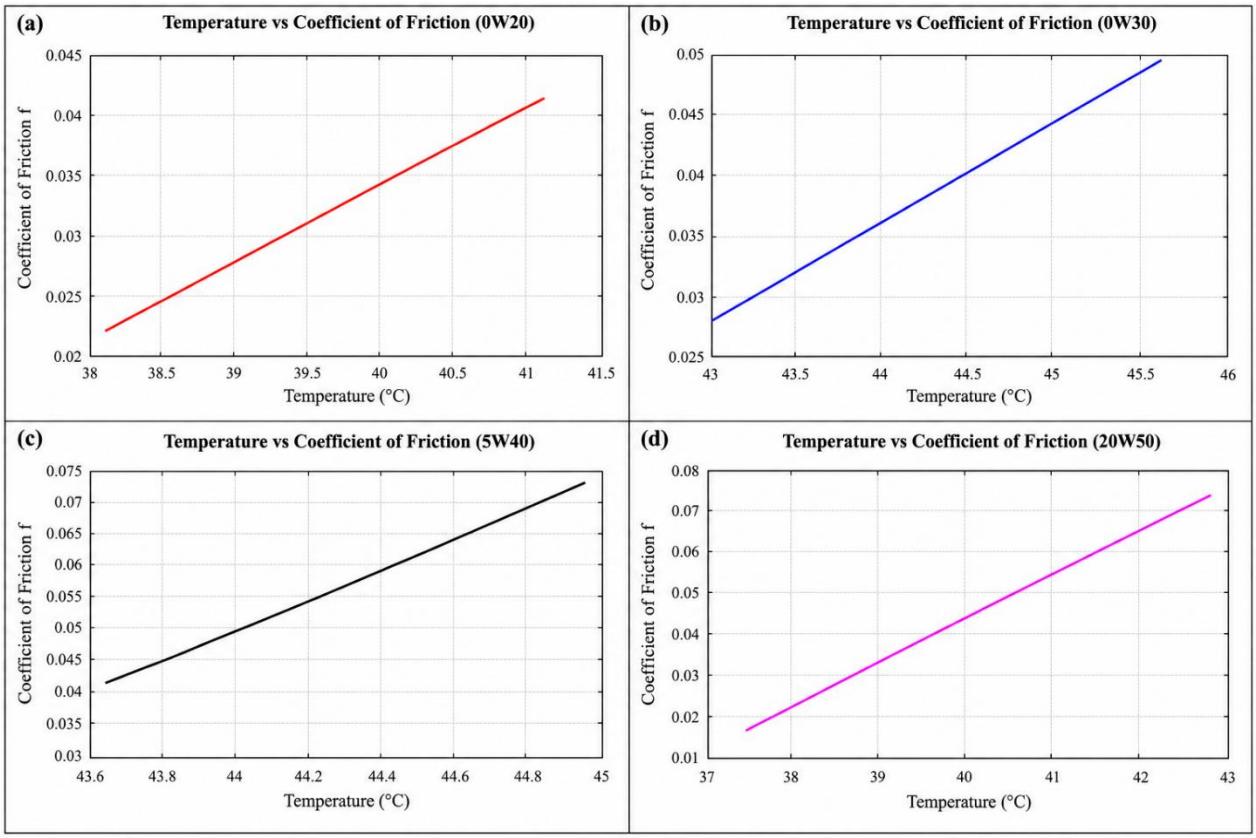


Fig. 5 Response of coefficient of friction (f) to oil film temperature variations for different lubricant grades

Abiding by the loading program considerations, experimental test trials have been carried out to recognize the sensitivity of load responses to variations imposed regarding speed profile within hydrodynamic journal bearing, Figure 6. Evidently enough, effecting permanent reductions from 105 rpm (MCR) down to 28 rpm (Dead Slow) triggers remarkable load reductions differing quantitatively with each individual lubricant oil grade examined. Overall, the degradation of shaft speed range by 73.3% has incurred correspondent load reductions by 74.60% for 0W20, 67.74% for 0W30 and 54.54% for 5W40 and by marginal 12.69% for 20W50 respectively. Evidently enough, the most prominent transition was recorded between 93 rpm and 70 rpm, where load reduction values assumed the percentages of 36.06%, 39.99%, 10.01% and 2.85%, respectively. Based on the acquired outcomes, lighter lubricants are markedly sensitive by variations made in shaft speed range. Yet, it must be observed that the 20W50 condition retains a comparatively high load as shaft speed is reduced. The most distinct transition occurred between 93 and 70 rpm, where the corresponding load reductions were 36.06%, 39.99%, 10.01% and 2.85%, respectively. Thus,

the experimental operating trajectory becomes progressively more speed-sensitive for the lighter oils, while the 20W50 condition maintains a comparatively high load as shaft speed is reduced.

