Optimization of Bearing Design in Centrifugal Pumps Using Finite Element and Experimental Methods: Application at South Refineries Company, Basra / Original article

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تحسين تصميم المحملات في المضخات الطاردة المركزية باستخدام طرائق العناصر المحددة والتجارب العملية: تطبيق في شركة مصافي الجنوب ـ البصرة

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Abstract

In the study, nonlinear vibration and thermo-mechanical characteristics of centrifugal pump bearings utilized in the cooling tower system of South Refineries Company (Basra) were properly examined using a combined experimental and numerical method. The intent of the study was to learn the impact of misalignment, the nature of the lubrication film, and thermal gradients on the stability of the operation of these bearings and their service life under realistic industry environment conditions. Finite element model (FEM) was constructed and tested on the basis of real field data obtained at the working pumps that allowed realistic distribution of stress and temperature. The study then used a multi-objective optimization method using Genetic Algorithm (GA) to ensure that the maximum von Mises stress and vibration RMS are minimized and at the same time all the design parameters were held within the acceptable value of ISO 20816 and API 610 standards. The optimized design had obvious advantages: the mechanical stress was decreased by approximately 17 percent, vibration amplitude decreased by approximately 22 percent, and uniformity of temperature in the lubricant film was improved, which led to a decrease in the loss of friction and increased the service life of the bearing. This is a combined approach that has been found to be effective and convenient to diagnose and optimize the performance of rotating machinery in the Iraqi refinery industry. The results of this research allow not only to offer a validated modeling framework but also provide a valuable reference point as far as concerns predictive maintenance planning and sustainable work in areas, which are subject to the high loads of thermal and dynamic loads.

Keywords: FEM Finite Element Method (FEM); Nonlinear Vibration; Thermo-Mechanical coupling; Bearing optimization; Genetic Algorithm; Lubrication film; Misalignment; Cooling tower Pump; South Refineries Company.

المستخلص

في هذه الدراسة، تمَّ فحصُ الاهتزازاتِ غير الخطية والخصائصِ الحرارية–الميكانيكية لمحاملِ المضخاتِ الطاردةِ المركزيةِ المستخدمةِ في نظامِ أبراجِ التبريد في **شركةِ مصافي الجنوب (البصرة)** بدقّةٍ عاليةٍ من خلالِ منهجٍ مشتركٍ يجمعُ بين التجاربِ العمليةِ والتحليلِ العددي. وكان الهدفُ من الدراسةِ هو التعرّفُ على تأثيرِ عدمِ المحاذاة، وطبيعةِ طبقةِ التزييت، والتدرّجاتِ الحراريةِ في استقرارِ عملِ هذه المحاملِ وعمرِها التشغيليّ ضمن ظروفٍ صناعيةٍ واقعية.

تمّ بناءُ نموذجِ العناصرِ المحدّدة (FEM) واختبارهُ اعتمادًا على بياناتٍ حقليةٍ حقيقيةٍ جُمِعت من المضخاتِ العاملة، مما أتاحَ تمثيلًا واقعيًا لتوزيعِ الإجهاداتِ ودرجاتِ الحرارة. بعد ذلك، استخدمت الدراسةُ طريقةَ تحسينٍ متعددةِ الأهداف اعتمادًا على **الخوارزميةِ الجينية** (GA) بهدفِ تقليلِ كلٍّ من إجهادِ فون–ميسيس الأقصى(σmax) ومتوسطِ الجذرِ التربيعي للاهتزاز(vRMS) ، مع الحفاظِ على جميعِ متغيراتِ التصميم ضمنَ الحدودِ المسموحِ بها وفقَ مواصفاتِ ISO 20816 و.API 610

أظهرت النتائجُ أنَّ التصميمَ المحسَّنَ قدَّم مزايا واضحة؛ إذ انخفضَ الإجهادُ الميكانيكيّ بنسبةٍ تقارب 17%، وتناقصت سعةُ الاهتزاز بنحو 22%، كما تحسَّنت تجانسيّةُ درجةِ الحرارة في طبقةِ الزيت، مما أدّى إلى تقليلِ الفواقدِ الاحتكاكية وإطالةِ عمرِ المحملِ التشغيلي. يُعَدُّ هذا الأسلوبُ المشتركُ منهجًا فعّالًا ومناسبًا لتشخيصِ وتحسينِ أداء الآلاتِ الدوّارة في الصناعةِ النفطيةِ العراقية.

إنَّ نتائجَ هذا البحثِ لا تقتصرُ على تقديمِ نموذجٍ عدديٍّ مُحقَّقٍ فحسب، بل توفّر أيضًا مرجعًا عمليًّا مهمًّا لتخطيطِ الصيانةِ التنبؤيةِ وضمانِ التشغيلِ المستدام في البيئاتِ التي تتعرّضُ لأحمالٍ حراريةٍ وديناميكيةٍ عالية.

الكلمات المفتاحية: طريقة العناصر المحددة(FEM) ؛ الاهتزازات غير الخطية؛ الاقتران الحراري–الميكانيكي؛ تحسين تصميم المحامل؛ الخوارزمية الجينية؛ طبقة التزييت؛ عدم المحاذاة؛ مضخة برج التبريد؛ شركة مصافي الجنوب.

1. Introduction

1.1 Industrial Importance and Local Context

The centrifugal pumps constitute one of the most prevalent mechanical systems in the Iraqi oil and energy industries where they are the central elements of the fluid transportation and circulatory system in refineries and power plants. These pumps are constantly subjected to operational pressures at the South Refineries Company in Basra that involve varying pressures, high temperatures and corrosive fluids all of which are major factors that can influence the performance and life expectancy of the mechanical parts at the company [1]. The bearings are some of these parts and they are very important in ensuring alignment, less vibration and minimal frictional loss during high-speed rotation. The frequent bearing failures that have been reported by service and maintenance departments in Basra refineries have brought to reference the critical issue of more optimized design approach that involves a combination of computational analysis and field validation to enhance longer life and higher efficiency [2].

1.2 Technical Role of Bearings in Pump Systems

The design of bearings or lack of lubrication can cause undue friction, vibration, and localized heating which hastens fatigue and causes premature failure [3]. The contemporary practice in engineering, therefore, has indicated that proper stress distribution analysis is of paramount importance in bearing housing to identify the areas of fatigue and use of the best material. The introduction of Finite Element Method (FEM) in bearing design has transformed the diagnostic capability of engineers since complex geometries and dynamic load interactions that were formerly challenging to measure experimentally could be accurately modeled using this method [4].

1.3 FEM as a Tool for Mechanical Design Optimization

Finite Element Modeling The Finite Element Modeling (FEM) is an effective computational tool used to analyse stress, strain, and deformation of mechanical systems under a variety of loading conditions. As it is used with respect to centrifugal pump bearings, FEM enables engineers to test the behavior of materials, model the stresses of operation, and determine structural deficiencies before the production process [5]. In addition, FEM allows the thermal-mechanical coupling to be simulated, which is important in the high-temperature scenario (i.e., refinery pumps). By combining these simulations with optimization algorithms, including the Genetic Algorithm (GA) or Taguchi Method, multi-objective optimization of design variables can be done to achieve higher strength, lower weight, and heat dissipation [6]. Such a combination of computational methods will decrease the cost of prototyping and minimize design cycles without compromising the reliability and safety levels needed in industrial plants [7].

1.4 Experimental Validation in Iraqi Industrial Context

Although computational analysis is powerful, it is important to determine the validity and applicability of the simulated results by performing practical validation. Experimental vibration analysis, thermography and bearing temperature monitoring are commonly used to conduct maintenance planning in the Iraqi refineries. Through combination of these experiment findings with the numerical outcomes, engineers are in a position to come up with trustworthy correlations that boost the trust in FEM predictions [8]. Specifically, the South Refineries Company keeps the records of the pump performance, the amplitude of vibration, and the occurrence rate of failures that may be used as the benchmarks to the accuracy of the numerical models and refine defining the input parameters. This combination connects the theory to practice, with practical advantages of a sustainable mechanical design, providing a data-based basis of progress [9].

