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Contents

Reviewing experimental and theoretical efforts and key findings regarding hydrodynamic journal bearing geometry

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المستخلص

تعتمد عملية المحمل العائم، خاصة فيما يتعلق بالتطبيقات البحرية، بشكل كبير على أداء أهم العوامل التشغيلية. على وجه التحديد، غالبًا ما يتعرض الزيت الزلق داخل المحمل العائم للتدهور الخطير والفشل النهائي في ظروف التشغيل الفعلية. بناءً على هذه الحقيقة، تهدف الدراسة الحالية إلى إجراء مراجعة للأدبيات حول الجهود المبذولة لتحسين أداء المحمل العائم استنادًا إلى اختيار التصميم الهندسي المناسب للمحمل العائم. تم تحليل البيانات المجمعة بدقة وتقييمها باستخدام الوسائل التجريبية والنظرية والعددية. تمثل النتائج المستخلصة من الاستعراض أساسًا متينًا لإجراء تعديلات واسعة النطاق على تصميم المحمل العائم للتطبيقات البحرية، ومن الممكن أن تُستخدم هذه البيانات في الأبحاث المستقبلية لتوسيع قدرات المحمل العائم ووظائفه لتحقيق أقصى أداء ممكن في ظروف التشغيل الفعلية.

Abstract

Journal bearing operation particularly in regard to marine applications is significantly affected by the performance of the most critical operational factors. Specifically, the lubricating oil film within journal bearing is so often than not subject to hazardous deterioration and ultimate failure in real operating conditions. Considering such fact, the current study is intended to carry out a literature survey regarding the efforts towards enhanced journal bearing performance based on proper selection of geometrical design for journal bearing. The aggregated data were thoroughly analyzed and assessed utilizing experimental, theoretical as well as numerical means. The outcomes derived from the conducted review represent firm grounds for carrying out extensive modifications into journal bearing design for marine applications. Further, such data will possibly be employed in future research investigations to extend the capability of journal bearing and its functions to attain the most possible enhanced performance in actual operating conditions. Apparently, the vast majority of both experimental and theoretical studies into journal bearing geometrical designs for enhanced performance, 66 in all, have been focused on surface texture accounting for 26.67 % (29 research studies) and 32.43 % (33 research studies) of the total investigations under study respectively. Regarding the experimental studies, realizing promoted performance of lubricating oil film by working on pressure profile has evidently obtained the largest contribution representing 35.5% of the overall bulk of the reviewed efforts, Figure 6.

Keywords: Hydrodynamic Lubrication, journal bearing geometry, operating condition.

Nomenclature		
C_0	total clearance	mm
C	radial clearance	mm
D	inner diameter for grooved bearing	mm
L	bearing length	mm
N	shaft speed	rpm
P	motor power	kW
P_{max}	maximum oil film pressure	bar
P_0	nominal bearing pressure	bar
r	Radius for Journal Shaft	mm
T	temperature	℃
W	applied load	N
Φ_s	shaft diameter	mm
CGB	circumferential grooved bearing	
CP	communication processor	
PLC	programmable logic controller	
PS	power supply	
PT	pressure transmitter	
SCADA	supervisory control and data acquisition	
TC	thermocouple	
UJBTR	universal journal bearing test rig	

1- Introduction

Safe navigation onboard ship is essentially dependent on a number of elements including Shafting Propulsion System (SPS). Such a crucial system relying chiefly on journal bearing ought to accommodate both adequately and efficiently to wide ranges of speed operating conditions. These involve slow speed, critical speed and high or rather full navigation speed. Being principally designed for operation in hydrodynamic lubrication region, journal bearing, Figure 1, ought to be maintained at the most possible optimal operating condition. The main reason for that lies in the fact that journal bearing contains the vital lubricating oil film between moving surface (journal shaft) and stationery surface (bearing). Severe operating conditions are so often than not affecting the lubricating oil film and could in certain cases incur very serious consequences such as hazardous deterioration and possibly the ultimate and disastrous failure of the whole SPS. Among the prominent serious consequences such undesirable situations could trigger is the misalignment between the main engine crankshaft, the intermediate shaft and the propeller shaft. Deterioration of journal bearing incurs increased operating and replacement costs, repetitive stop and costly downtime as well as reduced bearing life.

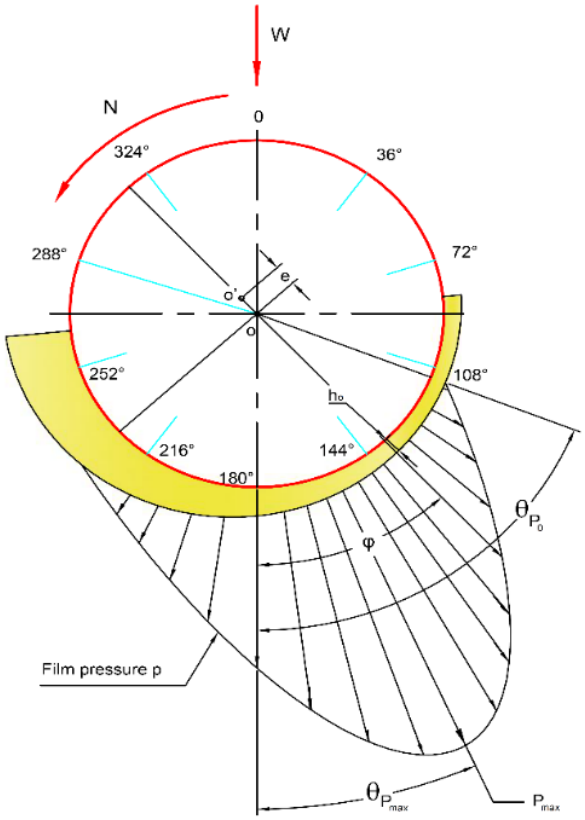

Figure 1: A schematic polar diagram of oil film pressure distribution with the minimum film thickness h_0, eccentricity e, angular location of the minimum film thickness ∅, shaft weight W, maximum film pressure P_{max}, position of maximum film pressure θp_{max} and terminating pressure of oil film θP_0.

Modification of journal bearing geometrical design, Figure 2, is definitely one of the foremost techniques to which shipyard arena manufacturers often resort for effecting tangible enhanced operational performance. Thus, the present study reviews different endeavors for enhancing performance of journal bearing based on possible geometrical designs. Additionally, it seeks to trace and highlight the most effective geometrical designs among all scanned efforts (66 research studies in all). The final objective behind the work at hand is also to identify the best contributions in this respect with view to benefiting from and building on the most significant achievements as well as attaining applicable geometrical design suitable for journal bearing even in the most severe operating conditions a ship may be face. To sum up, the present investigation is a step in a series of potential investigations for promoting journal bearing performance based on the aggregated data derived from the conducted review in regard to the most optimal geometry for enhanced performance in real operating conditions.

Figure 2: An illustration of different journal bearing geometries. (N. Marey et al., 2021)

2- The design related to the journal bearing

2.1 Research endeavors concerning journal bearing design

(Muzakkir et al., 2014), developed a test setup for tracing the possible reasons for heavy- duty, slow speed hybrid journal bearing tribological failure. Journal bearing was operated under the load of 373 N and journal speed of 27 rpm. Cylindrical magnetic bearing arrangement was confirmed to be inconsistent for heavy load and low speed operating conditions due to its very low static load-carrying capacity. To mitigate and contain the severity of the magnetic bearing failure, the study recommended the use of magnetic bearing arrangement lubricants.