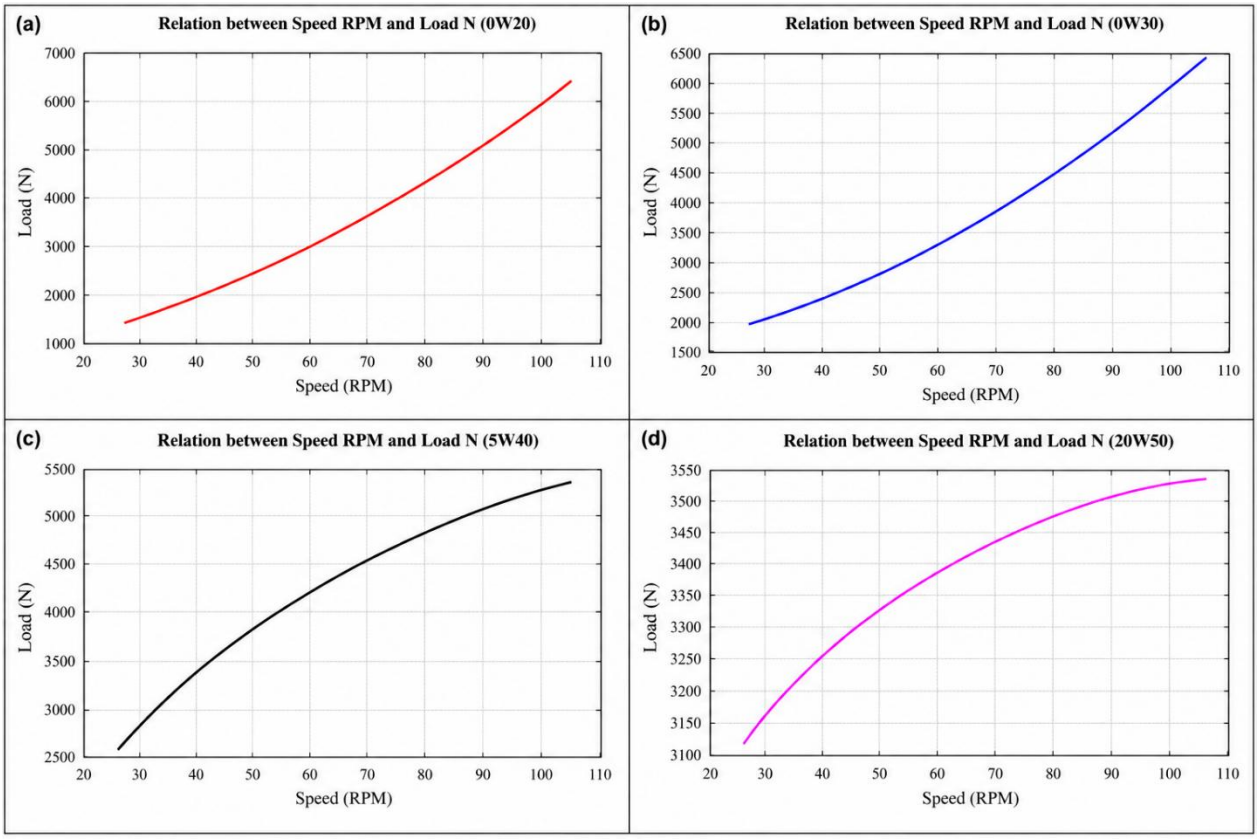


Fig. 6 Correspondence of load to journal shaft speed variations according to loading program

Notably, such a relationship is of much significance due to the fact that minimized speed operation simultaneously decreases the exerted load and undermines the hydrodynamic mechanism that sustains it. That is, degrading journal surface velocity reduces lubricant entrainment into the converging clearance and thus shifts the equilibrium eccentricity, attitude angle, pressure field as well as minimum oil film thickness. Exerting minimized load impacts for 0W20 and 0W30 as set by the loading program is true to unload the journal bearing. Nevertheless, the previously noted pressure loss reveals that such reductions are by no means to fully offset the deterioration of speed generated hydrodynamic support. In contrast, the diminishing load change of 20W50 together with its greater preservation of slow speed oil film pressure is a tight indication of viscous contribution to maintaining the supporting wedge. Therefore, it is inferred that slow steaming bearing reliability is for the most part dependent on intertwined shaft speed, load and oil viscosity operating conditions rather than the individual impact of speed or load imposed separately. Basic to

identifying the objectives of the current experimentation is to recognize the fact that the applied loads are imposed following the criteria set by the loading program. Consequently, these ought by no means to be taken as intrinsic load carrying capacity of the oils.