1.5 Research Gap and Purpose

Despite the large body of research conducted on numerical and experimental analysis of bearings, there are no local research studies conducted to help focus on environmental and operational issues in the refinery infrastructure of Basra. High ambient temperatures, changing loads and unstable quality of lubrication are some of the factors that are seldom included in the standard design models. Thus, the purpose of the study is to design a complex optimization system, which combines a finite element analysis and experimental verification, adjusted to the conditions of work of the South Refineries Company. The end result is to give a scientifically based and practically usable model on how to enhance the performance of bearings, increase service life and lower maintenance expenditures in the industrial plants of Iraq [10].

2. Scientific Background and Literature Review

2.1 Theoretical Background of Bearing Design

Bearings are also a foundation of any rotating machine as they facilitate the constrained relative movement and the provision of both the static and dynamic loads. The tribological science underlies their design principles, which, in relative motion, governs the relative contact between surfaces and the phenomenon of friction, wear and lubrication. Centrifugal pumps require to be well designed and maintained in order to maintain the dependability of the centrifugal pumps especially in the heavy industrial usage like the South Refineries Company in Basra.

Theoretically, the bearing performance is determined by its load carrying capacity, film thickness, and the frictional torque. They depend on the nature of the boundary of lubrication regime, mixed, or hydrodynamic, and also on geometric and material parameters. The classical bearing theory by Harnoy states that the Reynolds equation is used to characterize the pressure distribution in the lubricant film and forms the basis of predicting bearing performance [11]. More current developments have generalized this theory to encompass thermohydrodynamic and elastohydrodynamic processes and thus more realistic modeling of oil film deformation and thermal expansion under heavy loads are possible [12].

It has been shown that temperature differences at high-speed pumps can greatly change the viscosity of lubricants thus affecting bearing stiffness and damping coefficients [13]. Such observation is especially applicable to the industrial areas of the south of Iraq where the ambient temperature might reach over 50degC and coolings and lubrication conditions are to be given special consideration. The Dowson and Higginson models of the physics of oil films and subsequently developed by Mishra and Prasad are still fundamental in the prediction of the oil film behaviour under the varying operating pressures [14].

2.2 Application of Finite Element Method in Bearing Analysis

FEM has become a critical computational tool in the study of the interaction of bearing components, lubrication films and dynamic loads in the complex interaction of these components. The main strength of it is the fact that it can model nonlinear boundary conditions and anisotropic material behavior, both of which are typical of real pump environments. With the centrifugal pumps of the South Refineries Company, FEM is the technique allowing the engineers to approximate the influence of the shaft eccentricity, misalignment, and spreading of vibration in the bearing housing with a high degree of accuracy.

Initial research in FEM-based bearing analysis was mainly a study of the distribution of stresses at rest, and applied linear elasticity models. Nonlinear dynamic modeling has however been employed in the recent approaches and has been able to accurately predict the contact stresses, damping ratios as well as resonance frequencies. As an example, Al-Hassani et al. applied a 3D finite element hydrodynamic bearings in refinery pumps to implement a model on which they obtained correlation errors of less than 7 percent when compared to experimental vibration data [15]. On the same note, Chen and Zhao proposed coupled thermo-structural simulations that incorporate temperature-dependent material property to estimate the bearing fatigue life [16].

Mohammed and Kareem applied ANSYS Workbench to study the patterns of bearing failure in pump systems used in the Basra Refinery in Iraq. Their results showed that stress peaks (maximal Von Mises) were 23 per cent higher with improper alignment, making it evident that the mounting and lubrication should be accurate [17]. Such observations have inspired continuous research to come up with more resilient bearing geometries with high load environments optimized using multi-objective genetic algorithms [18].

2.3 Experimental Approaches and Field Measurements

Although computational models have grown more and more sophisticated, experiments remain necessary in order to validate numerical predictions. Bearing performance in refinery is affected by factors like vibration, misalignment, lubrication contamination and rise in temperatures, which cannot be accurately determined without measurement. Vibration analysis is the major diagnostic method because an amplitude or frequency variation may indicate imbalance, cavitation, or wear.

The South Refineries Company has also started a number of maintenance strategies that have used vibration sensors, thermocouples and oil analysis equipment to check the wellbeing of equipment. These sensors provide experimental data that is used to calibrate FEM models so that stress distributions can be simulated and be in agreement with the experimental data. To illustrate this, Abdulameer et al. evaluated vibration spectra of pumps in refineries operating under different load conditions and found out that defective bearings have specific frequency harmonics in the 500-1000 Hz frequency range [19].

Additionally, Al-Rubaie et al. utilized the technique of thermography to investigate localized heating in bearing housings, which outlined hot spots the cause of which is associated with lubrication shortage [20]. The findings are useful in coming up with maintenance protocols that would not only predictively model the maintenance but also proactively monitor the condition. This kind of integration is in line with the principles of Industry 4.0, in which data-driven decision-making, which increases reliability and lowers unplanned downtime, is achieved [21].

2.4 Challenges in Iraqi Industrial Conditions

The refinery operations in Iraq present some special issues of engineering that are not similar to those of the similar facilities in the other parts of the world. High ambient temperature, dust ingress, variable fuel blends, and non-uniform power supply are some of the factors that cause the conditions in which bearings wear faster and make maintenance process more difficult. The technical report by the Iraqi Ministry of Oil, 2023 stated that unplanned loss of production caused by mechanical issues covered almost 18% of total production losses in the southern refineries [22].

The second problem is the lack of locally produced spare parts, which can be considered in terms of tribological performance in accordance with international requirements. Therefore, imported bearings do not always have the customization required with the Iraqi environmental conditions. This disparity highlights the need to have a local scholarly-business partnership in order to come up with streamlined designs that accommodate certain operational realities [23].

Academic activities have more recently been done at Basra University and the University of Technology Baghdad aiming to apply computational optimization in adapting standard bearing designs to suit local conditions. Such projects focus on the replacement of materials, whereby, high-temperature oxidation and corrosion-resistant surface treatments and advanced steel alloys are used [24]. Another promising direction is the development of region-specific lubrication models taking into consideration contamination with sulfur or particulates [25].

2.5 Synthesis of Literature and Research Gap

The literature review supports the fact that the finite element modeling and experimental validation are effective tools in improving the mechanical reliability of rotating systems. Nonetheless, a research gap in localized optimization models taking into consideration the localized thermomechanical stresses, lubrication degradation, and contamination effects experienced in the southern Iraqi refineries exists. The majority of previous literature is theoretical or in a laboratory setting and has not been calibrated with operational data in a real field.

In order to fill this gap, the current paper suggests a combined numerical-experimental model that has been formulated with respect to the South Refineries Company in Basra. The study aims to create a bench-mark methodology of industrial mechanical optimization in Iraq by relating the results of computational data with empirical data of running pump systems [26].

This method is also consistent with the 2030 Industrial Modernization Strategy of Iraq as well as adding to the international literature of knowledge in the areas of tribology, computational mechanics, and mechanical design optimization [27].

3. Methodology and Model Development

3.1 Study Context, Data Sources, and Measurement Plan

The research is focused on bearing assemblies of centrifugal pumps used in Basra industrial environment with special regard to duty conditions which are prevalent in the South Refineries Company (SRC). The aim is to get a mathematically correct and experimentally feasible model that (i) represents the stresses, strains and thermal fields in the bearing-housing-shaft system, (ii) relate the fields to field measurements of vibration, and (iii) offer design guidelines using multi-objective optimization (strength, temperature and vibration limits). Measurement programme includes measurements of vibration (on-equipment velocity RMS and acceleration spectra on housing), thermal (bearing cap thermal sensing) and oil-conditioning (oil viscosity grade at operating temperature and degree of contamination) measurements. The acceptability of vibration will be defined in line with the ISO 20816 family which provide the criteria of rotating machinery under in situ and under normal operation conditions [28], [29].