(Gralde, 2014), Carried out an extensive investigation into start -stop journal bearing test rig. The study combined a manufactured test rig to the development of test rig software via MATLAB. Further, an engine lubricant was applied for the lubrication process of journal bearing. Speed variations ranged from 0 rpm up to 1000 rpm in 60 seconds duration under variable load impacts of 500 N, 1000 N, 3000 N and 5000 N. Based on the conducted study, it was possible to obtain torque amid shaft and bearing. Also, the study scope extended to trace transient states of journal bearing via a functioning test-rig.

(Chasalevris & Dohnal, 2015), investigated the possibility of minimizing vibrations in rotating shafts by introducing a variable geometry journal bearing in the final form provided by detailed design procedure. Speed limits ranged from 500 rpm up to 5000 rpm and the beams were displaced for applying the preloading for external springs. Vibration amplitude was suppressed by up to 7% compared to a conventional journal bearing. Based on the presented study, it was possible to change the effective damping and stiffness of the system through selective activation of an additional fluid film during critical operation.

(Blomstedt, 2017), introduced systems for measuring and controlling test parameters regarding tribological values and their validation. Thermocouples, displacement sensors and oil film pressure and temperature sensors were all integrated into the test rig. Also, three hydraulic cylinders were added to exert dynamic alternating loads ranging from 0 up to 100 kN. Shaft rotation speed ranged from 0 rpm up to 3000 rpm. Reducing oil pressure was found to reduce test bearing friction and vice versa. Temperature rise of oil was demonstrated to be less in bearing contact area. Also, rotational load featured higher friction than that of static load.

(Kulkarni, 2018), conducted an experimental investigation into the impact of speed and load variations on journal bearing circumferential distribution. Also, weight was added to derive the different speed variation readings. Hydrodynamic journal bearing created load supporting fluid film according to both shape and relative motion of the sliding surface. Such fluid film had the potential of preventing the metal-to-metal contact between the shafts and the bearing. Consequently, load action on journal bearing shaped the pressure profile where no friction emerged.

(Marey, 2018), designed and constructed a journal bearing test rig of multiple functions to investigate single grooved journal bearing. The selection of test rig components involving drive motor, drive shaft, bearing assembly and data acquisition system was given a special consideration. The constructed test rig unit was capable of containing wide-range test trials regarding journal bearing lubrication. Applying the different speed ranges of 50 rpm, 100 rpm, 150 rpm and 200 rpm respectively at constant load, the study assured adequate conformity between experimental test rig results and their peers derived theoretically. Such an outcome has stressed the validity of the constructed system for potential future experiments. Moreover, (N. Marey et al., 2021) carried out thorough modifications to journal bearing structure. Such modification procedures have involved adding a hydraulic loading system which facilitated even a wider range of experimental test trials. Precision of all conducted procedures and relevant outcomes were ensured via Supervisory Control and Data Acquisition (SCADA) system carried out by (Marey & Ali, 2023) . As such, the structure was transformed into a Universal Journal Bearing Test Rig (UJBTR). A system that integrated all essential monitoring devices necessary for the extensive and possibly enhancement of the foremost operational factors affecting operational conditions.

3- Experimental investigation into journal bearing geometry

3.1 Modifications of geometrical design of plain bearing

Bearing type is by all means one of the foremost factors upon which the behavior of hydrodynamic journal bearing in actual operating conditions essentially rely. Specifically, plain bearings are known to be one of one of the most effective bearing types that is commonly utilized in marine applications. Modifying plain bearing in terms of geometry can offer numerous advantages as well as tangible enhancement of journal bearing performance. Consequently, introducing innovative modifications regarding plain bearing geometrical designs for promoted operation has been the main interest of a considerable number of research investigations.

(Ahmed et al., 2013), presented a thorough evaluation regarding the individual impacts of the different variables on maximum oil film pressure. Maximum oil film pressure was evidently affected by the model terms of speed, load and oil-feed pressure. Variable speed ranges from 100:1000 rpm have been applied as well as a pressure sensor of MEAS (M5156) model, 10 MPa range and accuracy of roughly (0.001± 1% measured value) MPa. Maximum oil film pressure could accurately be estimated based on regression model and the deviation ratio was just quite negligible amounting to around 1%.

(H. C. Liu et al., 2016), examined the individual squeeze impact pertaining to the formation of hydrodynamic lubricating film in a slider on disc contact. The study involved variable modes of non-steady motions, which were analyzed on both experimental and theoretical grounds under load impact of roughly 5 N. Realizing the final steady speed at startup/shutdown process was confirmed to bring the change rate of film thickness to a maximum. Squeeze effect or rather change rate of film thickness obtained its maximum value on reaching the final steady speed.

(Mansoor & Shayler, 2018), traced the impact of oil feed pressure on friction torque factor applying light, steady loads. Shaft rotation speed ranging from 400 rpm up to 2000 rpm was controlled utilizing an electronic inverter connected to the motor. Applying a specific load SL of 4.3 bar, the study assured that the reduction of feed pressure would increase cavitation area. In such a condition, pressure gets lower in the low-pressure zone of the film. Hence, the reduction of film area incurs correspondent reductions in friction torque. As a result, eccentricity ratio and circumferential- average surface shear stress are both reduced.

(X. Zhang et al., 2019), demonstrated the significant impact of axial misalignment in regard to journal bearing seizure load. The experimental study involved a motor rated power of 5.5 kW, a rated torque amounting to 35 NM as well as a 1500 r/min rated rotational speed. The increase in clearance decreased seizure load and hence could provide a better aligned condition. Yet, regarding misaligned condition, there appeared to be an optimum radial clearance for a given misalignment angle. Consequently, seizure load was confirmed to be considerably affected by axial misalignment.

(Cui et al., 2023) traced the formation and evolution pertaining to transfer film concerning fabric composite lubricated plain bearing within cryogenic and wide temperature range. Integrating in-situ Fourier Transform Infrared (FTIR) microscopy, time evolution and time dependence of

lubricating transfer film morphology and composition concerning PTFE fabric composite through spherical plain bearing tribotester was unraveled. Also, conducting test trials at a wide range of temperature, the study pointed out the significant role of transfer and molecular reorientation of PTFE regarding PTFE fabric composite lubrication.

Notably, this group of research investigations considered promoting performance of journal bearing based on a number of crucial factors involving oil film pressure and temperature distribution, eccentricity as well as the oil film thickness. Yet, some other significant operational factors were not given due interest. These involve the oil supply pressure and temperature, the different viscosities and the vibrations.

3.2 Promoting grooved bearing performance

Another bulk of crucial research investigations focused on enhancing hydrodynamic lubrication within journal bearing via modifying groove positions, numbers or distributions.

(Ahmad et al., 2013), were concerned with promoting journal bearing lubrication performance depending on oil supply pressure at variable groove locations. Providing different measurements regarding frictional force, torque and friction coefficient, the study assured the sensitivity of torque and frictional force to variations made in groove position and oil supply pressure. The experimental test trials have been conducted at speed ranges of 500 and 800 rpm under 15 kN radial load impact.

(Adatepe et al., 2013), examined tribological tendencies related to non-grooved and micro-grooved journal bearings applying dynamic loading. Speed variations ranging from 400 up to 2000 rpm were tested to determine frictional moment variations in liquid friction zone exerting versatile suspended static loads on the bearing. Micro-grooves were concluded to have a crucial impact in the shapes of oil film thickness, friction coefficient and friction force under the operating conditions of dynamic load.

