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Design Optimisation of Rolling Element Bearings: A Literature Review

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Abstract

Optimisation is the process of finding the best design parameters that meet engineering needs and provides an inexpensive and flexible tool to define optimal designs to the industry prior to physical application. Engineers use empirical studies, statistical methods and optimisation techniques to evaluate research and determine the best design. In recent years, optimisation studies in the field of engineering has become an area of intensive work. The design optimisation of the bearings is one of these studies. In the design of bearings, there are various constraints such as geometric, kinematic, power, performance, long life and high reliability. An optimal design methodology is needed to perform these constraints collectively. In the literature, there are studies in which conventional and intelligent optimisation techniques are used for the optimisation of bearings. In this article, a source research is carried out, which includes the studies for the optimisation of bearings.

1. INTRODUCTION

Engineering design is an iterative process, which also addresses all parameters that may have an impact on target to achieve a particular goal. Mechanical design involves an optimisation process where designers always evaluate specific requirements (strength, deviation, weight, wear, corrosion, etc.) based on their needs [1]. Engineering design problems often have large scale and nonlinear or limited optimisation problems [2]. Design optimisation consists of a search field that contains appropriate solutions to specific objectives (objective functions) and a search process that contains optimisation methods [3]. Appropriate solutions are a set of all designs (design variables) characterized by all possible values of the design parameters. There are many applications where optimum design methods are useful in system design [4].

Conventional optimisation methods are commonly used in mechanical design problems. Conventional methods can use only a few design variables due to complexity and convergence problems. As the design parameters increase, the complexity increases and this makes it difficult to reach an optimum solution. They also have significant drawbacks, such as slow merger against local minimum (or maximum) problems [5]. In addition, as most of the mechanical design problems contain certain limitations, this makes it difficult to solve them with conventional optimisation algorithms [6]. An optimisation problem is too hard to be solved through conventional optimisation methods if it contains objective functions and constraints that are not expressed as explicit functions of design variables or is too complex to be manipulated [5,6]. Therefore, in recent years, intelligent optimisation methods have been used extensively in this field.

The main purpose of the design optimisation of rolling element bearings is to increase the service life and the reliability of the bearing. There are three critical parameters in the design of rolling element bearings. These are static load capacity (Cs), dynamic load capacity (Cd) and elastohydrodynamic minimum film

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thickness (H_{min}). The maximization of bearing performance is concerned with the maximization of these parameters. To obtain the optimum bearing design, the radial load capacity values (Cs and Cd) can be increased by optimizing the design, using optimisation techniques, whereby the radial forces and the ones acting on the conveying surface moving in the axial direction can be reduced.

In order to increase the working life of a bearing, the internal design variables of the bearing must be optimised. As bearings have a complex structure, there are many design variables and constraints in it. This is a phenomenon that makes it difficult to solve bearing design optimisation with conventional optimisation methods.

2. ROLLING ELEMENT BEARINGS

Rolling element bearings are used as an important component in most mechanical and aerospace engineering applications. Rollers or the rolling elements are machine elements that enable performance of a job by rolling element bearings between the inner and outer rings with at least friction and loss (Fig. 1).

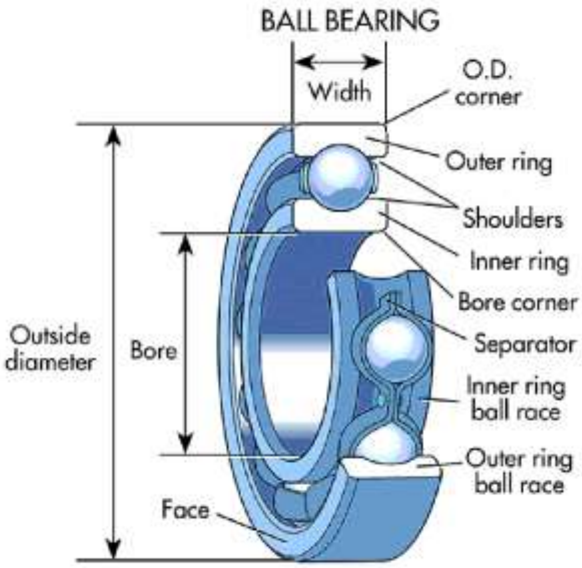

Figure 1. *Elements of a cylindrical rolling element bearing [7]*

The force is transmitted from the bearings to the shaft journal by the rolling elements between the two rings. The fact that coefficient of friction is low due to the bearings in rolling element bearings is the most significant advantage of rolling element bearings over sliding bearings. There are five types of rolling elements used in bearings with rolling elements. These are balls, cylindrical rollers, spherical rollers, tapered rollers and needle rollers.