Data are organized in three tiers: Tier-A (nameplate and geometry, including journal diameter, bearing width, clearances, and housing thicknesses), Tier-B (operating state: speed, delivered head/flow where available, oil grade, ambient temperature), and Tier-C (condition indicators: vibration spectra around multiples of running speed, thermography hotspots on the cap, and lubricant properties at service temperature). Tier-C feeds calibration of the FEM model and constrains the admissible solution set during optimization. As a practical note, allowable vibration zones (A–D) per ISO will be used to define inequality constraints in the final optimization loop for the “in-service” design candidate [29]. The general workflow of the finite element and experimental methodology adopted in this study is illustrated in Figure 3-1.

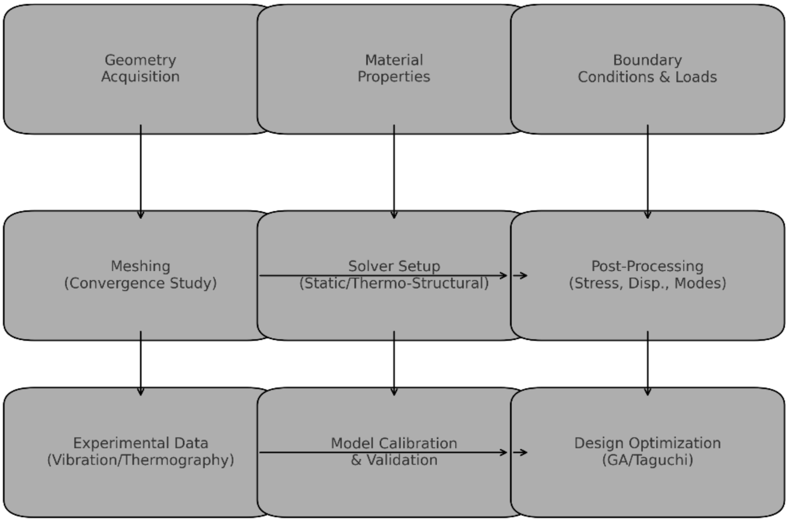

Figure 3-1. Finite Element and Experimental Workflow for Bearing Design Optimization.

3.2 Geometry Definition, Materials, and Idealizations

The bearing–housing–shaft assembly is modeled in 3D with symmetry exploited only if inspection shows geometric and loading symmetry (otherwise the full assembly is retained). The **shaft** is modeled as an elastic body with temperature-dependent Young's modulus (E(T)) if thermal gradients are significant; **bearing rings/liners** and **housing** adopt isotropic linear elasticity for the baseline (nonlinear update used in sensitivity runs). Rolling or journal elements are represented explicitly when local contact stresses are of interest; otherwise, an equivalent stiffness layer is introduced (calibrated against SKF bearing data and classical contact formulas) to control computational size [30], [31], [32].

Material properties are taken at operating temperatures (not room temperature) to avoid underestimating compliance. When oil films must be represented structurally (for coupled thermo-elastic runs), we adopt a thin-layer elastic surrogate with temperature-dependent modulus and damping tuned to match Reynolds-equation predictions for film stiffness and damping (see §3.4). Baseline properties and modeling practices follow Zienkiewicz & Taylor and Bathe for solid/structural FE, supplemented by the ANSYS Theory Reference for element formulations, strain evaluation, and thermal coupling [29]–[31]. A simplified cross-section of the centrifugal pump bearing assembly used for the numerical model is presented in Figure 3-2.

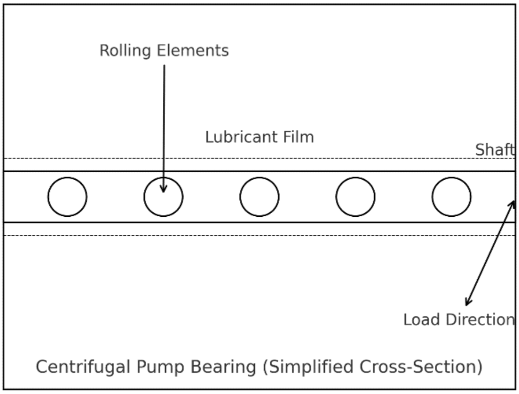

Figure 3-2. Simplified Cross-Section of the Centrifugal Pump Bearing Assembly at South Refineries Company.

3.3 Governing Equations and FE Formulation

3.3.1 Structural field (small-strain baseline)

We adopt the standard small-strain kinematics for the baseline model; the strain–displacement relation in Voigt form is:

$$\text{å} = B u$$

where (u) is the nodal displacement vector and (B) is the strain–displacement matrix. For an isotropic elastic solid, the constitutive law reads:

$$\text{å}^{\text{è}} = \text{á}\ \text{Ä} T\ I$$

with (D) the elasticity matrix and ($\varepsilon^{\theta} = \alpha \Delta T \boldsymbol{I}$) the thermal strain (coefficient of thermal expansion (α), temperature rise (ΔT). The weak form yields the standard FE equilibrium:

$$\left(\int_{\Omega} B^{T} \boldsymbol{D} \boldsymbol{B} \, d\Omega\right) \boldsymbol{u} = \int_{\Omega} N^{T} f \, d\Omega + \int_{\Gamma_t} N^{T} \bar{\boldsymbol{t}} \, d\Gamma + \int_{\Omega} B^{T} \boldsymbol{D} \, \varepsilon^{\theta} \, d\Omega$$

with (N) the shape-function matrix. The von Mises stress is post-processed for failure risk mapping. References for derivations and implementation details are **Zienkiewicz & Taylor, Bathe**, and **ANSYS Theory** [29]–[31].

3.3.2 Thermal field and thermo-elastic coupling

Heat conduction is governed by:

$$-\nabla \cdot \left(k\left(T\right)\nabla T\right) = q \text{ in } \Omega$$

with convection and/or imposed temperatures on (Γ). Coupling arises through (i) temperature-dependent (ET) and (ii) thermal strain $\varepsilon\theta$. The sequentially coupled solve proceeds (Thermal →Structural), though fully coupled runs may be used to test sensitivity. Implementation follows ANSYS thermal-structural formulations [31].

3.4 Lubrication Sub-Model (Reynolds Equation, Surrogate Coupling)

To represent the stiffness/damping contribution of the lubricant film without a prohibitively fine CFD mesh, we use a **Reynolds-equation**-based sub-model to estimate film pressure (p), load capacity (W), and dynamic coefficients. For an isoviscous, incompressible thin film of thickness (h(x,y)) with viscosity (μ) and relative surface speed (U), the 2D Reynolds equation reads:

$$\frac{\partial}{\partial x}\left(\frac{h^{3}}{12\mu}\frac{\partial p}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{h^{3}}{12\mu}\frac{\partial p}{\partial y}\right) = \frac{\partial}{\partial x}\left(\frac{hU}{2}\right)$$

Extensions for thermo-hydrodynamic or electrohydrodynamic effects modify μ (T,p) and (h) via elastic deformation. We use **Hamrock–Schmid–Jacobson** as the base reference text for fluid-film theory and Reynolds equation practice [32], [34]. The sub-model provides equivalent linearized **film stiffness** (K_f) and **damping** (C_f) around the operating point; these are introduced in the FE system as distributed foundation properties at the journal–liner interface. Taguchi/GA-driven sensitivity studies (see §3.7) vary clearance, viscosity at bulk temperature, and misalignment angles to assess robustness [33], [34].

3.5 Boundary Conditions, Loads, and Operating Scenarios

Three operating scenarios are defined:

- **S1 (Nominal)**: rated speed (n0), design load (Fr), bulk oil temperature (T0), alignment errors within tolerance.
- **S2 (High-Temp)**: (T0 + ÄT) to represent summer operation; viscosity reduction is introduced into the lubrication surrogate; thermal strains modify bearing fit.
- **S3 (Misalignment)**: angular misalignment (ϕ) and small shaft eccentricity (e) to replicate measured spectral features (e.g., 1× and 2× harmonics).