The impact of alterations in groove location on temperature and pressure profiles within journal bearing was the main focus of (Ahmad et al., 2014). Those profiles were measured at speed variations involving 300, 500 and 800 rpm under versatile radial loads of (10 and 20 kN). Locating oil groove supply in the converging section, close to the minimum oil film thickness position, was evident to reduce temperature values.

(Binu et al., 2015), have traced the nature of hydrodynamic pressure distribution related to two-axial groove journal bearings. The study introduced a novel test rig integrating a drive unit containing a 5 HP AC Motor, with a unit for controlling speed combined with a hollow shaft utilizing belt drive. Operating the structure at a speed of 1200 rpm, the study revealed the experimentally derived pressures which were less by around 20% than their peers acquired theoretically.

(Chatterton et al., 2017) investigated the twin groove cylindrical journal bearing regarding rotational speeds as well as static loads. The study involved testing the 160 mm diameter bearing under severe operating conditions at speed ranges from 66 rpm up to 1440 rpm under variable

applied loads ranging from 0 kN up to 350 kN in a vertical direction. Increased load, deformation of bearing housing as well as bending of shaft were all concluded to have significant impacts on performance. Also, increasing static load, particularly at loaded part of the bearing, was ascertained to increase bearing deformation significantly.

(Marey, 2018), carried out an experimental investigation into single grooved journal bearing. Test Rig components were carefully selected and designed. The introduced test rig unit offered a valuable chance to carry out extensive tests regarding journal bearing lubrication. Test rig was operated at the variable speeds of 50 rpm, 100 rpm, 150 rpm and 200 rpm consecutively under constant load. Conformity between experimental test trials and theoretical investigations stressed the potential of the constructed system to contain even more elaborate studies in the future.

In addition, Marey et al, conducted a series of research investigations into the most influential operational factors affecting the oil film lubrication within journal bearing utilizing the Universal Journal Bearing Test Rig (UJBTR). The behavior of journal bearing at variable speeds, loads, oil viscosities and oil supply pressure was extensively evaluated. (N. Marey, 2019), (N. Marey et al., 2022), (N. Marey, 2023) and (N. A. Marey et al., 2024).

Resuming research efforts towards optimal grooved bearing performance, (Marey et al., 2023) carried out an experimental investigation into hydro-thermal performance regarding journal bearing lubricating oil film profile within diesel engine at slow speeds. Considering the loading program of slow speed diesel engine, the study examined oil film temperature and pressure profiles utilizing variable grade fluids. With medium viscosity lubricant grades, the increase of shaft speed was demonstrated to incur reductions in the difference between optimal and heavy loads. For shaft rotational speeds of 43 rpm, 90 rpm and 104 rpm, those differences represented 22%, 9.7% and 2.1% respectively. A proper selection of a lubricant was thus concluded to provide improved operational behavior, reduced cost and extended life for journal bearings.

Based on the aforementioned group of investigations, a considerable improvement in the performance of journal bearing could be achieved depending on grooved bearing. Consequently, this type of bearing is the most practical type that is commonly utilized in marine applications currently. Notwithstanding, this bulk of research endeavors did not pay much consideration to the negative impact of vibrations on the behavior of journal bearing. Vibration impact is by all means one of the serious factors that could affect performance and operation, and is thus in need of due attention at the initial phases of journal bearing design and construction.

3.3 Experimental test trials on elliptical bearings

The ability of elliptical bearing to promote performance via enhanced dynamic characteristics and more stability gave the momentum for another group of research investigations. Such bearing type is mainly characterized by a horizontal clearance that ranges from 1.5 times to double its vertical clearance, or rather, from 33% up to 50% preload. Such an advantage means offering optimal damping as well as load capacity through re-orienting split angle between halves. Hence, from a dynamic perspective, it is a highly asymmetric bearing (Leader, 2012).

(Aher et al., 2013) worked on the lubricating oil film within elliptical journal bearing. Temperature and pressure increase in regard to the hydrodynamic journal bearing lubricating oil film under high speed rotating machinery was elaborately investigated. A noncircular elliptical bearing at constant load of 500 N and variations of speed ranges involving 1000, 1500 and 2000 rpm was employed. Results demonstrated the increase in the values of both pressure and temperature profiles under such specific operating conditions.

(Singla et al., 2014) traced the load carrying capacity of lobe bearing based on different comparisons between it and that of plain journal bearing. The variable loads of 300, 450, 600 and 750 N were applied at corresponding rotational speeds of 1000 rpm, 1500 rpm and 2000 rpm respectively. The study assured the ability of lobe manufactured bearing to yield more stability and elevated load carrying capacity at both higher and lower speeds alike than those provided by plain journal bearing.

(Zhang et al., 2019) proposed a mechanism for suppressing rotor vibration amplitude within adjustable elliptical journal bearing during normal speed operating conditions. The attempt to mitigate the impact of synchronous unbalanced load was carried out at shaft speed of 2000 rpm under constant load amounting to 200 N. A dynamic lubrication program was established where numerical simulations were conducted. Adjustable elliptical bearing suppressed forced vibrations significantly.

More important still, (Amine et al., 2023) introduced an approach combining both experimental and numerical procedures for tracing oil film thickness as well as friction regarding a wide elliptical thermoelastohydrodynamic (TEHL) considering sliding conditions extending from pure rolling to opposite sliding. The impact of varying ambient temperature, normal load and entrainment speed on film thickness and friction in a wide range of sliding conditions was verified. Also, a simple formula was created for estimating minimum film thickness depending mainly on classical dimensionless parameters and SRR and employing numerical parametric investigation as well as relevant results.

The above mentioned group of research studies are evident to lack the effect of bearing material on the performance of journal bearing. Utilizing a suitable material in the construction of journal bearing is definitely one crucial step towards achieving enhanced performance and reduced maintenance costs for journal bearing in actual operating conditions.

3.4 Enhanced performance based on tilting pad bearings

Tilting pad journal bearing was also a crucial focus of attention for a considerable number of research studies, aiming at achieving enhanced performance of operating conditions. Involving numerous bearing pads which pivot to generate a pressure field in oil film, tilting pad journal bearing could effective support the applied load. (Salazar & Santos, 2017) utilized hybrid lubrication for promoting dynamic performance of the system in regard to active tilting pad journal bearings supporting flexible rotors. The study employed a test rig involving AC motor power of 3 kW, a maximum rotor speed of 7000 rpm and a bearing load of 1440 N. Hybrid lubrication was confirmed to enhance the system dynamic performance considerably.

(Cerda & Ferreira, 2018) introduced active characteristics into standard leading edge groove (LEG) tilting pad journal bearing employing theoretical and experimental procedures. The evaluation of the feasibility of such technique was conducted at journal rotational speeds of 1000 rpm, 2000 rpm and 3000 rpm subsequently, exerting bearing mean loads of 1000 N and 5000 N respectively. The proposed design had the capability of modifying both its steady state and dynamic properties via an electrical signal fed into a servo-valve marked by a high-response.

(Ciulli et al., 2018) sought to satisfy the requirements pertaining to the next-generation high power density turbomachinery efficiency. The study involved description of a novel test rig regarding static as well as dynamic characterization in regard to high performance tilting pad journal bearings. Employing a motor of 4000 rpm maximum speed, a nominal torque of 3000 Nm, and a maximum static load of 270 kN, the study demonstrated the capability of the proposed model design to carry out the process of data acquisition effectively.