The bearings can carry both radial loads and axial loads as shown in figure 1. Both loads can move together or separately. Rolling element bearings with cylindrical rollers have a larger contact with both slots therefore that they can handle large amounts of radial loads, however they are generally not preferred where the axial load is large. Slots of most of the rolling element bearings are fitted with separators. Separators are fitted to prevent friction, wear and rubbing of the rolling elements against each other [8]. Bearing elements have advantages in terms of cost, size, weight, bearing capacity, durability, accuracy and friction.

Rolling element bearings are subject to fatigue in high speed operations in all industrial sectors. Fatigue life is directly proportional to the dynamic capacity of the bearing. Therefore, the rolling element bearing design is a delicate process due to its non-linear and statistically ambiguous behaviour.

3. LITERATURE REVIEW

There are some studies in the literature that demonstrate the use of optimisation methods for different bearing types. The first aspect that stands out in the literature is the low number of studies conducted on this subject. It is possible to collect these studies under two main headings. These can be gathered under two headings namely, the studies carried out through conventional optimisation techniques and the studies carried out through intelligent optimisation techniques.

3.1. Studies Carried Out Using Conventional (Traditional) Optimisation Techniques

Conventional optimisation methods use a central node that bears the responsibility or coordination responsibility to decide on the optimal or near-optimal resolution of the problem. These methods are analytical and use differential equation techniques in finding optimum points. Because some practical problems include objective functions that are continuous and / or non- derivatised, conventional optimisation techniques have limited scopes in practical applications. However, a review carried out on calculation optimisation methods provides a basis for the development of most of the numerical optimisation techniques presented in the following sections.

Asimov's study on the optimisation of rolling element bearings is a pioneering endeavour in this field [9]. In this study, Asimov realised the optimum design of the length and diameter of a rolling element bearing that supported a certain load at a certain speed. In the study, the weighted sum of friction loss and shaft bending was minimized using the Newton- Raphson method.

Another pioneering study is the study of Seireg and Ezzat [10], which applies programming techniques for the development of bearing design systems. In the study, an automatic system was proposed for the selection of bearing length, radial clearance and average viscosity of the lubricant. The system optimises the performance of a hydrodynamic sliding bearing under certain speed and load.

Maday [11], Wylie and Maday identified design criteria to maximize the load bearing capacity of the bearing, using limited variable methods for calculating the variable to determine the optimum configuration of hydrodynamic bearings [11,12].

Seireg reviewed some examples for the use of optimisation techniques in the design of mechanical elements and systems [13]. These include gears, rolling element bearings, rotating disks, pressure vessels, shafts under bending and twisting, longitudinal impact beams as well as issues for elastic contact and load distribution.

Changsen described a design technique using numerical gradient-based optimisation technique for rolling element bearings [14]. He proposed five objective functions for the design of rolling element bearings: maximum fatigue life, maximum wear life, maximum static load ratio, minimum friction moment and minimum rotation rate. In the study, the concept of multi-purpose optimisation of rolling element bearings was proposed and only the basic concepts and solution techniques of the optimisation problem were presented without any illustration. Objective functions proposed for the optimisation of rolling element bearings were shown to be non-linear in conjunction with the geometric and kinematic constraints.

Hirani et al. introduced a design methodology for the design of engine journal bearings using various models developed by the same authors [15]. Selection of the length and diameter of the bearing cavity was described by means of limiting the minimum film thickness, maximum pressure and maximum temperature. A flowchart was shown for the effectiveness of the method proposed.