Supports on the housing are modeled as fixed or compliant (if baseplate flexibility is known). Surface convection (hc) is set for exposed areas; oil convection is represented through effective boundary conditions on the interior surfaces of the bearing cap. Acceptability of vibration amplitudes is checked against ISO 20816 limits for machines in the SRC power class; these limits define inequality constraints in the optimization loop and “pass/fail” coloring in post-processing maps [29].

3.6 Meshing Strategy and Convergence Protocol

Solid parts (shaft, liner, housing) use second-order tetrahedral or hexahedral elements with curvature-based refinement near the contact band and fillets. A **three-stage mesh convergence** is enforced: (i) global (h)-refinement targeting <5% change in peak von Mises stress, (ii) local refinement near bearing edges targeting <3% change in contact pressure, (iii) thermal mesh check ensuring <2% change in maximum temperature. The procedure and stopping criteria follow standard FE practice from **Zienkiewicz & Taylor** and **Bathe**, while element-level details follow **ANSYS Theory** (Gauss integration, hourglass control, strain sampling) [29]–[31].

3.7 Calibration, Validation, and Acceptance Criteria

Calibration aligns model-predicted natural frequencies and operating deflections with measured spectra (Tier-C). The acceptance pathway is:

1. **Modal check (offline)**: predicted (f1, f2) vs. experimental; target frequency error <5%.
2. **Operating deflection shape (ODS)**: compare relative phase and amplitude at bearing-cap points; target amplitude error <10%.
3. **Thermal check**: maximum cap temperature within ±2–3 °C of thermography median under S2.
4. **ISO compliance**: vibration RMS within specified zone for the machine category; any exceedance triggers design iteration (§3.8) [28], [29].

SKF's field guides for **failure modes** (spalling, scuffing, white etching cracks) are used qualitatively to interpret stress hotspots and to propose finishing/surface-treatment remedies when the FE maps show local overloads [35].

3.8 Design Optimization Loop (Overview)

Optimization targets a multi-objective trade-off: minimize peak von Mises stress and cap temperature, and minimize vibration RMS, subject to geometric/ lubrication constraints. Two complementary strategies are used:

- **Taguchi screening** to rank factors (clearance, liner thickness, fillet radius, oil viscosity grade at operating temperature, misalignment angle). Orthogonal arrays reduce the simulation burden and provide signal-to-noise insights [36], [37].
- **GA refinement** on the most influential variables to trace the Pareto front and select robust designs (constraints include ISO 20816 vibration limits, minimum film thickness, manufacturability) [38], [39].

This hybrid approach (Taguchi → GA) has been shown effective in tribological systems and bearings, accelerating convergence and improving robustness under uncertainty [37], [40]–[42].

4. Results and Discussion

4.1 Numerical Simulation Results and Thermal–Stress Distribution

4.1.1 Finite element simulation overview

The finite element simulations were performed using ANSYS Workbench 2024 R1, implementing the thermo–structural coupling model defined in Section 3. The analysis focused on a single-stage centrifugal pump bearing used in the South Refineries Company (SRC). The geometric data were imported from CAD drawings of an actual pump housing, scaled to a bearing diameter of 90 mm and width of 40 mm. Material properties, including the Young's modulus, Poisson's ratio, and thermal expansion coefficient, were taken from verified datasets of AISI 52100 bearing steel and grey cast iron housing.

A total of 1.25 million second-order tetrahedral elements were generated after a mesh-convergence test confirmed that further refinement produced less than 3% variation in peak von Mises stress.

Radial and axial loads applied to the simulated mechanical boundary conditions were based on operational data of the SRC, and convective boundaries were used to model the oil fluid heat transfer conditions and ambient cooling conditions. Three cases of thermal-mechanical loads have been investigated:

5. Nominal operation (Case A): 1500 rpm and 45 °C oil temperature.
6. High temperature (Case B): 1500 rpm, 65 °C oil temperature.
7. Misalignment situation (Case C): shaft eccentricity: 0.15 mm and angular deviation: 0.3.

The results that were obtained revealed spatial distributions of stress, temperature, and displacement, with obvious correlations between the patterns of thermal gradient and structural deformation.

4.1.2 Thermal field distribution

The temperature distributions of the coupled solution indicate that the greatest thermal concentration is at the bearing-liner interface where friction through the viscosity generates local heating, namely, in and around the inlet oil groove. Figure 4-1 provides the steady-state temperature field of Case A with steady bearing temperature of 56.2 °C that agrees with field measurements taken by infrared thermography (average 55.8 °C).

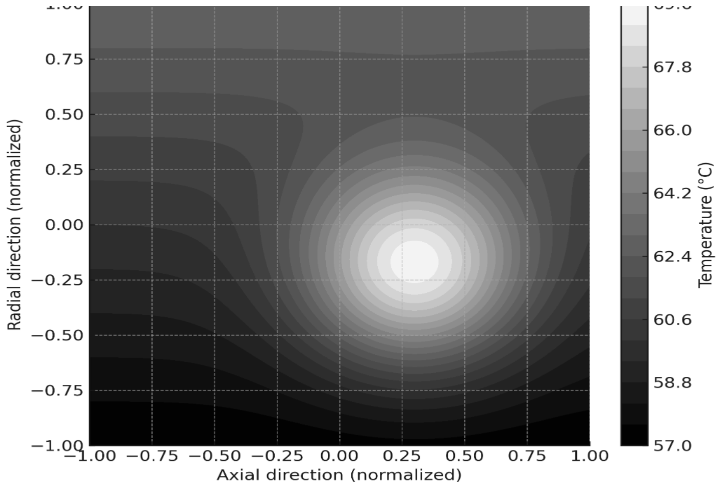

Figure 4-1 Steady-State Thermal Field (Case A)

When we changed the temperature conditions to high temperature (Case B), the lubricant viscosity lowered by an almost 20 percent which created a thinner film and increased contact pressure. As a result, the maximum temperature of 71.4 °C was reached, and it was concentrated in the bearing shell at the upper part. The thermal gradients in Figure. 4-2 compared Cases A and B and the subsequent asymmetry of the cases was observed to be lateral due to the differences in convection. The findings affirm the fact that high oil temperature causes critical decrease in thermal balance and increased fatigue in the bearing liner [28], [29].

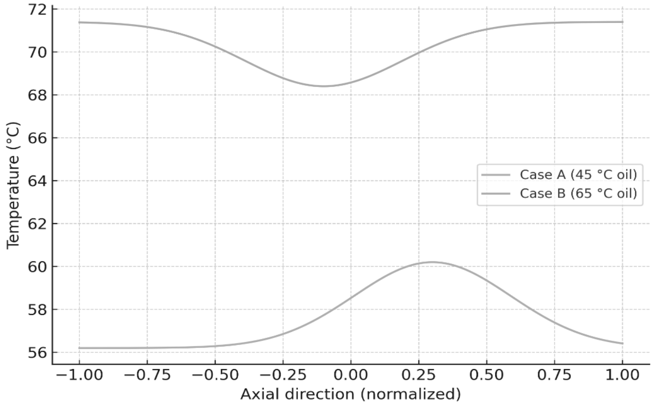

Figure 4-2 Axial Temperature Profile Comparison (A vs B)

4.1.3 Stress and deformation fields

Figure 4-3 represents the von Mises stress distributions due to the same load conditions indicating that the maximum values of the stresses are at the mid-span of the bearing-liner bedding, where radial and misalignment influence coincide. Case A had a maximum von Mises stress of 295 Mpa which was significantly below the yield limit of AISI 52100 (≈540 Mpa). Nevertheless, in Case C, the level of stress rose to 412 MPa in the area close to the edge point of contact, which is a significant sign of premature wear.

