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ADAPTIVE MULTI-OBJECTIVE OPTIMIZATION OF DEEP GROOVE BALL BEARINGS FOR HYDROGEN COMPRESSOR APPLICATIONS USING DYNAMIC CROSSOVER AND MUTATION PROBABILITIES

Prasun BHATTACHARJEE[1]
Somenath BHATTACHARYA[2]

Abstract

Deep groove ball bearings (DGBBs) used in hydrogen compressor systems operate under high loads, leading to elevated Hertzian contact stress and frictional torque. Optimal bearing design is therefore essential to enhance load capacity and operational efficiency. This study presents a multi-objective optimization approach for DGBBs considering basic dynamic load rating, Hertzian contact stress, and frictional torque. The objective is to maximize dynamic load rating while minimizing contact stress and torque. A customized adaptive genetic algorithm based on the NSGA-II framework is developed. Unlike conventional methods, crossover and mutation probabilities are dynamically varied during the optimization process. This adaptive strategy improves the balance between exploration and exploitation. Key design variables include ball diameter, number of balls, and bearing geometry. The model is evaluated under realistic loading conditions relevant to hydrogen compressor applications. Results obtained using static genetic parameters show limited Pareto front diversity. In contrast, the adaptive approach generates a wider and more uniformly distributed Pareto front. Improved convergence and better spread of solutions are observed. Significant reductions in Hertzian stress and frictional torque are achieved. Simultaneously, higher dynamic load ratings are obtained. The adaptive algorithm effectively avoids premature convergence. It provides a broader set of optimal design solutions. This enhances decision-making flexibility in bearing design. The proposed method demonstrates strong potential for high-load applications. It offers a robust framework for advanced bearing optimization. The study contributes to improved performance and reliability of DGBBs in energy systems.

Keywords: Adaptive genetic algorithm, Deep groove ball bearing, Dynamic load rating, Frictional torque, Hertzian contact stress, Hydrogen compressor systems.

JEL Classification: C61, C63, L93, Q42

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[1] PhD, Jadavpur University, India, prasunbhatta@gmail.com
[2] PhD, Jadavpur University, India, snb_ju@yahoo.com

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1. Introduction

The growing global demand for energy, coupled with the gradual depletion of fossil fuel reserves, has accelerated the transition toward sustainable and alternative energy systems. This transition has been further intensified by geopolitical uncertainties, particularly in major oil-producing regions such as the Middle East, where conflicts and supply disruptions have introduced significant volatility in energy availability and pricing. Such instability has exposed the limitations of fossil fuel–dependent systems and has underscored the urgent need for reliable, efficient, and low-carbon energy solutions. Among the various alternatives, hydrogen-based energy systems have emerged as a promising pathway for achieving long-term energy sustainability [1].

Hydrogen compressor systems play a vital role in the hydrogen energy infrastructure by enabling high-pressure storage and transportation. These systems operate under severe mechanical conditions characterized by high cyclic loads, elevated pressures, and continuous operation. Under such demanding environments, the reliability and performance of mechanical components, particularly rolling element bearings, become critical. Deep groove ball bearings (DGBBs), owing to their simple design, versatility, and capability to support combined loading conditions, are widely used in such applications. However, their performance under high-load and high-stress conditions requires careful optimization [2].

The behavior of DGBBs in such environments is governed by three key performance parameters: basic dynamic load rating, Hertzian contact stress, and frictional torque. The dynamic load rating determines the load-carrying capacity and fatigue life of the bearing, while Hertzian contact stress governs the localized stress distribution at the contact interface between rolling elements and raceways. Excessive contact stress can lead to fatigue failure mechanisms such as spalling and subsurface cracking. Frictional torque, on the other hand, directly influences energy efficiency and thermal characteristics, with higher torque leading to increased power loss and heat generation. The simultaneous consideration of these parameters results in a complex multi-objective design problem due to their inherently conflicting nature [3].

Recent advancements in bearing design have increasingly relied on computational optimization techniques to address such challenges. Various metaheuristic algorithms, including genetic algorithms, particle swarm optimization, whale optimization, and moth flame optimization, have been successfully applied to improve bearing performance. These approaches have demonstrated significant improvements in dynamic load capacity, frictional power loss, and lubrication characteristics, particularly in the design of hybrid bearings with ceramic rolling elements. Additionally, the integration of artificial intelligence techniques has enabled the optimization of renewable energy systems, including wind turbine components, where bearing performance plays a crucial role in system efficiency and reliability [4].