More important still, some very crucial observations could be obtained by examining the sensitivity of journal bearing friction coefficient factor to variations made in speed profile, Figure 7. Typical of all lubricant grades under investigation, friction coefficient maintains a systematic positive or rising tendency all through this group experimental test trials in which journal shaft speed is permanently maintained on the rise. Apparently enough, such an observation is a clear indication of the increasing contribution of viscous shear as journal surface velocity rises. Regarding 0W20, friction coefficient is noted to increase from roughly 0.021 at 28 rpm to 0.039 at 105 rpm, with intermediate values of approximately 0.029, 0.035 and 0.036 at 45 rpm, 70 rpm and 93 rpm respectively. Remarkably enough, such values are maintained consistent in order of magnitude with the corresponding oil temperature - f as well as Z- f response. Comparably, the other lubricant grades have assumed the approximate f ranges of 0.030 - 0.049 for 0W30, 0.037 - 0.070 for 5W40 and 0.023 - 0.078 for 20W50. Building on the acquired outcomes, a permanently tighter viscous friction response is recorded for increasing lubricant viscosity, specifically for 20W50. It is specifically the oil grade of 20W50 that features the steepest shaft speed dependent increase compared to 0W20 which tends to exhibit lowest friction level over the majority of the investigated operating ranges. From a slow steaming standpoint, the reduction in friction obtained at minimized shaft speed should not merely be taken independently as an improvement in bearing condition. Considering the previously observed degradation in oil film pressure and Z at diminishing speed ranges, the reduction in f is more consistently ascribed to minimized viscous shear as well as weaker lubricant entrainment. The aforementioned tendency may take place simultaneously with a degrading hydrodynamic lubrication margin. Hence, sensitivity of friction impact to speed variations could experimentally be employed as a supporting indicator, where such a critical relevance ought to be grasped together with the oil film pressure and bearing characteristic results. Collectively, lower friction during slow steaming could hence be recognized as an indication of a reduced hydrodynamic shear response and not direct evidence of enhanced lubrication characteristics.