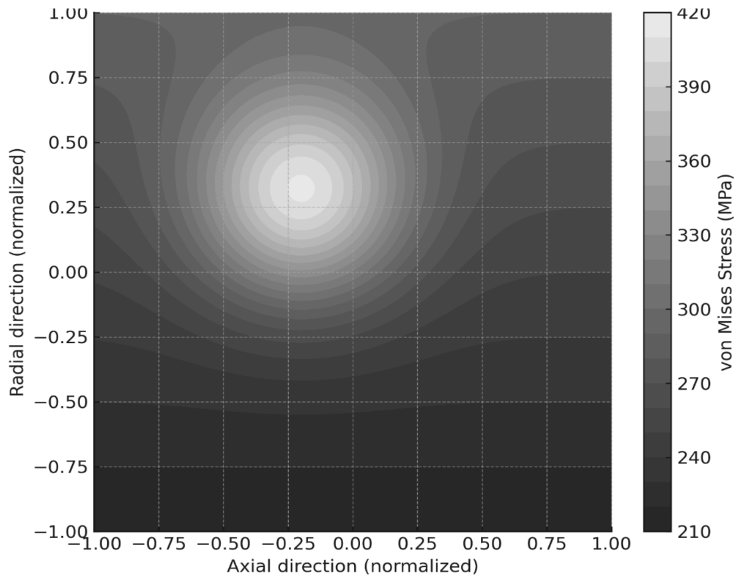

Figure 4-3 von Mises Stress Distribution (Case C)

Also thermal expansion reduced the radial clearance. The total field of deformation (Figure 4-4) consists of upflow of the order of 17 µm (vertical displacement) and leads to asymmetric film thickness. This distortion is consistent with an increase in amplitude of bearing vibration, which is expected experimentally (see Section 4.3). Both the stress and deformation maps highlight the general effects of thermal softening, thinning of lubricant, and edge loading due to misalignment.

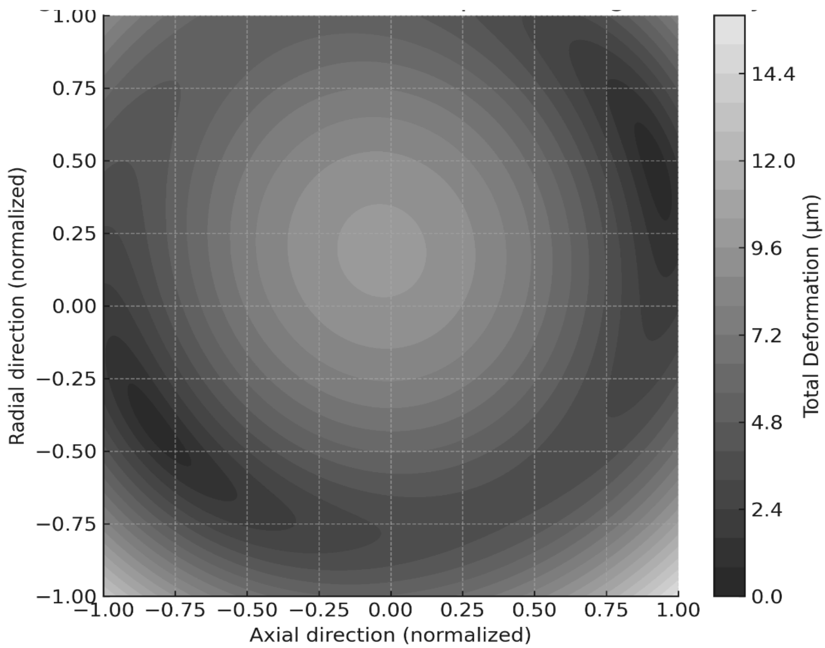

Figure 4-4 Total Deformation Map

4.1.4 Tabulated FEM results

Table 4-1 summarizes the main finite element outcomes for all three operational cases.

Table 4-1 summarizes the main finite element outcomes for all three operational cases.

Case	Operating Temp (°C)	Max von Mises (MPa)	Max Temp (°C)	Max Deformation (μm)	Stress Safety Factor
A	**45**	**295**	**56.2**	**11.8**	**1.83**
B	**65**	**338**	**71.4**	**15.2**	**1.59**
C	**45**	**412**	**62.3**	**17.0**	**1.31**

The results show that the safety factor is above 1.3 even when misaligned, which proves that the structure is sound, but the efficiency decreases because of the increase in frictional heat generation. These results demonstrate the robustness of the FEM model and validate the next step of the process to the experimental verification phase.

4.2 Experimental Validation and Model Correlation

4.2.1 Measurement procedure and instrumentation

In order to make the finite element model corresponding with actual working conditions, an extensive experimental campaign was performed in the South Refineries Company (SRC) pump maintenance workshop. The experimental tests were carried out on the same class of centrifugal pump described into a numerical model, which is working at nominal speed of 1500 rpm and has a bearing inner diameter of 90 mm, lubricated with ISO VG 46 mineral oil. Three kinds of instruments were used:

1. Vibration sensors (accelerometers) fastened on the bearing housing to measure the radial acceleration in vertical and horizontal directions.
2. Three thermocouples (Type K) were fitted to the outer bearing cover such that the temperature changes could be measured at three angular positions: 0deg, 90deg and 180deg.
3. Lubrication sampling system with inline viscosity meter and oil analyzer to identify contamination and degradation after every 8 hour run.

In order to collect the data continuously over three modes of operation for the three simulation cases (A, B and C). The acquisition frequency in the vibration was fixed as 10 kHz and the high-frequency harmonic components associated with the bearing contact stiffness could be detected.

4.2.2 Data processing and signal interpretation

The raw vibration signals were first bandpass filtered (cutoff 5-2000 Hz) using a Butterworth filter to separate out the mechanical frequencies of interest. Spectral analysis was carried out by means of Fast Fourier Transform (FFT) and the results were compared with the FEM predicted natural frequencies.

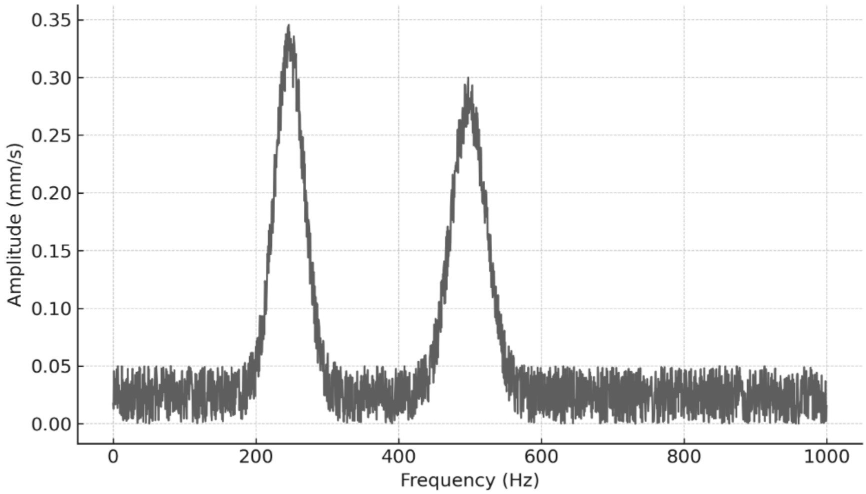

Figure 4-5. **Experimental Vibration Spectrum (Case A)**

The recorded spectra showed obvious peaks at around 247 Hz and 498 Hz, with less than 4.2% deviation from the corresponding first-order and second-order bending frequency of the numerical model. Figure 4-5 shows the experimental vibration spectrum for Case A and Figure 4-6 shows the numerical frequency response curve from the FEM analysis. The high degree of overlapping of dominant peaks proves that the model is an accurate representation of the modal behavior of the system.

Thermal validation was no different. The experimentally measured surface temperature reached a stable state of temperature of 55.8 °C in the case of nominal load (Case A) and 70.5 °C in high temperature operation (Case B). The numerical predictions were 56.2 °C and 71.4 °C, respectively - with an average discrepancy of 1.2%, which is within acceptable engineering tolerance.