Several studies have also explored the enhancement of static and dynamic capacities of rolling element bearings through intelligent optimization strategies, considering multiple performance criteria simultaneously. The application of multi-objective optimization frameworks has provided valuable insights into the trade-offs between load capacity, stress distribution, and frictional behavior. However, most of these studies have employed conventional implementations of evolutionary algorithms with fixed crossover and mutation probabilities [5].

The use of static genetic parameters often limits the effectiveness of the optimization process, as it may lead to premature convergence and insufficient exploration of the design space. This limitation becomes more pronounced in complex engineering problems involving nonlinear interactions among design variables and conflicting objectives. To overcome these challenges, adaptive optimization techniques have been proposed, in which algorithmic parameters are dynamically adjusted during the optimization process to improve search efficiency [6] [7].

In this context, the present study proposes an adaptive multi-objective optimization framework for the design of deep groove ball bearings operating under high-load conditions representative of hydrogen compressor applications. The approach is based on the NSGA-II algorithm, with dynamically varying crossover and mutation probabilities to enhance both exploration and exploitation capabilities. The optimization problem is formulated with the objective of maximizing the basic dynamic load rating while minimizing Hertzian contact stress and frictional torque.

Key design variables, including ball diameter, number of rolling elements, and bearing geometry parameters, are considered under realistic operating conditions. A comparative analysis is performed between the proposed adaptive approach and conventional static-parameter genetic algorithms. The results demonstrate that the adaptive method yields a more diverse and well-distributed Pareto front, providing improved trade-offs among the governing performance parameters.

The proposed framework offers a robust and efficient approach for the optimal design of deep groove ball bearings in high-load applications. By integrating adaptive evolutionary algorithms with fundamental principles of rolling contact mechanics, the study contributes to the development of advanced bearing systems suitable for emerging hydrogen-based energy infrastructures. The findings are expected to support the broader transition toward sustainable energy systems in the face of fossil fuel depletion and geopolitical uncertainty.

2. Literature Review

The design and optimization of rolling element bearings have attracted significant attention due to their critical role in mechanical and energy systems. Traditional bearing design approaches are largely based on empirical relations and standardized formulations, which, although reliable, often fail to capture the complex interactions between geometric parameters, loading conditions, and performance characteristics. As a result, modern research has increasingly focused on computational and optimization-based techniques to enhance bearing performance.

Early studies in this domain primarily addressed the estimation of dynamic load rating and fatigue life using classical formulations based on rolling contact fatigue theory. These approaches provided a foundation for understanding bearing performance but were limited in their ability to address multi-parameter interactions. Subsequent research introduced numerical methods to evaluate contact stress, lubrication regimes, and frictional behavior, thereby improving the predictive capability of bearing models [8].

With the advancement of computational intelligence, metaheuristic optimization techniques have been widely adopted for bearing design. Genetic algorithms (GA) have been extensively used to optimize bearing parameters such as ball diameter, number of rolling elements, and internal geometry to improve load-carrying capacity and fatigue life [8]. Particle swarm optimization (PSO) and other swarm-based techniques have also been applied to minimize frictional losses and enhance lubrication performance. More recent approaches, including whale optimization and moth flame optimization, have demonstrated improved convergence characteristics in solving complex bearing design problems [9].

Significant progress has also been made in the optimization of hybrid bearings incorporating ceramic rolling elements, particularly for applications involving electrical insulation and high-speed operation. These studies have shown that advanced optimization techniques can effectively enhance both static and dynamic load capacities while reducing frictional power loss and improving elastohydrodynamic lubrication characteristics [10]. Furthermore, the application of multi-objective optimization frameworks has enabled simultaneous consideration of conflicting performance parameters, such as load capacity, contact stress, and frictional torque, leading to more balanced and efficient bearing designs [11] .

In parallel, optimization techniques have been successfully applied to renewable energy systems, particularly in the design of wind turbine components. These studies have highlighted the importance of bearing performance in improving overall system efficiency and reliability. Multi-objective optimization approaches have been used to minimize generation cost, maximize energy output, and improve component durability under varying environmental conditions [12].