(Lou et al., 2019) considered the impact of fluid pivot journal bearing (FPJB) performance in relation to the one-sided floating state. Larger recess area ratio was concluded to incur a smaller recess pressure while bearing capacity was constant. Also, squeeze- film appeared between the pad and the bearing house. Recess pressure rose from 448 up to 1800 and remained constant from 2242 to 3300 rpm. Determination of the floating state of the pad and bearing performance calculation depended on essential data of recess pressure and floating heights of each displacement measuring point.

The possibility of utilizing alternative materials in regard to tilting pad thrust bearings working in transition to mixed friction was experimentally researched by (Wasilczuk & Wodtke, 2024). The behavior of fluid film bearings in such specific operating regimes was investigated for four tilting pad bearings of variable material compositions. The study involved stopping under load and reproduction of Stribeck curve applying reduction of rotational speed to minimized values. The involved analysis has assured the possibility of employing less popular material compositions concerning bearings utilized in specific conditions. DLC/Steel bearing demonstrated elevated and much more stable performance particularly at start-stop.

Scanning such group of investigations indicates the shortcoming in regard to the impact of critical operational factors which affect journal bearing performance in real operating conditions particularly that of overload. Also, tilting pad bearing is one of bearing types that was not practically utilized in regard to marine journal bearing as other alternative geometrical designs were concluded to yield better operational characteristics.

3.5 Applying surface texture techniques

Several research investigations have been oriented towards the influence of surface texture regarding the critical operating factors of bearing lubrication, load-carrying capacity as well as wear resistance. (Kumar Gupta et al., 2013) integrated micro-dimples into bearing surface and concluded that the increase of pressure in textured bearing exceeded that of smooth journal bearing. A commercial oil grade Hydrol 68 was utilized under variable loads from 100 N up to 800

N, for speed ranges of 1000, 2000 and 3000 rpm respectively and constant oil feed pressure of 0.05 MPa. Surface texture was found to be apparently affected by variations of speed.

(Singh & Rana 2014) were specifically focused on improving hydrodynamic and journal bearing performance relying on surface texture techniques. A novel laboratory setup involving a speed of 1500 rpm was introduced. The textured bearing included eight grooves each of which was 1 mm wide. The distance between each groove was 8 mm. Maximum pressure was evidently affected by changing certain parameters such as shaft speed, bearing context texture as well as loading conditions.

(Dadouche & Conlon, 2016) traced the impact of surface texture and contaminated fluid in regard to steady-state performance characteristics in as far as heavily-loaded journal bearings are concerned. Journal shaft was run at 16500 rpm exerting a static load of 22250 N, a dynamic load of 1335 N and a power of motor of 37 Kw. Based on the study, dimples were demonstrated to be capable of capturing contaminant particles and hence reducing the risk of bearing failure.

(Dong et al., 2017) worked on the impact of texture distribution on bearing vibration and rotor stability. Experimental test trials involved high speeds of 2800 rpm and 3600 rpm in addition to the lower speed of 1000 rpm. Acceleration amplitude of textured bearings under such specific operating conditions was apparently less than that of non-textured bearings. Also, damping effect of surface-textured bearings by far exceeded that of non-textured bearings. Increasing rotating speed would evidently maximize shaft frequency amplitude.

(Qi et al., 2019) outlined the effects of Laser Surface texturing on tribological properties of Polytetrafluoroethylene (PTFE)/ Kevlar Fabric Composite weave. Friction tests comprised variable rotation speeds of 200 r/min, 400 r/min, 600 r/min and 800 r/min under wide range load impacts of 542 N, 1084 N and 2168 N respectively. Friction and wear in a tribosystem were considerably reduced when Structural Laser Surface Texturing(LST) technology was applied. LST was thus confirmed to enhance tribological performance and reduce wear rate.

(Putignano et al., 2019) investigated the possibility of reducing friction rates by means of utilizing soft matter laser micro-texturing. Employing a Femtosecond laser manufacturing process, the study could produce a pattern of micro dimples on a Fluoro-elastomer. Soft contacts were assured to contain friction levels provided that a consistent theoretical optimization of dimple structure was carried out.

(Galda et al., 2019) introduced the characteristic parameters including sliding velocity, Hersey number and friction torque when lubrication regimes transition took place. The experimental study involved numerous journal bearing types as well as the variable speeds of 100 rpm and 500 rpm. Friction torque was considerably affected by textured sliding surfaces of journal bearings during shutdown.

(Vlădescu et al., 2019) applied laser surface texture to internal combustion engine journal bearing shells. Impacts of such a condition were experimentally tested at the variable speeds of 750 rpm up to 4000 rpm under exerted loads of 1 up to 8 kN. Laser-etched patterns were applied to surface of

shell components to discern the impact of surface texturing on crankshaft bearing. Locating textured micro-features outside load area was ascertained to reduce friction levels significantly.

(Li et al., 2023) intended to introduce the acting mechanisms related to abrasive wear comprising two-body and three-body abrasion affecting tribological systems. Utilizing bearing steel (100 Cr6) pins and discs in a flat-on-flat contact and interracial media, the study assured the significant impact of speed-induced hydrodynamic impact on frictional behavior of the system. Film thickness could be increased by 14% and friction could also be decreased by 2/3 as a result of increasing a speed-dependent hydrodynamic impact.

(Kajihara, 2024) carried out a surface treatment relying on Laser Induced Particle Impact Test (LIPIT) for enhancing tribological properties related to material surface. Considering particle mass, material surface was found to be impacted with a velocity of 400m/s to 750 m/s employing LIPIT. Results strongly referred to the capability of LIPIT to contain frictional resistance. The reason for that was attributed to the potential of dimple textured surface generated by LIPIT to promote lubricant retention.

Surface texturing is absolutely one of the promising design techniques that is likely to bring about considerable enhancement in journal bearing operation for marine applications. Hence, such field is so crucial and is still in need of thorough investigations and analysis concerning the oil film lubrication within journal bearing.

4- Theoretical Studies

In fact, a considerable improvement in the performance of hydrodynamic journal bearing can be attained via employing theoretical means. A significant bulk of research studies worked on such a crucial objective by applying theoretical approaches involving Reynold's equation, Sommerfeld number and last but not least the Navier Stoke equations. On the other hand, another group of no less importance investigations tended to realize such enhanced behavior via introducing or rather employing theoretical analyses. Those analytical studies can safely be divided into categories based on the focus point for each of them. Individual Investigations into each of FLUENT, MATLAB, GAMBIT and COMSOL were carried out and the related analyses as well as the derived outcomes have all been introduced. (Zhang et al., 2023) introduced a thorough review where beneficial guidelines regarding self-powered methods for creating smart bearings were proposed. The study involved the underlying theory, modelling techniques, methodologies as well as technologies. Further, topology, mechanisms and advantages of wireless power transfer related to a self-powered smart bearing were all illustrated. Useful tips for performance development and for promoting the applicability of self-powered smart bearings at working conditions were suggested. Those mainly involved design methodologies and technologies concerning a wide range of transducers. Also, potential research orientations and opportunities for self-powered smart bearing systems were extensively investigated.

4.1 Theoretical efforts regarding journal bearing geometry

4.1.1 Plain bearing

(K¨alvelid, 2016) constructed a numerical modelling related to plain journal bearings within oil system pertaining to a heavily-loaded engine applying the system analysis software of GT-S. Lower engine speeds involving 600 rpm and 950 rpm were applied for calculating bearing loads utilizing GT-SUITE. Considering the split lines for main bearing in the models, the study concluded the increase of oil volume flow rate by 13-16%. Based on the study, geometric irregularities could accurately be identified utilizing the Reynold's equation.