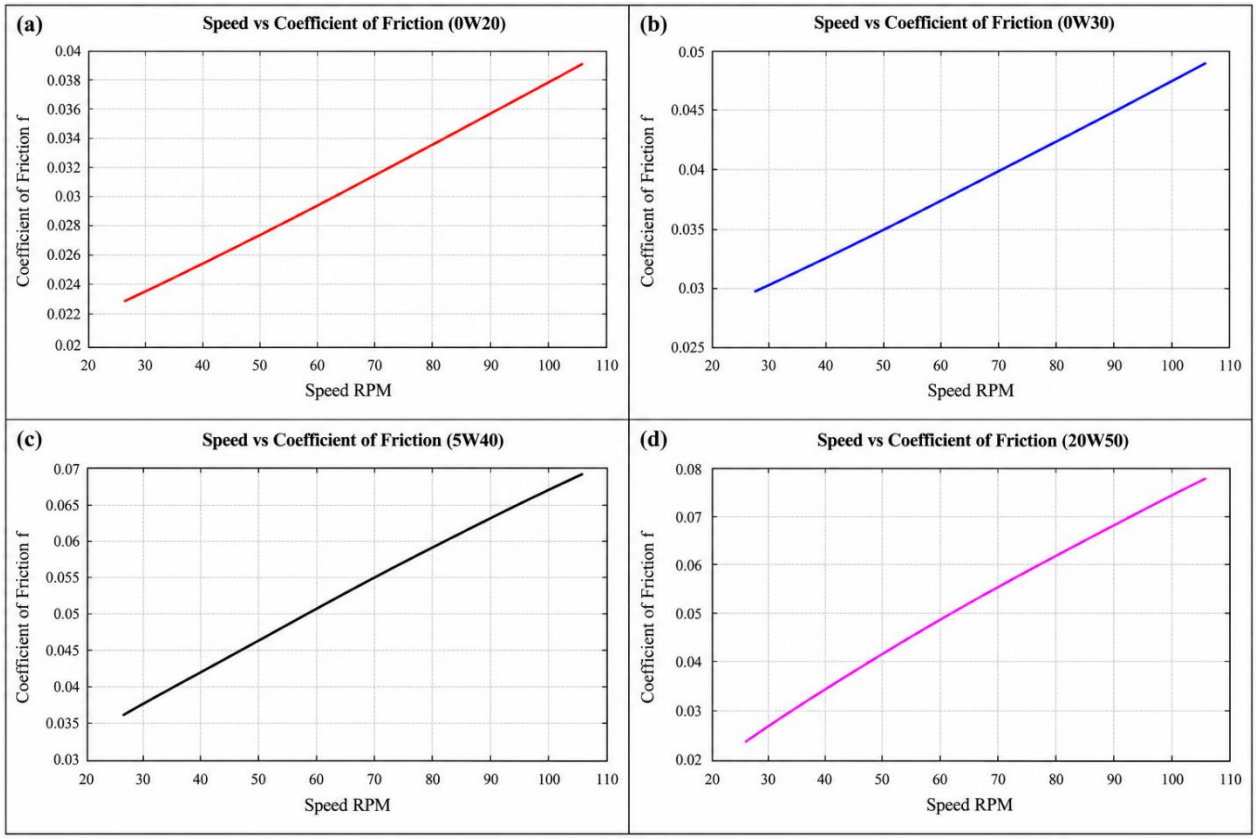


Fig. 7 Coefficient of friction changes based on journal shaft speed variations

6. Conclusion

The current investigation is basically meant to assess the potential obstacles that are so often than not encountered in case slow steaming measures are to be carried out as SEEMP energy efficiency approach (MARPOL VI). Specifically, the study pays special attention to the optimal method for identifying the shaft speed range at which hydrodynamic journal bearing lubrication could be maintained. For the intended purposes, the present analysis incorporates the measured shaft speed into all the key operational contributors involving load response, oil film pressure, temperature as well as lubricant grade impacts. Further, Stribeck curve ($f - Z$), Figure 8, helps identify the safe boundaries in which lubrication process is most likely to remain within hydrodynamic region regarding slow steaming and considering all tested lubricant grades under investigation. Considering the experimental cumulative outcomes, the 93 rpm down to 70 rpm interval has been demonstrated to be the foremost influential transition all through slow steaming range being investigated. Carrying out systematic reductions in shaft speed ranges, maximum oil film pressure is emphasized to drop from 5.22 bar to 3.38 bar for 0W20, 6.64 bar to 4.56 bar for 0W30, and 5.93

bar to 4.54 bar for 5W40. Comparably, pressure profile pertaining to 20W50 has evidently featured mere degradations ranging from 4.12 bar to 3.83 bar. The derived outcomes add much weight to the fact that lighter lubricant grades are more sensitive to the loss of speed induced entrainment, whereas elevated viscosity takes a considerable share in slow speed pressure preservation. Correlating the examined pressure trends with the adopted bearing-characteristic transition criterion ($Z = 1.7 \times 10^{-6}$), linear interpolation is demonstrated to place the oil grade 0W20 transition at 79 rpm. Consequently, shaft speed ranging from 93 rpm up to 80 rpm could safely be deemed as a conservative common criterion considering hydrodynamic operating boundaries concerning the complete lubricant set and not merely an absolute universal safety limit.

Further, below roughly 79 rpm toward 65 rpm, operating conditions have largely become lubricant dependent. To illustrate, 0W20 turns to the thin-film side of the adopted criterion, whereas 0W30, 5W40 as well as 20W50 tends to maintain a measurable thick-film margin within the interpolated range. Also, given the fact that the available oil temperature - f and Z - f data are not utterly numerically identical, friction is considered as a supporting qualitative indicator and is by no means employed to rank the lubricant grades or even to advocate the optimum oil. In light of the conducted test trials, slow steaming capability could never be fully assessed relying on rpm solely. Rather, the crucial maneuverability has to be evaluated considering the cumulative impact resulting from all critical operational factors put together and excluding none whatsoever. Additionally, taking SEEMP perspective into much consideration, the fixed pitch propeller relation ($P\alpha N^3$) makes it quite obvious that minimizing shaft speed from 93 rpm up to 80 rpm corresponds to about 36% decrease regarding theoretical propulsive power demand relative to the 93 rpm reference. Nevertheless, the transition of oil grade 0W20 near 79 rpm emphasizes that further theoretical energy-saving potential ought to be maintained within the boundaries of marine journal bearing lubrication integrity.