Despite these advancements, most existing studies rely on conventional implementations of evolutionary algorithms with fixed crossover and mutation probabilities. While these approaches have demonstrated effectiveness in generating optimal solutions, they often suffer from limitations such as premature convergence and reduced diversity of the Pareto front. Static parameter settings restrict the algorithm's ability to adapt to different stages of the optimization process, leading to suboptimal exploration of the design space.

To address these limitations, recent research has explored adaptive and self-tuning optimization strategies, where genetic parameters are dynamically adjusted during the search process. These approaches enhance the balance between exploration and exploitation, resulting in improved convergence and diversity of solutions [9]. However, the application of such adaptive strategies to the multi-objective optimization of deep groove ball bearings, particularly in the context of hydrogen compressor systems, remains limited.

Therefore, there exists a research gap in developing an adaptive multi-objective optimization framework that integrates bearing mechanics with dynamic genetic operators to achieve improved performance under high-load conditions. The present study aims to address this gap by proposing a customized adaptive NSGA-II approach for optimizing deep groove ball bearing design considering dynamic load rating, Hertzian contact stress, and frictional torque.

3. Methodology

3.1. Problem Formulation

The design of deep groove ball bearings (DGBBs) for high-load applications involves the simultaneous consideration of multiple conflicting performance parameters. In the present study, the optimization problem is formulated to enhance bearing performance under operating conditions representative of hydrogen compressor systems. The primary objective is to achieve an optimal balance between load-carrying capacity, contact stress, and frictional losses.

The optimization problem is defined with three principal objectives: maximization of the basic dynamic load rating, and minimization of Hertzian contact stress and frictional torque. These objectives are inherently conflicting in nature. An increase in load-carrying capacity generally requires modifications in bearing geometry, such as increased ball diameter or number of rolling elements, which may lead to higher frictional torque. Similarly, reduction in contact stress often demands design adjustments that influence both load capacity and torque characteristics.

3.2 Design Variables and Constraints

The optimization process considers key geometric parameters of the bearing, including ball diameter, number of rolling elements, and mean diameter. These variables directly influence load distribution, contact mechanics, and frictional behavior. The design is subjected to a set of physical and geometric constraints to ensure feasibility. The equivalent dynamic load acting on the bearing must remain within the permissible load-carrying capacity. Additionally, the contact stress is restricted below an allowable limit to prevent premature fatigue failure. Geometric constraints are also imposed to maintain feasible bearing dimensions and proper assembly conditions. The equivalent dynamic load is evaluated by considering both radial and axial components of loading, ensuring realistic representation of operating conditions. These constraints collectively ensure that the optimized solutions are not only mathematically optimal but also physically realizable [13] [14].

3.3 Mathematical Modeling

The dynamic load rating is evaluated based on standard bearing design relations, which relate the load capacity to geometric parameters such as ball diameter and number of rolling elements. Hertzian contact stress is calculated using classical contact mechanics theory, considering the load distribution among rolling elements and the resulting contact ellipse. Frictional torque is estimated as a function of load, bearing geometry, and frictional characteristics, providing a measure of energy loss within the system. These models are integrated into the optimization framework to evaluate the performance of each candidate solution during the evolutionary process [15] [16].

3.4 Adaptive Multi-Objective Optimization Approach

To solve the formulated multi-objective problem, an adaptive version of the Non-dominated Sorting Genetic Algorithm II (NSGA-II) is employed. Unlike conventional implementations, where crossover and mutation probabilities remain constant, the present approach introduces dynamically varying genetic parameters to enhance the search efficiency [17] [18].

The adaptive mechanism is designed to improve the balance between exploration and exploitation during the optimization process. In the initial stages, higher mutation probabilities are employed to encourage exploration of the design space and avoid premature convergence. As the algorithm progresses, mutation is gradually reduced while crossover becomes more dominant, facilitating convergence toward optimal regions of the solution space [19] [20].

This adaptive strategy enables the algorithm to effectively navigate the complex, nonlinear design space associated with bearing optimization, resulting in improved diversity and convergence of the Pareto-optimal solutions.

3.5 Solution Procedure

The optimization process begins with the initialization of a population of candidate bearing designs, each defined by a set of design variables. For each individual, the objective functions are evaluated using the mathematical models described earlier. The population is then ranked based on non-dominated sorting, and a crowding distance measure is used to preserve diversity. Selection, crossover, and mutation operations are applied to generate new candidate solutions. The crossover and mutation probabilities are dynamically adjusted at each generation according to the adaptive strategy. This process is repeated iteratively until a predefined convergence criterion is satisfied [21] [22].