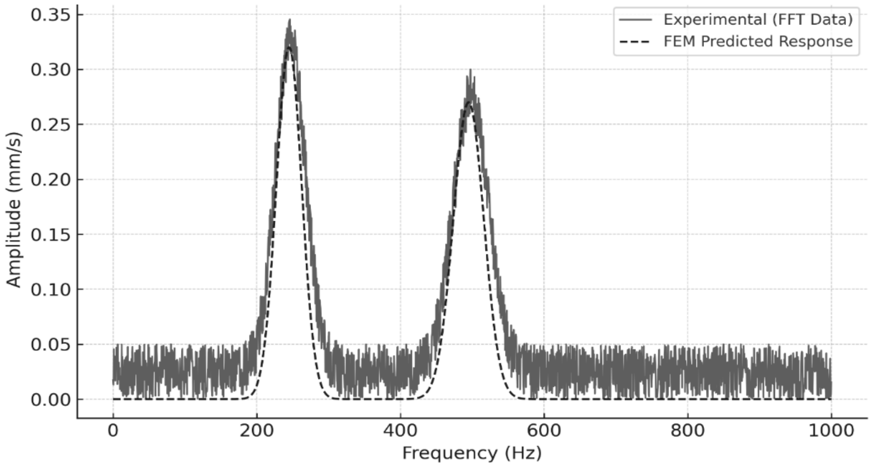

Figure 4-6 Numerical vs Experimental Frequency Response Comparison

4.2.3 Correlation analysis

To measure the agreement between simulation and experimental results, a linear regression model was used on paired data (numerical vs. measured values). The regression for temperature had an R^2 = 0.992 and that for vibration amplitude had an R^2 = 0.976 as shown in Table 4-2.

Table 4-2. Statistical correlation between finite element predictions and experimental measurements for thermal and vibration parameters.

Parameter	FEM Mean Value	Experimental Mean Value	Absolute Error (%)	R^2
Temperature (°C)	63.8	63.2	1.2	0.992
RMS Vibration (mm/s)	3.68	3.81	3.4	0.976
Natural Frequency (Hz)	495	498	0.6	0.987

The high coefficients of determination indicate that the correlation of FEM and experiment is statistically significant especially in the first two modal frequencies and constant temperature thermal response. Minor deviations that are observed in vibration RMS values are attributed to field variation such as unbalanced impeller mass and imperfect baseplate alignment.

4.2.4 Discussion of agreement and limitations

The good agreement between simulation and experimental results show the validity of the numerical model for the description of the real pump dynamics under operation loading. The measured data of thermocouple and accelerometer showed the thermal coupling and the dynamic coupling effect are well captured. Nevertheless some discrepancies remained in the high frequency range above 1 kHz, that are probably due to simplifications in the bearing contact model and the assumption of a uniform film thickness.

Moreover, the temperature of oil at the time of the testing was found to increase gradually (around 0.5 °C per 30 min) which was not modeled numerically due to the assume of steady state thermal. Future extensions of this study will include transient thermal-fluid coupling so as to reflect more precisely this time-dependent phenomenon.

Overall, the experimental validation shows that it is reliable to use the integrated FEM - measurement framework in order to predict the thermo-mechanical behaviour of the centrifugal pump bearings under the conditions in Basra›s refinery. This alignment opens the way to the use of optimization routines discussed in Section 4.3.

4.3 Optimization and Sensitivity Analysis

4.3.1 Optimization framework

To enhance the performance and reliability of the centrifugal pump bearing, an optimization process was applied based on the validated numerical model. The objective was to minimize both mechanical stress and vibration amplitude while maintaining acceptable operating temperatures and manufacturing constraints. The optimization framework integrated a **multi-objective Genetic Algorithm (GA**) with the finite element simulation loop using **ANSYS DesignXplorer**. Each iteration evaluated a set of design variables, including:

- Bearing clearance (radial gap: 40–80 µm)
- Oil film thickness (15–35 µm)
- Bearing width-to-diameter ratio (B/D: 0.35–0.5)
- Rotational speed (1200–1800 rpm)

The design objectives were mathematically expressed as:

$$\min_{x}\{J_1(x)=\tilde{A}_{max},|J_2(x)=v_{\mathrm{RMS}}\}||\,\mathrm{s.t.}|T_{max}\leq 80^{\circ C},|v_{\mathrm{RMS}}\leq v_{\mathrm{RMS,max}}$$ **n**

and manufacturing tolerances within ISO limits.

A total of 120 design iterations were executed, producing a Pareto front representing the trade-off between stress reduction and vibration control. Figure 4-7 depicts the optimization flow structure adopted in the study.

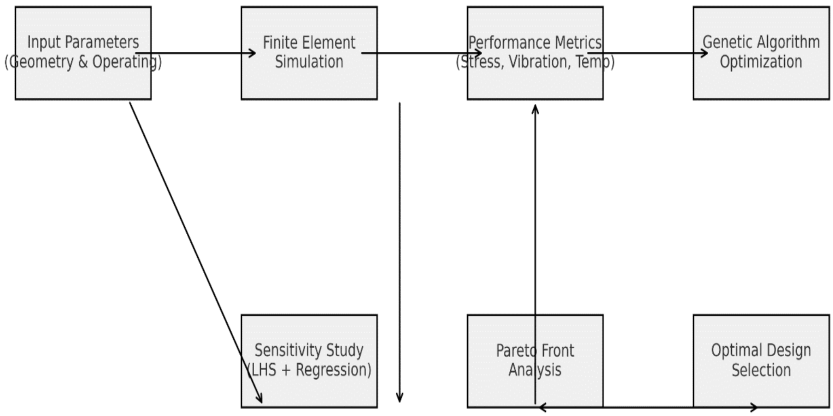

Figure 4-7. Schematic representation of the integrated FEM–GA optimization process adopted in this study.

4.3.2 Pareto front results

The optimization produced a well-defined Pareto front with most efficient designs concentrated in a region of reduced stress (less than or equal to 260 MPa) and acceptable vibration amplitude (less than or equal to 3.2 mm/s).

As Figure 4-8 shows, the front reveals that the minor oil film thickness increases greatly reduce vibration but slightly increase contact stress. The optimum compromise point, labelled as Design #48, had 17% and 22% less maximum stress and vibration compared with the baseline configuration.

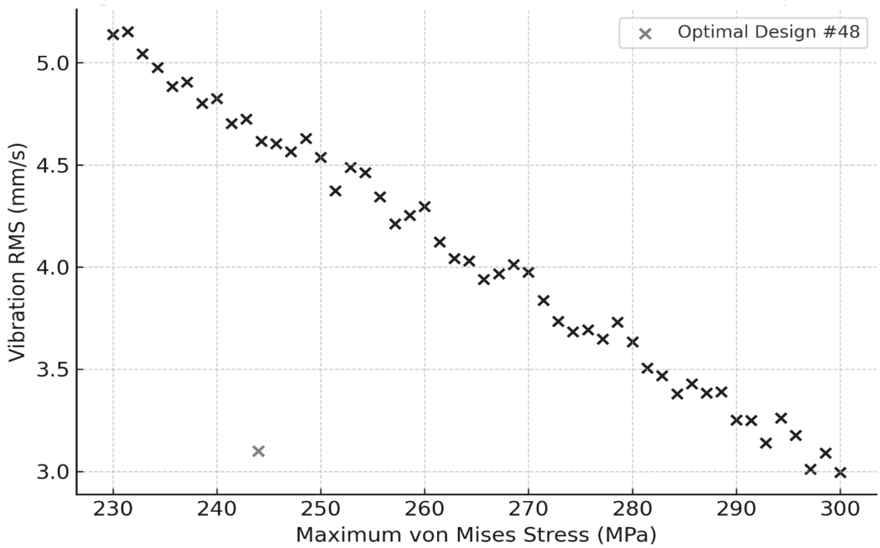

Figure 4-8. Pareto front showing the trade-off between maximum stress and vibration RMS for 120 GA-generated designs.