(N. Marey et al., 2018) provided a computational investigation into oil film pressure distribution of plain journal bearing utilizing CFD package ANSYS. ver.15.0. Also, an experimental journal bearing test rig was constructed for simulating journal bearing performance within the shafting system of the ship at variable speeds of 50 rpm up to 400 rpm at constant load. The introduced discipline could facilitate investigating oil film pressure behavior extensively. The most critical operational factors involving oil properties and design schemes could all thus be elaborately studied and enhanced.

(S. Cui, Gu, Wang, et al., 2018) examined hydrodynamic journal bearing behavior at startup. The rotor speed increased linearly from 0 up to 1000 rpm in 0.1s, 0.2s and 9.3s respectively. Hydrodynamic oil force at startup was evident to increase sharply incurring a sharp decrease in contact force. Increasing the relative clearance of bearing led to reductions in contact force as well as contact time. Also, high start-up acceleration was found to reduce contact force considerably.

(S. Cui, Gu, Fillon, et al., 2018) investigated the impacts of surface roughness on transient characteristics of hydrodynamic cylindrical bearings during startup. Hydrodynamic pressure was derived based on the modified average Reynolds equation with Finite Element Method (FEM). Rotational speed rose linearly up to 1000 rpm within 0.1s. The study concluded the considerable impact of surface roughness on the transient characteristics of the bearing in the initial phase of start-up.

(ERHUNMWUN & AKPOBI, 2019) traced the influence of changing radial clearance on the variations of fluid pressure profile. The study involved a journal shaft speed of 1000 rpm and an oil dynamic viscosity of 0.19 PA.s. Steady state and constant temperature were involved in the study and a numerical solution for short journal bearing under steady state was also developed. It was recommended to increase radial clearance in the design of journal bearing. In such a way, bearing pressure could considerably be reduced.

(ERHUNMWUN & AKPOBI, 2019) discussed the variation in fluid viscosity combined with changes in lubricant pressure within hydrodynamic journal bearing. Introducing a parametric study in which the Finite Element Method (FEM) was employed, the researchers analyzed the pressure performance of the bearing via Classical Reynolds Equation. The linear relation between Fluid viscosity and bearing pressure was both demonstrated and confirmed.

(Xiang, Han, Wang, Wang, et al., 2019) intended to examine certain journal bearing essential characteristics involving mixed lubrication and wear. A numerical transient Mixed Lubrication-Wear Coupling model was developed. Simulations were obtained and an external force of 1000 N

was exerted on the top of bearing shell along the vertical direction. Based on the simulated outcomes, the distribution trend of lubrication performances was considerably affected by transient wear process. Further, results revealed two wear stages occurring under mixed lubrication condition.

(Xiang et al., 2020) introduced a novel transient tribo-dynamic model for journal bearings. Applying variable speed ranges from 0 up to 4000 rpm and exerting an external load of 1 kN, the researchers assured that severe asperity contact maximized maximum temperature at the initial start-up stage. A short acceleration time was demonstrated to lessen asperity contact pressure and to increase temperature relatively. Also, a smaller radial clearance and a thinner bearing would incur a larger maximum temperature and thermal expansion.

(Dond et al., 2023) carried out a computational fluid dynamics study on the behavior of fluid film journal bearings with variable geometrical designs. CFD approach was applied to identify the performance characteristics of plain and elliptical journal bearings introducing an alternative approach regarding thermo- hydrodynamic analysis. The study involved analytical investigations over a wide range of speeds from 500 up to 1000 rpm and lubricant viscosity at 1000 N load. Theoretical outcomes were validated via computational methodology. Pressure distribution in elliptical bearing exceeded that of plain bearing and reached 370.44 %.

4.1.2 Groove bearing

(Brito et al., 2016) worked on detecting risky strong negative flow rate in one of the grooves testing a wide range of loading angles. Such a serious condition for bearing performance was traced at journal shaft speed of 3000 rpm and load variations from 0.2 up to 10 Mpa. Impacts of grooves in single and twin axial groove journal bearings under variable load directions were also among the main research objectives. Groove flow rate distribution could be optimized via a groove deactivation strategy.

(Sep et al., 2017) were concerned with promoting bearing performance via eliminating abrasive wear of grooved journal bearings. Utilizing clean oil, the study employed ANSYS Fluent application at journal speed of 600 rpm and load carrying capacity was derived relying on hydrodynamic pressure distribution. Abrasive wear resistance could be enhanced by eliminating wear debris or contaminants from contact zones of mating surfaces.

(Chen et al., 2017) applied stabilized term in free boundary problems for optimizing bi-directional-rotation herringbone-grooved journal bearings. Textured groove appearance was optimized applying Fluid Dynamic Bearings (FDBs) to spindle motors. MATLAB-based Code was employed for evaluating groove design. The study involved the variable speed variations of 4000 rpm, 6000 rpm and 8000 rpm subsequently. Load carrying capacity was considerably promoted by increasing bearing length. That is mainly due to the expansion of hydrodynamic-pressure-generating region.

(Y. Zhang et al., 2019) intended to minimize computational costs via calculating fluid film pertaining to a finitely long journal bearing provided by two axial grooves. The study proposed a new semi analytical approach in regard to nonlinear fluid film forces, where pressure distribution

was expressed as a particular solution and a homogeneous solution. Pressure distribution of the particular solution was derived based on Sommerfeld transformation. The study could both introduce fluid film force of a finitely long journal bearing with two axial grooves and offer savings in computational costs depending on Reynolds equation.

(Xiang et al., 2019) traced lubrication performance of micro-grooved journal bearings via a transient hydrodynamic lubrication comparative analysis based on a numerical model. Applying a rotational speed range of 2500 rpm, the study assured the rise in axial movement frequency with the increase of fluctuation amplitude of load capacity. Also, load capacity related to micro-grooved bearing could be reduced by increasing groove angle.

(Chatterton et al., 2019), worked on reducing total power loss resulting from shear stresses in oil-film bearings related to a steel roll forming machine. Performance of all bearings was simulated employing a precise Thermo-Elasto- Hydro- Dynamic (TEHD) model. The introduced analysis involved modelling and experimental test trials were carried out at a rotational speed of 1200 rpm. Two hydraulic actuators with a maximum force of 400 kN were employed to apply vertical loads on top of bearing case. Simulation outcomes referred strongly to the possibility of reducing overall power loss in bearings via utilizing a lubricant with kinematic viscosity of approximately half the reference oil value.

Besides, (N. A. Marey et al., 2024) introduced a novel numerical CGB model for assessing operational conditions in light of simulation analysis. Applying variable journal shaft speeds from 25 rpm up to 125 rpm under versatile load impacts, the study tested the two lubricant grades of 5W40 and 0W30. Maximum oil film pressure could be reduced by 1.17 bar and 0.97 bar when shaft velocity was decreased by 80% for the two lubricants respectively. Additionally, increasing load impact from 1079 N up to 1471 N at the constant speed of 75 rpm incurred reductions in maximum oil film pressure ratio by 0.14 and 0.18 regarding the previously mentioned fluid grades respectively.

4.1.3 Elliptical bearings

(Phalle et al., 2012) introduced a theoretical analysis for the behavior of a 2- lobe worn multi-recess hybrid journal bearing system compensated with numerous flow control devices. Finite Element Method was applied for solving the Reynolds equation governing lubricant flow within clearance space. Optimal selection of the compensating device and offset factor value was assured to achieve tangible improvement in bearing performance.

(Biswas, 2015), investigated the operational behavior of a 3-lobe bearing depending on a three-dimensional and transient computational fluid dynamics analysis. Considering the impacts of surface roughness as well as a gas turbine gravity, the researchers carried out meshing of the part related to oil flooded region utilizing GAMBIT. The study ascertained the increase of total pressure with the expansion of surface roughness area.