3.6 Performance Evaluation

The performance of the proposed adaptive optimization approach is assessed by comparing the obtained Pareto front with that generated using conventional static genetic parameters. The comparison focuses on the spread, diversity, and convergence of solutions, as well as the improvement in key performance parameters such as dynamic load rating, contact stress, and frictional torque.

4. Results and Discussion

The performance of the proposed adaptive multi-objective optimization approach is evaluated through a comparative analysis with the conventional NSGA-II algorithm employing static crossover and mutation probabilities. The comparison is based on the characteristics of the obtained Pareto fronts in terms of their distribution, extent, and the trade-off relationships among dynamic load rating, Hertzian contact stress, and frictional torque.

The Pareto front generated using static genetic parameters exhibits a nonlinear but uneven distribution of solutions. A clear trade-off is observed in which an increase in dynamic load rating is associated with a reduction in Hertzian contact stress, which is consistent with fundamental bearing mechanics, as higher load capacity generally results from improved load distribution and increased contact area. The frictional torque shows a relatively small variation within the range of approximately 0.015 kN·m to 0.017 kN·m. However, the distribution of solutions is predominantly concentrated within an intermediate region, with only a limited number of solutions extending toward higher dynamic load ratings. In this case, the dynamic load rating reaches approximately 140–150 kN, while the Hertzian contact stress varies between about 1.0×10^4 MPa and 1.7×10^4 MPa. The clustering of solutions indicates that the static genetic algorithm has a limited ability to explore the full design space and tends to converge prematurely to a restricted set of solutions.

In contrast, the Pareto front obtained using dynamically varying crossover and mutation probabilities demonstrates a significantly improved distribution and extent of solutions. The adaptive approach enables a broader exploration of the design space, particularly toward higher dynamic load ratings, which extend up to approximately 180–200 kN. Correspondingly, the Hertzian contact stress is reduced in the high-capacity region, with values approaching approximately 1.0×10^4 MPa to 1.65×10^4 MPa. The frictional torque remains within a narrow and controlled range of approximately 0.0153 kN·m to 0.0156 kN·m, indicating that the improvement in load-carrying capacity and reduction in contact stress are achieved without a significant increase in frictional losses. The Pareto front in this case is more continuous and uniformly distributed, providing a smoother transition between different design configurations and enabling a more comprehensive representation of the trade-off among the objective functions.