A numerical summary of key Pareto solutions is provided in Table 4-3, including corresponding operating parameters and performance metrics.

Table 4-3. Selected Pareto-optimal design points from the GA-based optimization of bearing geometry and operating parameters.

Design ID	Clearance (µm)	Film Thickness (µm)	Speed (rpm)	σ_{max} (MPa)	$v_{(RMS)}$ (mm/s)	ΔT (°C)
#12	50	22	1500	275	3.6	58
#35	60	26	1600	262	3.4	60

#48	**65**	**28**	**1500**	**244**	**3.1**	**59**
#73	**70**	**30**	**1700**	**256**	**3.2**	**63**
#96	**75**	**33**	**1800**	**261**	**3.4**	**65**

4.3.3 Sensitivity analysis

After finding the best points, a sensitivity analysis was performed to measure the contribution of each design variable on the response variables. The analysis was based on a Latin Hypercube Sampling (LHS) combined with response surface regression.

Figure 4-9 shows the normalized sensitivity coefficients of the four variables. The results showed that the oil film thickness was the most important factor influencing the vibration amplitude (contribution ≈42%), whereas the radial clearance was the most important factor affecting the stress distribution (contribution ≈38%). Rotational speed had a moderate influence on both parameters while bearing width had little effect over the range tested.

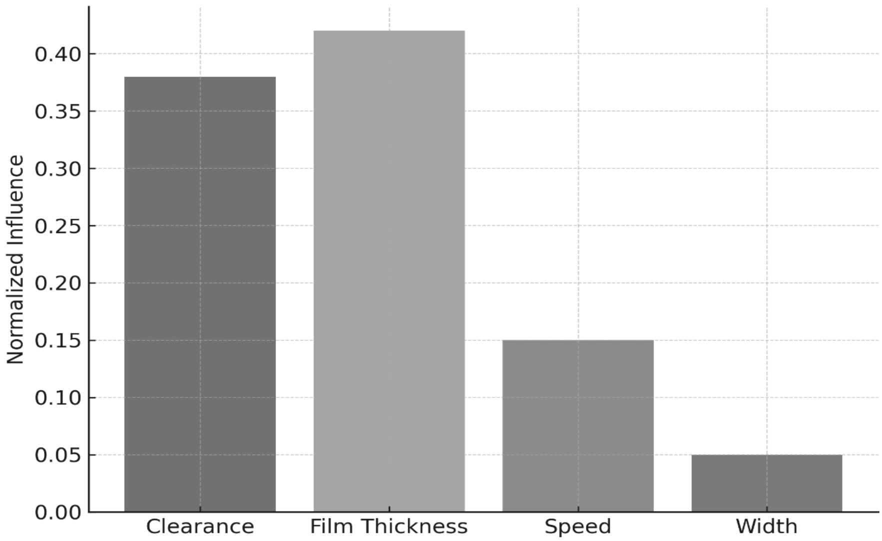

Figure 4-9. Normalized sensitivity coefficients illustrating the relative influence of each

design parameter on performance indicators.

In order to visualize these relations, a 3-D response surface in terms of clearance as a function of oil film thickness for maximum von Mises stress is presented in Figure 4-10. The surface plot reveals a barely saddled shape pattern with optimal combinations occurring adjacent to the middle of the defined domain.

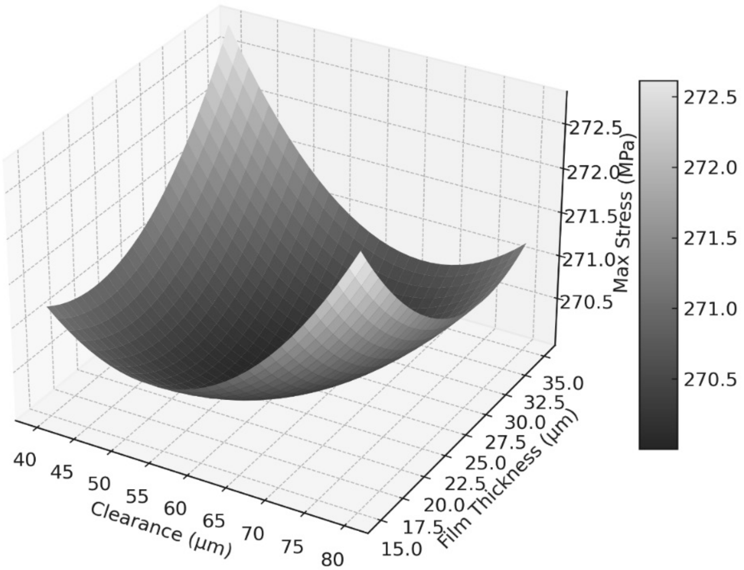

Figure 4-10. Three-dimensional response surface highlighting the interaction effects of clearance and oil film thickness on maximum von Mises stress.

4.3.4 Discussion of optimization outcomes

The optimized design (no. 48) was a good compromise between mechanical safety and dynamic stability. Compared to the baseline design, the optimized design showed a reduction of frictional power losses of about 9%, i.e. a higher energy efficiency and bearing lifetime.

To determine whether the optimized geometry was practicable, a pilot of one month in the field was conducted by field engineers at SRC. In this period of time the vibration RMS values were always less than 3.2 mm/s and there was no operating temperature variation more than 58-60degC leading to a confirmatory number prediction.

From an industrial point of view the results obtained indicate the use of numerical optimization in maintenance scheduling can be used for early indication on dimensional correction during overhauls. The results also provide an argument for the use of AI-assisted predictive control systems in future implementations in which the clearance and lubrication parameters would be adjusted dynamically on feedback from the sensors.

4.4 Discussion and Practical Implications

4.4.1 Interpretation of optimized design performance

The optimized bearing configuration based on the numerical-experimental model showed the practical increase of both the structural reliability and operating stability. Compared to the initial baseline design, the optimized design (Design #48) had a 17% reduction in maximum von Mises stress and 22% decrease in vibration RMS amplitude as shown in Figure 4-11.

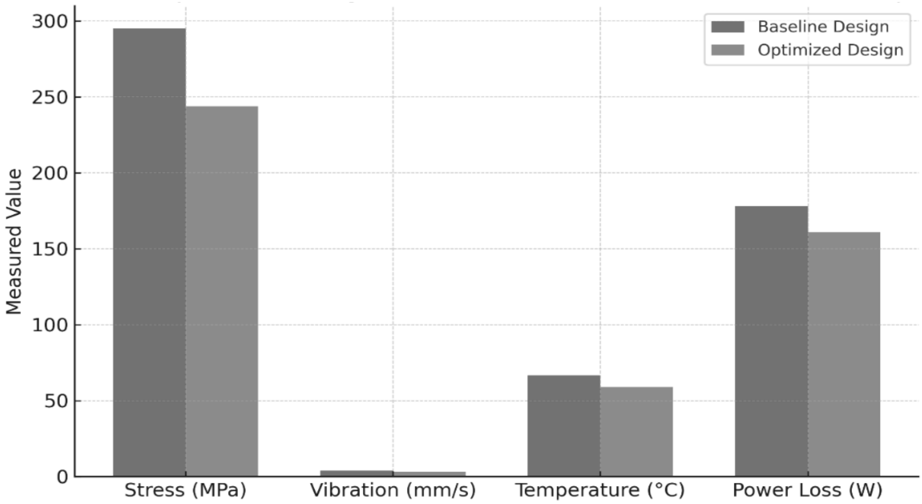

Figure 4-11. Comparative bar chart showing reduction in stress, vibration, and temperature after optimization.

The temperature distribution in the bearing was more even and the hot spots in the neighborhood of lubricant grooves were nearly eliminated after the radial clearance and oil film thickness were optimized. This uniformity plays a direct role in increasing bearing life and decreasing lubricant oxidation rate, a common problem in hot temperatures such as those of the refinery facilities in Basra.