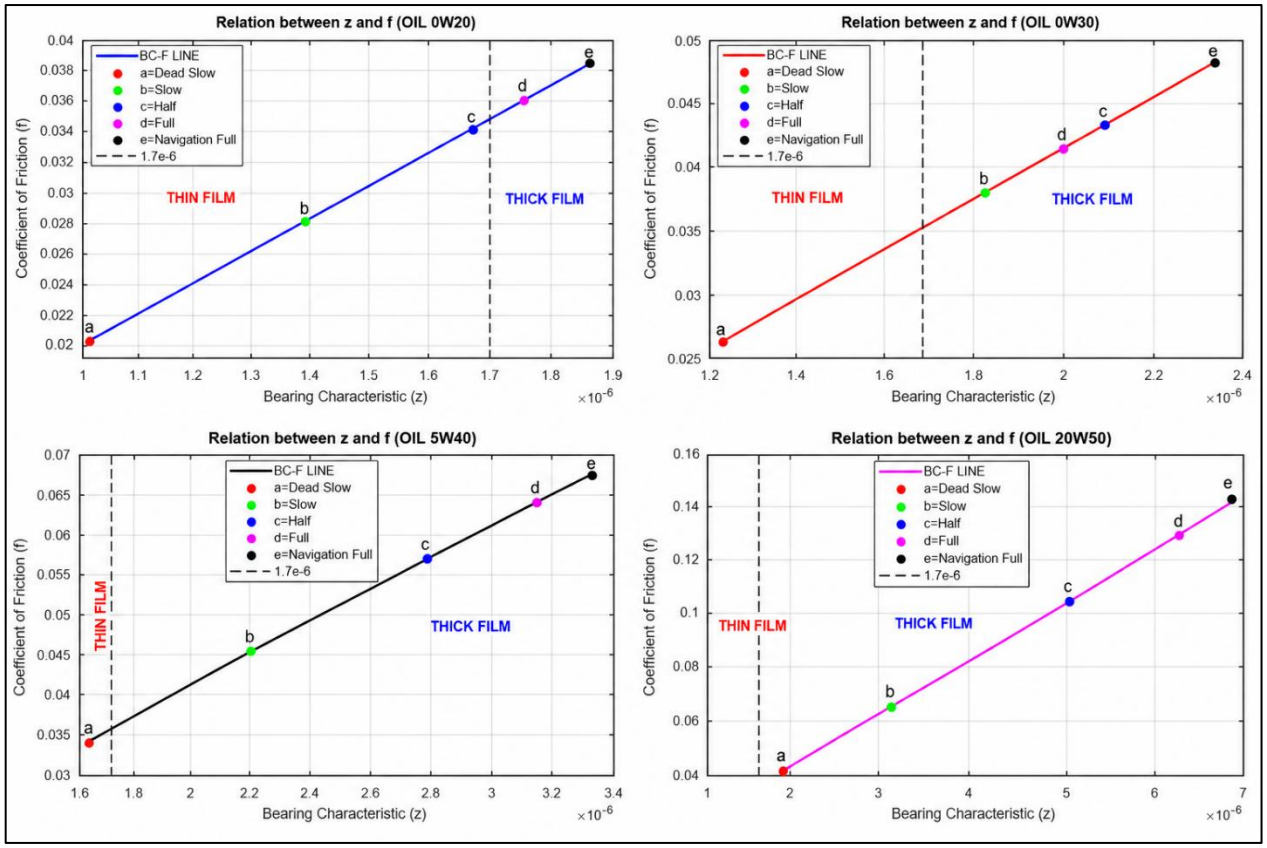


Fig. 7 An illustrative Stribeck curve indicating the frictional characteristics of the four oil grades examined experimentally observing loading program

To sum up, the proposed SEEMP objective must by all means be expressed as the maximum tribologically permissible shaft speed reduction and not merely the maximum achievable rpm reduction. More importantly and given the very specific operating conditions onboard ships, other major contributors could incur considerable variations in the performance of the lubricating oil film within marine journal bearing. All such potential impacts ought to be taken into much consideration before slow steaming measures could safely be carried out. To mention but a few, the most significant operating and environmental contributors could involve adequacy of lubricating oil cooling system, the liability of marine diesel engine to overload conditions, fuel properties as well as rough seas.

Declarations

- **Ethics approval and consent to participate**: Not applicable.
- **Consent for publication**: Not applicable.

- **Availability of data and materials**: The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.
- **Competing interests**: The authors declare that they have no competing interests.
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- **Acknowledgments:** N/A.
- **Author Contributions Statement:** N.M. conducted data collection and curation, writing original draft, methodology, formal analysis and conceptualization. R.J carried out formal analysis, investigation, methodology, review and editing. Both authors contributed to interpreting results, drafting the discussion, and reviewing the manuscript critically for intellectual content.
- **Corresponding Author:** nour_marine@aast.edu

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