(El-said et al., 2017) devised a mathematical model for investigating the behavior and stability of three-lobe journal bearing with a bushing surface textured with uniform micro protrusions.

Maximum pressure of protruded three-lobe bearing has been evident to exceed any other bearing particularly that of plain bearing. All of the attitude angle, friction loss and load carrying capacity could be enhanced by increasing eccentricity ratio of protruded three-lobe bearings. Protruded three-lobe bearing was concluded to outperform plain bearing.

In addition, (Boedo, 2022) presented an analysis regarding steadily loaded, oscillating elliptical journal bearings. The impact of surface ellipticity concerning self-acting partial arc journal bearings under steady load and sinusoidal oscillation for mass conserving cavitation was addressed. Employing a Generalized Warner Bearing (GWB) formulation for computational efficiency, the study ascertained the positive impact of an elliptical sleeve at small oscillation amplitude on bearing performance.

4.1.4 Tilting pad bearing

(Cerda et al., 2013), investigated a tilting-pad journal bearing static and thermal performance under controllable lubrication both experimentally and theoretically. It was possible to enhance modelling of tilting- pad bearing with controllable regime when injection system is switched off. At the same year, (Cha et al., 2013) examined dynamic response of tilting pad journal bearing under bad compliance. Exerting a static load of 30000 N at shaft speed of 3000 rpm, the study demonstrated the increase of journal orbit size and oil film pressure when pad backing compliance was elevated. Bad compliance was assured to have a considerable impact on dynamic behavior of tilting pad journal bearings at higher dynamic loads.

Parallel to that (Hou et al., 2013) traced the influential impacts on local parameters involving eccentricity, preload as well as compressibility. A relatively small attitude angle of Local Bearing Parameters (LBP) was incurred by tilting characteristics of pads. The study proposed some very crucial practical characteristics regarding the design and analysis of Tilting Pad Journal Bearing (TPJB) with LBP configuration.

(Asgharifard & Ahmadian, 2015), proposed a novel technique for modeling and identifying weak nonlinear performance of tilting pad journal bearings (TPJBs). In such a way, an accurate reduced order model with nonlinear impacts could be constructed. The nonlinear model facilitated providing a fast computational tool for investigating nonlinear behavior regarding rotating systems supported on TPJBs.

(Dang et al., 2016), investigated the effects of load direction of static and dynamic characteristics of TPJB. Applying an on-nominal geometry, the study manifested the significant effect of load direction on non-nominal five-pad tilting-pad journal bearings. The study involved a rotational speed of 1200 rpm under a static load impact on each bearing of 5 KN. Load direction was obvious to exert a much more impact on dynamic characteristics than static one.

Besides, (Suh & Choi, 2016) were focused on the effects of pivot design and angular misalignment on tilting pad journal bearing characteristics. Fluid pressure amid two plates in motion at variable velocities was solved based on Generalized Reynolds equation. The novel 3D TPJB numerical model could be applied to rotor dynamic analysis with long rotor simulation featuring angular

misalignment between spinning journal and bearing. Angular misalignment in cylindrical pivot TPJB produced both asymmetric film clearance as well as pressure distribution in axial direction.

(Mehdi et al., 2018) illustrated the dynamic characteristics related to composite tilting pad journal bearing of turbine/generator applications. Fabricating composite tilting pad journal bearings integrating carbon fiber/epoxy composites and a backup metal, the researchers offered guidelines for enhancing performance and durability. Variable bearing loads have been applied and controlled employing a load control system. The analysis results were ascertained via an industrial test bench. The ability of hybrid composite tilting pad journal bearing to tolerate friction and prevent rotor damage in the absence of lubricating oil condition was verified.

On the other hand, (Liu et al., 2023) proposed a thermal elastohydrodynamic lubrication (TEHL) model observing pivot deformation as well as journal misalignment regarding tilting pad thrust bearings. Model verification was achieved employing an electromagnetic hydraulic collaborative controllable loading technology. Based on the conducted study, pivot deformation was evident to enhance the uneven load phenomenon under the journal misalignment. The study recommended considering pivot deformation in numerical calculations due to its significant impact on minimum film thickness.

4.1.5 Surface texturing bearing

(Ganji, 2013) investigated the possibility of estimating load carrying capacity of journal bearing at variable surface texture depths. Utilizing elliptical dimples, the study worked on enhancing journal bearing performance based on both texture density and depth modifications. Applying full texture was assured to promote load carrying capacity. Calculations were carried out and texture density was revealed to increase load carrying capacity.

Employing computational techniques, (Kumar Gupta et al., 2013) introduced the full effects of spherical dimples in regard to the behavior of hydrodynamic porous journal bearing. Applying journal shaft speeds of 2000 rpm and 4000 rpm, the study assured the significant impact of such dimples on bearing performance. Increasing dimple depth was demonstrated to enhance load carrying capacity. Further, load carrying capacity was found to decrease with the increment in permeability parameters.

(Woloszynski et al., 2015) employed a spectral element solver for the Navier-Stokes equations regarding slider finite bearings textured with multiple spherical dimples. In addition, the study introduced the inertia impact of hydrodynamic bearings. Inertia effect was apparently influenced by spatial arrangement of dimples. Increasing Reynolds number was also evident to promote Inertia effect.

(Hamdavi et al., 2016) investigated pressure distribution and load carrying capacity performances under the impact of partially textured surface related to hydrodynamic long journal bearing. Reynolds equation was applied for obtaining pressure distribution and load carrying capacity equations. Partially textured region was concluded to enhance load carrying capacity and pressure distribution pertaining to partially textured journal bearing.

(Y. Zhang et al., 2016) illustrated tribological performance of journal bearing under the impact of sphere dimples. The study pointed out the effects of variable distribution forms and geometry parameters on load carrying capacity as well as friction characteristics. Optimal circumferential range angle and maximum depth of sphere dimples were evident to maximize load carrying capacity and minimize friction factor. Increasing area density of texture was found to promote load carrying capacity.

(Kumhar & Patel, 2017) applied a numerical approach for examining and predicting the performance characteristics related to grooving journal bearing. A CFD Software Fluent was utilized to derive lubricant Flow solutions as well as thermal equations. Applying a shaft speed of 2000 rpm and changing groove diameter, number and pattern, the study assured that increased pressure would have a positive effect on journal bearing performance.

(Gropper et al., 2016) introduced the optimal texturing criteria via employing numerical models. The study confirmed the considerable impact of contact type and operating conditions on texturing parameters. Surface texturing was assured to be a feasible method for promoting contact performance in regard to load carrying capacity, minimum film thickness, friction and wear.

(Tala-Ighil & Fillon, 2017) investigated the operational behavior and evolution of fully and partially textured hydrodynamic main journal bearings utilizing two lubricants. Numerical simulations were conducted to analyze viscosity impact utilizing two different lubricants. The study involved journal shaft speeds of 80 rpm, 600 rpm and 2000 rpm, under the load impact of 667 N. Enhancing friction coefficient and minimum film thickness was assured to be dependent on hydrodynamic lubrication regime, lubricant viscosity and journal shaft speed.

(Meng & Khonsari, 2017) were concerned with the prediction of micro-textured parallel surfaces behavior employing a computational model. The model applied simultaneous solutions regarding Stokes equation as well as energy equation in fluid film. The impact of viscosity wedge regarding pressure distribution and load carrying capacity for textured surfaces was elaborately discussed. Viscosity wedge and geometrical wedge effect were obvious to affect shearing stress of Fluid. Additionally, viscosity wedge effect increased with narrowing texture while it weakened geometry wedge effect.