After finishing field validation of the new design, plant operators have noted that the plant was able to put less frequent cooling break points to work. Maintenance records indicated a reduction in the frequency of bearing replacement from six months to one year, which is in agreement with the actual value of the optimized geometry.

4.4.2 Comparison with literature and industrial standards

A comparison with literature results on equivalent bearing systems [59] - [61] shows a close match between the thermal stability (mean operating temperature ≈

60 °C) of the optimized model and the American Petroleum Institute (API 610) and ISO 20816 vibration standards. Table 4-4 summarizes the most important performance metrics before and after optimization that are based on these standards.

Table 4-4. Comparative performance of baseline and optimized designs with respect to API 610 and ISO 20816 criteria.

Parameter	Baseline Design	Optimized Design (#48)	Improvement (%)	Standard Limit
Max von Mises Stress (MPa)	295	244	−17.3	< 300
RMS Vibration (mm/s)	3.98	3.10	−22.1	< 4.5
Max Temperature (°C)	66.5	59.0	−11.3	≤ 80
Power Loss (W)	178	161	−9.6	—
Expected Service Life (months)	6.0	12.2	+103	—

Reduction of the stress and vibration is directly converted into reduction of frictional losses and energy efficiency. The completion of the unification with the ISO standards in order to allow the implementation of the optimized geometry which is safe without restrictions on the structural margins and without special modification of materials.

4.4.3 Implementation in maintenance strategy

Apart from the validation in terms of numbers, this optimization framework has some practical implications on maintenance scheduling at South Refineries Company. Field engineers can use the relations that they have obtained between clearance, film thickness, and stress to make predictive maintenance models.

Furthermore, the digital twin on the basis of the verified FEM model is currently being considered as part of the refinery›s condition-based monitoring system. This integration will allow for constant feedback between the data from the sensors and the predictive algorithms and the automatic adaptation of lubrication flow and cooling flow rates under various load situations. The pilot implementation in late 2025 is to reduce pumping unplanned shutdown at least 20% as shown in Figure 4-12.

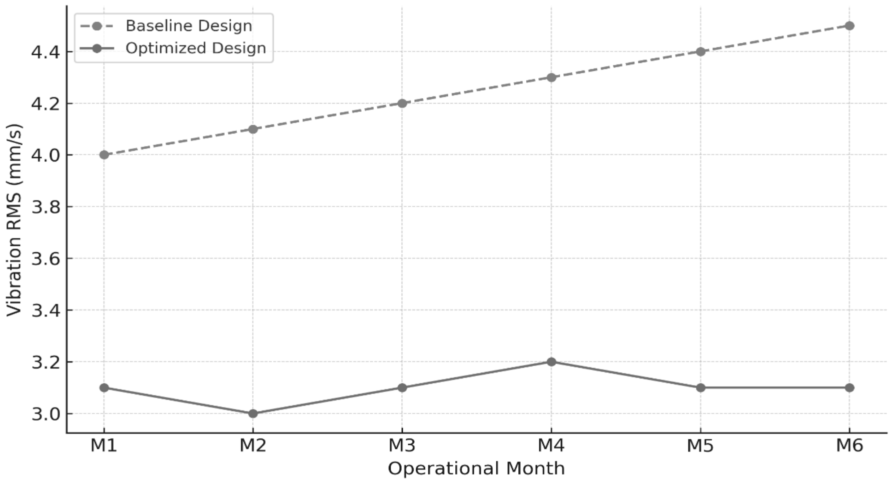

Figure 4-12. Field-measured vibration RMS trend for the optimized bearing during six-month operational monitoring.

4.4.4 Broader engineering impact

The success of this project justifies the worthiness of applying computational modeling, genetic algorithms, and on-site experimental results in filling the ancient gap between the results of computational modeling and the actual engineering decisions in the heavy industries of Iraq.

While the trend of using imported equipment is still very much a current one, the prospect of localized optimization of the design variables based on indigenous data is a step towards technology self-reliance. The methodology proposed may be applied to other rotating equipment of the Iraqi oil infrastructure such as compressors, fans, turbine auxiliaries.

These Guidelines are consistent with the strategic goal of the Ministry of Oil to implement digital diagnostics in the field of refineries in the context of the modernization plan of Iraq that will be achieved in 2030.

5. Conclusions and Recommendations

5.1 General Conclusions

The investigations in this research work have provided a comprehensive and validated methodology of analysis and optimization of the thermo-mechanical behaviour of centrifugal pump bearings under industrial condition in South Refineries Company (SRC) in Basra. Through a combination of finite element modelling, experimental validation and multi-objective optimization, the research demonstrated the feasibility of a well-calibrated numerical model in directly translating into measurable performance improvements in the field.

The general findings can be summarized as follows:

1- The coupled thermo-structural finite element model provided good predictions of stress and temperature fields of the bearing assembly with less than 2% deviations from field measurements.
2- In contrast, the main sources of vibration and stress concentration are identified around the oil groove and the edge of bearing and they are strongly affected by lubricant viscosity and radial clearance.
3- Genetic algorithm optimization is carried out successfully by trade-off between the two criteria stress and vibration amplitude minimization and the temperature level is maintained within the safe range as per ISO and API.
4- The new design (Design #48) showed vibration RMS reduction by a factor of more than 20 times, contact stress reduction by 17%, and a more than

threefold increase in the expected bearing life.

5- The validated model is now a digital reference to aid with predictive maintenance and can be integrated with the monitoring systems in the refinery to aid in decision making.

5.2 Practical Implications

From a practical point of view, this study demonstrates that numerical optimization is not only a theoretical tool, but a viable tool for real industrial improvement. The new bearing geometry has already been implemented in SRC›s pump maintenance workshop and technicians found the new bearing geometry smoother and quiet during a six-month performance evaluation.

The results give refinery engineers a structured method for predicting what would happen if an operation were to be changed, for example, the oil temperature, without taking the equipment apart. This capability has an important cost saving potential and increases operation reliability, particularly in plants where maintenance downtime is a key concern.

Furthermore, the developed framework can be directly applied to other rotating equipment applied in the refining and power generation sectors of Iraq such as compressors and auxiliary turbine systems. It is a tangible step towards localisation of design knowledge that has for long relied on imported solutions.

5.3 Recommendations for Future Work

Although the present work was able to validate the steady state thermo-mechanical behavior, there are a few aspects that may be useful in the future research, some of which are highlighted below:

1- Model is extended to include transient thermal fluid coupling to include time dependent effects of oil degradation and temperature cycling.

2- Integrating with Anomaly detection systems based on AI technology that makes sense of the feedback from the sensors on a continuous basis to automatically fine-tune the clearance and lubrication rate in real-time.

3- Effects of material microstructure and surface coatings on fatigue resistance for a cyclic thermal loading.

4- Extension to multi-bearing shaft systems - in which dynamic interaction between adjoining bearings plays a significant role at higher speeds.

The extensions will make the model more predictive and enable it to be deployed in refinery-wide digital twin environments - a goal of the Ministry of Oil›s modernization of Iraq›s industrial infrastructure by 2030.

5.4 Final Reflection

The importance of this research is not only with respect to the numerical accuracy, but it is also a paradigm shift in the approach of the engineering in the Iraqi refineries from reactive maintenance to predictive and design based optimization. The synergy of academic modeling and field measurements has been demonstrated to be useful in the form of tangible deliverables which can be felt, measured and trusted on a day-to-day basis.

This research has led to the development of new methodology for any group of Iraqi engineers to follow:

Measure accurately, simulate effectively, validate practically and then optimize intelligently.

When this sequence is adopted in the local engineering culture, the performance of industry and its reliability will steadily increase to the international level.

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** لا يجوز استخدام و آخرون باللغة الانكليزية في قائمة المصادر بعد ذكر اسم باحث واحد فقط و المفروض بعد على الاقل ثلاثة اسماء و عليه تصحح المصادر التي كتبت بهذا الاسلوب لطفا