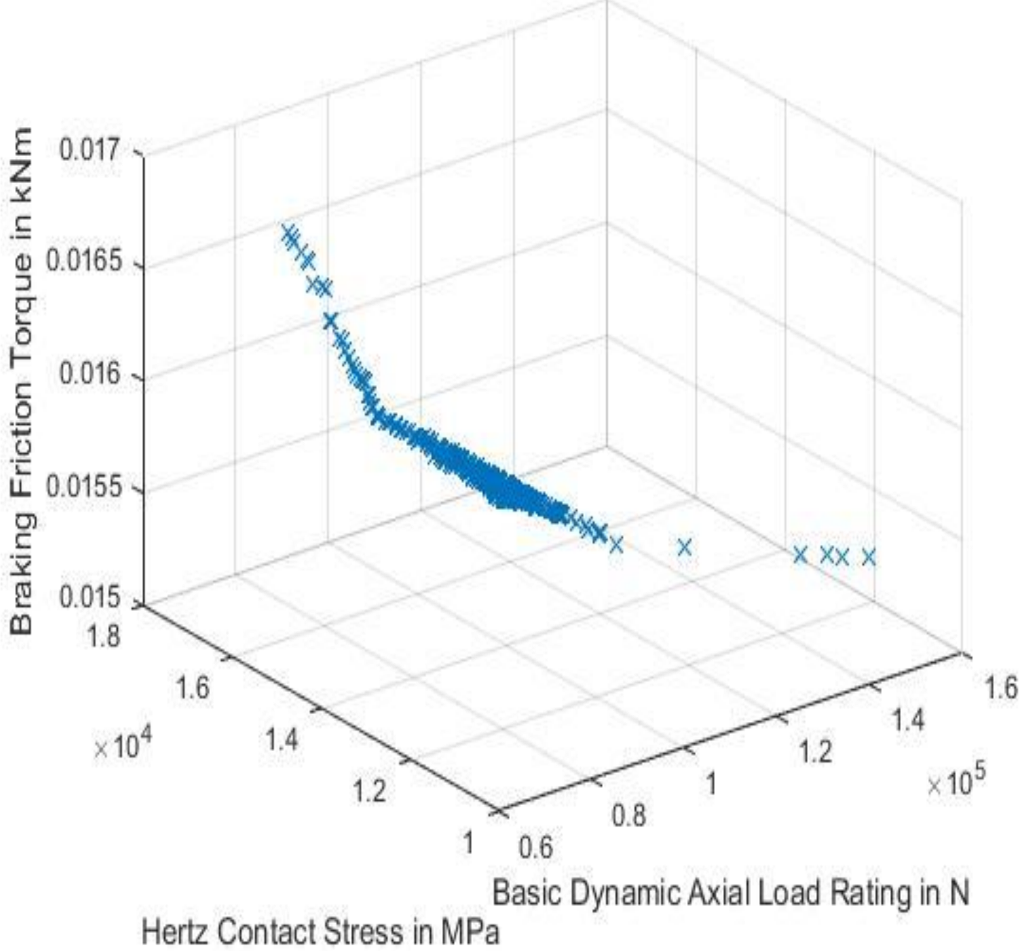

Figure 1. Pareto front obtained using NSGA-II with static crossover and mutation probabilities

The improvement observed in the adaptive approach can be attributed to the dynamic adjustment of crossover and mutation probabilities during the optimization process. In the early stages, higher mutation rates facilitate exploration of the design space, allowing the algorithm to identify diverse candidate solutions. As the optimization progresses, the reduction in mutation probability and increased influence of crossover enhance convergence toward optimal regions. This adaptive balance between exploration and exploitation prevents premature convergence and improves the overall quality and diversity of the obtained solutions.