(Wang et al., 2018) worked on improving the performance of hydrodynamic journal bearing via introducing modifications to surface textures. The impact of multiple texture distributions on performance was investigated. The study involved the development of geometries and dynamic models with pure concave/convex textures. Convex texture enhanced load capacity whereas concave spherical texture reduced it. Introducing a novel concave-convex composite texture was thus recommended for enhanced bearing lubrication behavior.

(Shinde et al., 2018) employed both numerical and experimental analysis for better identifying the performance characteristics related to Conical Shape Hydrodynamic Journal Bearing (CSHJB). Thin film flow physics of COMSOL Multiphysics 5.0 was utilized and partial ellipsoidal dimple shape texturing was tested. Applying a journal shaft speed of 1500 rpm under an external load of

50 N, the study demonstrated the considerable impact of the orientation of ellipsoidal dimples on the static performance characteristics pertaining to CSHJB.

(Gao et al., 2024) employed high speed ball-end milling process for assessing generation method and antifriction behavior concerning discrete micro-pit surface texture. The study traced the primary mechanism related to the interval and distribution of micro-pit texture applying Fluent fluid simulation as well as reciprocating sliding friction test. Textured surface provided by micro-pit features was concluded to yield evident antifriction capability. In comparison, with polished surfaces, textured surface granted a decreased percentage in regard to friction coefficient amounting to 61.5%. Besides, both of oil film bearing capacity and antifriction ability were evidently affected by the interval.

5- Results and discussion

The current study is intended to cover the most significant research efforts for enhancing journal bearing performance based on a number of innovative geometrical designs, variable materials and lubricant grades over a period of roughly 10 years Figure 3. Basically, five patterns of geometrical designs were considered, investigated and analyzed and the most crucial design and operational factors involved have also been extensively studied. The given graphs are meant to illustrate the relation between each of the experimental and theoretical studies on the one hand, and the bearing geometry on the other. Notably, it is observed that the experimental studies, Figure 4, tracing the surface texture bearing have assumed the largest percentage amounting to roughly 26.67%. In comparison, the researches examining surface texture bearing have also come in the first place among the studies conducted theoretically Figure 5, yet with a slightly higher percentage of about 32.43%. Besides, it is noted that the percentages of experimental studies concerned with both elliptical and tilting bearings equaled and accounted for the least portion of researches with just 13.33%. Theoretical researches investigating elliptical bearings represented the least share of studies with a minimized percentage of 8.1%. In addition, it is inferred that the percentages related to the experimental studies and focusing on both plain and groove bearings levelled out where they recorded 23.33%. In contrast, the bulk of theoretical studies having plain bearings as their main focus have marginally exceeded that pertaining to grooved bearings by 5%. Based on the derived outcomes, it is concluded that the investigations focused on surface texture bearings by far exceeded all other examined study fields whether they were carried out on experimental or theoretical grounds.

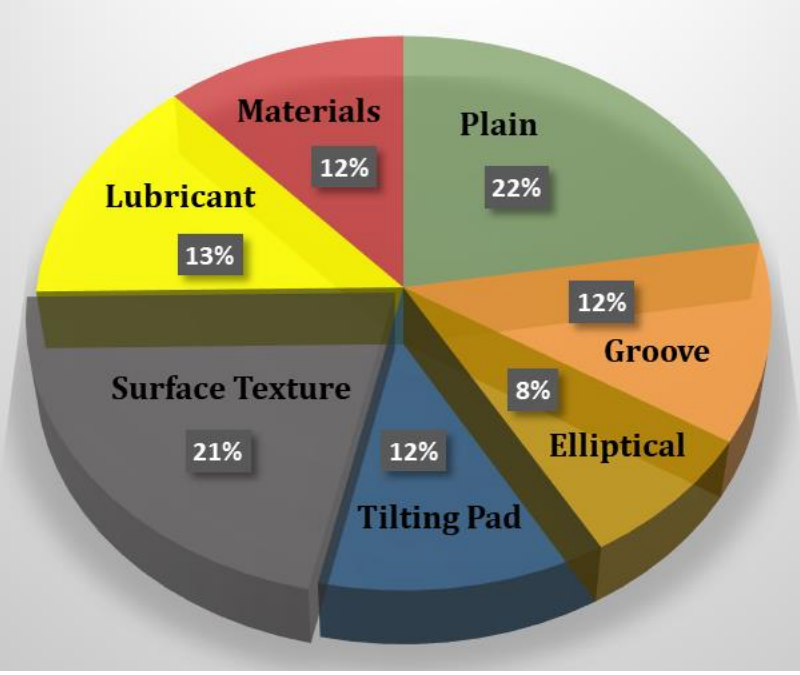

Figure 3: A chart representing the percentages of research efforts towards enhanced journal bearing performance over the covered period.

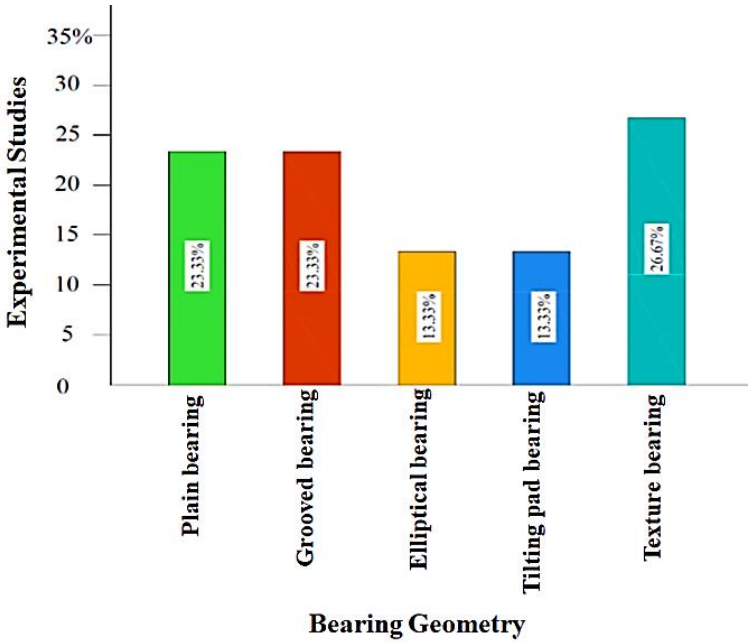

Figure 4: Experimental studies Vs different bearing geometries.

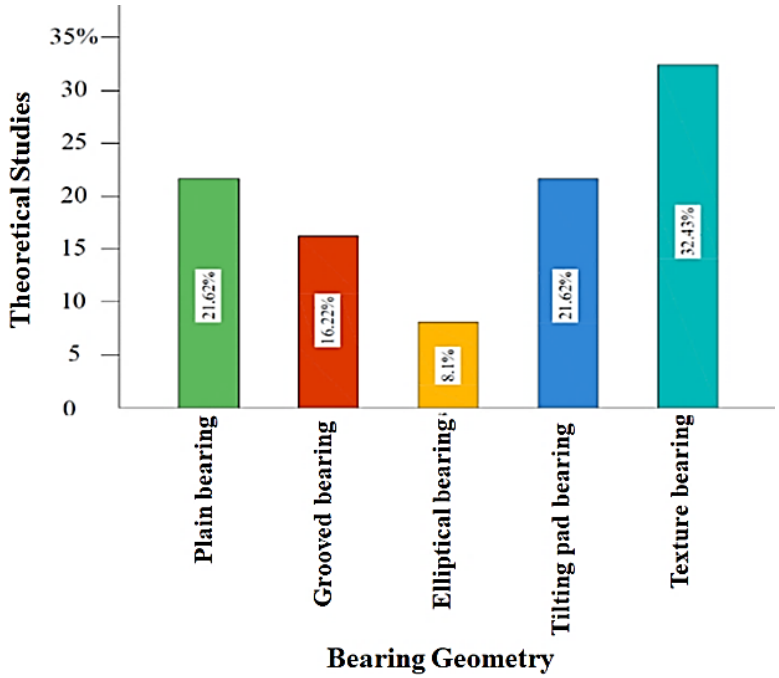

Figure 5: Theoretical studies Vs different bearing geometries.