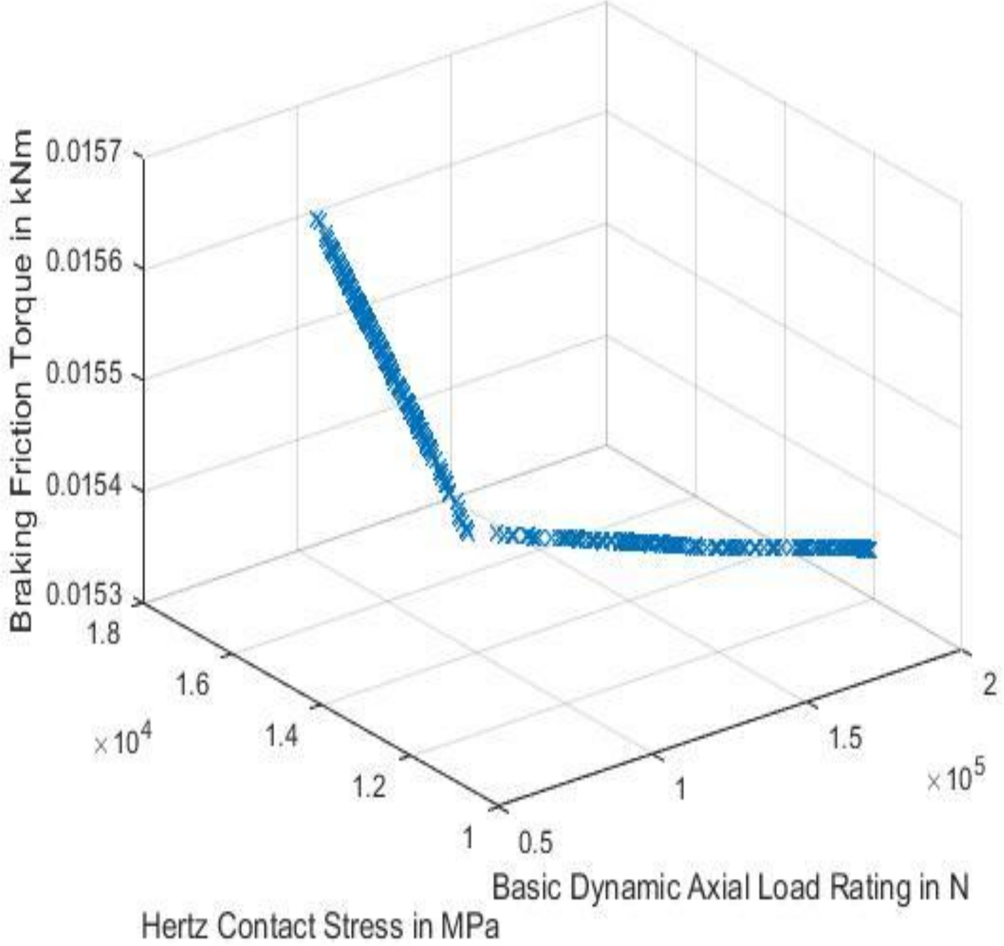

Figure 2. Pareto front obtained using NSGA-II with proposed adaptive crossover and mutation probabilities

From an engineering perspective, the adaptive optimization approach provides a wider range of feasible design solutions for deep groove ball bearings operating under high-load conditions. The extension of the dynamic load rating range, along with the reduction in

Hertzian contact stress, contributes to improved fatigue life and reliability of the bearing. At the same time, the relatively stable and controlled frictional torque ensures that energy efficiency and thermal performance are not adversely affected. The improved Pareto front thus offers greater flexibility in selecting optimal bearing configurations based on specific performance requirements.

Overall, the results demonstrate that the proposed adaptive multi-objective optimization framework significantly enhances the exploration capability and convergence behavior of the genetic algorithm. The method produces a more diverse and well-distributed set of Pareto-optimal solutions, extending the achievable design space and providing improved trade-offs among dynamic load rating, Hertzian contact stress, and frictional torque.

5. Conclusions

In this study, an adaptive multi-objective optimization framework has been developed for the design of deep groove ball bearings operating under high-load conditions relevant to hydrogen compressor systems [23] [24]. The problem was formulated by simultaneously considering three critical and conflicting performance parameters, namely dynamic load rating, Hertzian contact stress, and frictional torque. The objective was to enhance load-carrying capacity while reducing contact stress and maintaining acceptable frictional behavior, thereby improving overall bearing performance and reliability. A comparative analysis between conventional static genetic parameters and the proposed adaptive approach clearly demonstrates the advantages of dynamically varying crossover and mutation probabilities [25] [26]. The Pareto front obtained using static parameters exhibits a limited spread with noticeable clustering of solutions, indicating restricted exploration of the design space and a tendency toward premature convergence. In contrast, the adaptive approach produces a more extended and uniformly distributed Pareto front, enabling improved coverage of both intermediate and extreme design regions.

The adaptive optimization framework successfully extends the achievable dynamic load rating from approximately 140–150 kN in the static case to nearly 180–200 kN, while simultaneously reducing Hertzian contact stress in the higher capacity region. Importantly, this improvement is achieved without significant variation in frictional torque, which remains within a narrow and controlled range. This demonstrates that the proposed method is capable of identifying superior design configurations that offer a better balance among load capacity, stress distribution, and frictional performance. The enhanced performance of the adaptive approach is attributed to its ability to balance exploration and exploitation during the optimization process. Higher mutation rates in the early stages allow effective exploration of the design space, while gradual reduction in mutation and increased crossover facilitate convergence toward optimal solutions. This dynamic adjustment prevents premature convergence and improves both the diversity and quality of the obtained

Pareto-optimal solutions. From an engineering standpoint, the results indicate that the adaptive framework provides a broader and more practical set of design alternatives for deep groove ball bearings in high-load applications. The reduction in Hertzian contact stress contributes to improved fatigue life, while the increased dynamic load rating enhances load-carrying capacity. The controlled frictional torque ensures that efficiency and thermal considerations remain within acceptable limits. These improvements are particularly relevant for hydrogen compressor systems, where bearings are subjected to demanding operating conditions.

Overall, the proposed adaptive multi-objective optimization approach offers a robust and efficient methodology for bearing design, integrating fundamental contact mechanics with advanced evolutionary algorithms. The study demonstrates that dynamic control of genetic parameters can significantly enhance optimization performance and expand the feasible design space. The findings provide valuable insights for the development of high-performance bearing systems and can be extended to other engineering applications involving complex multi-objective optimization problem.

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