Figure 6 is an outline of the uninterrupted series of research efforts exerted on the way towards promoting oil film performance concerning a wide range of journal bearing types. In regard to the experimental studies, working on enhancing lubricating oil film via oil film pressure profile apparently accounted for the largest percentage representing 35.5%. In comparison, research investigations employing Reynolds equation represented the greatest share of theoretical studies aiming at promoting oil film performance and accounted for a relatively higher percentage of 53.8%. Studies based on numerical analysis have however occupied the major percentage of 58.6 % exceeding their counterparts conducted theoretically by 27.8 %. On the other hand, the same figure illustrates that the fewest experimental researches were focused on all of the radial clearance, hybrid lubrication and static as well as dynamic load representing a percentage of roughly 3.2%. Furthermore, the least amount of research studies conducted via theoretical means has been in the side of both Navier stokes equation and Sommerfeld number by an equal percentage of 7.7%. Besides, researchers working on oil film performance enhancement numerically and employing Gambit and Comsol have assumed the same percentage of 3.4%. It is obvious that the percentage of experimental studies working on the oil film thickness and that related to numerical studies applying Mat-lab, Gambit and Comsol both acquired a levelled out percentage of 12.9 %. Also, the percentage of theoretical studies based on the theoretical analysis 30.8 % was considerably larger than its peer percentage for experimental studies utilizing friction coefficient 19.4 %. Finally, it is clear that the endeavors towards improving the oil film performance and focusing on the numerical analysis by far exceeded all other research study orientations over the covered period under study.

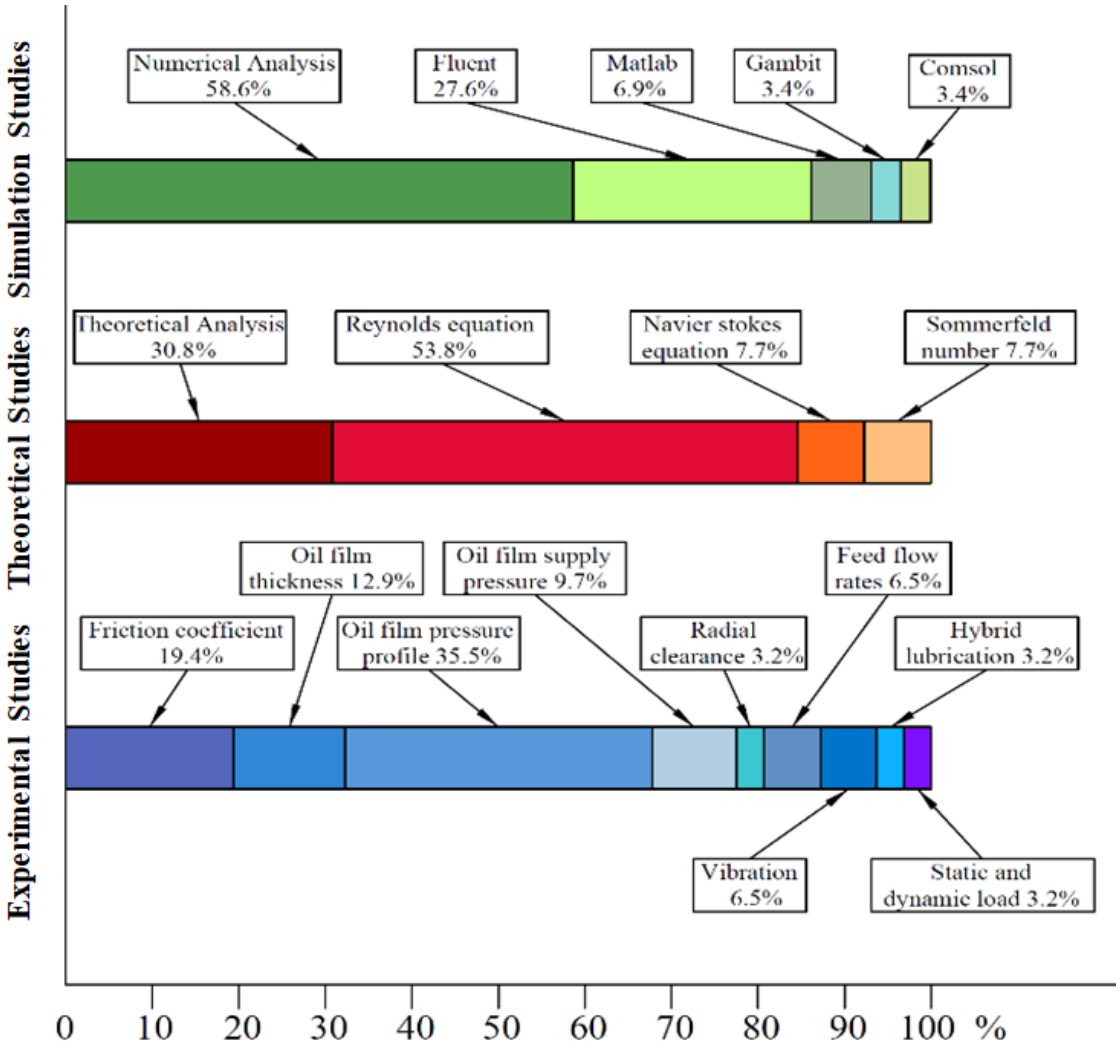

Figure 6: Results based on literature survey of different studies related to journal bearing.

6- Conclusion

A comprehensive survey of previous research endeavors regarding journal bearing performance enhancement based on innovative geometrical designs was thus carried out and reviewed. Notably, the vast majority of the scanned investigations under study worked on such objective depending on introducing novel modifications into surface texture patterns. The bulk of researches related to surface textured bearing accounted for the foremost efforts intended to realize tangible improvements in performance representing the percentages of 26.67 % and 32.43 % in terms of experimental and theoretical investigations respectively. All in all, the current investigation can be said to provide beneficial outcomes based on the analysis of the aggregated data. All such data provide useful guidelines for all those concerned with hydrodynamic lubrication within journal bearing. The analysis outcomes can as well be used to enhance and extend the limitations related to journal bearing design and construction as well as the performance of the lubricating oil film within journal bearing.

7- Recommended future works

Based on the obtained results and the relevant analysis, a number of considerations and design criteria observing surface texture techniques were acquired. Those will definitely be applicable and will as well be of much benefit in the potential future investigations into marine journal bearing. Accordingly, experimental studies utilizing Universal Journal Bearing Test Rig (UJBTR) (Marey et al., 2021) as well as other numerical investigations employing ANSYS Software (Marey et al., 2024) applications applying surface texture laser techniques are intended to be carried out in the near future aiming at effecting a tangible improvement in journal bearing performance for marine application specifically.

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