3.2 Studies Carried Out Using Intelligent Optimisation Methods

In recent years, some optimisation methods which are conceptually different from conventional mathematical programming techniques have been developed. These methods are labelled as modern or non-conventional optimisation methods. Most of these methods are inspired by biological structures and herd behaviours in nature. Intelligent optimisation methods that are intensively used are as follows:

- Genetic algorithms
- Simuluated annealing
- Particle swarm optimisation
- Ant colony optimisation
- Fuzzy optimisation

Most of these methods have been developed in recent years and have emerged as popular methods for solving complex engineering problems. Genetic algorithm (GA) is based on the principles of natural genetic and natural selection of candidate solutions to an optimisation problem [16]. Simulation of Annealing (SA) is based on heating of the solids and then slowly cooling them [17]. Both Genetic Algorithms and Simulation of Annealing are stochastic methods that are highly applicable to the solution of discrete optimisation problems that are highly likely to find the global minimum. Particle Swarm optimisation (PSO) is based on the behaviour of a live colony, such as a batch of insects, a flock of birds or a school of fish [18]. Ant colony optimisation (ACO) is an optimisation approach modelled on the actions of an ant colony [19]. In ACO, the ants were inspired by their ability to find the shortest path from food sources to their nests without using their eyesight. Fuzzy Logic is a form of logic where accuracy values of variables can be any real number between 0 and 1 [20]. It is an approach that deals with the concept of partial reality in which the value of the truth may vary between completely right and completely wrong.

In recent years, it is observed that there are increasing number of studies carried out on bearing design using the approaches mentioned here. The GA methods Choi and Yoon developed to determine the design parameters of an automotive wheel bearing in a type of double-row angular-ball bearing is one of them [21]. In the study, the design problem of rolling element bearings is seen as a limited optimisation problem. It is seen in the study that a wheel bearing unit optimally designed increased the system life without any violation of limitations.

Kalita et al., in their study carried out on multi-purpose optimisation for the design of bearings, made a weighed combination of purpose functions consisting of dynamic capacity, static capacity and minimum film thickness [22]. The multipurpose problem was transformed into a problem of scalar optimisation. Deterministic algorithms and stochastic algorithms were used in this study to solve the limited scalar optimisation problem. Internal penalty function method was used as the deterministic approach and Simulation of Annealing and Genetic Algorithms were used as the stochastic approaches.

Chakraborthy et. al. proposed a method that used Genetic Algorithm to solve problems that arise in designs based on the standard bearing tables of rolling element bearings and performance characteristics of bearings [23]. In the study, the design parameters used in conventional optimisation techniques were increased from three to five. In addition, a design model that took into account the fatigue life which was not taken into account in the tables was presented.

Gupta et al., optimised static capacity, dynamic capacity and the elastohydrodynamic minimum film thickness in bearings using multi-objective optimisations [24]. Dynamic and static capacities were discovered to be very sensitive to changes in the inner channel curvature coefficient.

Rao and Tiwari, identified a procedure to solve the classified, constrained, nonlinear optimisation problem for the design of rolling element bearings [25]. The mounting angle was derived from the design parameters. A total of ten design variables were considered in the study in which there were five design parameters. Problem was optimised in two stages. GA was used for optimisation. It was seen that dynamic capacity had been developed based on those listed in standards.

Rao and Tiwari developed a bearing design method through realistic constraints for single-purpose optimisation and with the help of Genetic Algorithm [26]. In the study, they discovered that optimised design parameters provided a better fatigue life than those listed in standard catalogues. They carried out a convergence study to ensure that optimised design of the local variables would not be affected by the local extremities (minimal and maximal).

A nonlinear constrained optimisation problem was proposed by Kumar et al. for the design of cylindrical rolling element bearings and a procedure was described for the solving of the optimisation problem [27]. In the design of cylindrical bearings, four geometric variables and five constraint constants were selected for optimisation of the basic dynamic capacity. Geometric constraints were formulated from the standard boundary dimensions in bearing standards. The input of the design problem was selected from the bearing standards and catalogues available for a designer. Using real coded genetic algorithms, the bearing design problem was optimised and the resulting bearing dynamic capacity was compared to the values in standard catalogues. A sensitivity analysis was performed to see the effect of manufacturing tolerances on design variables.

Bearing design problem was optimised by Kumar and Tiwari using genetic algorithms for the design of cylindrical rolling element bearings [28]. When optimised bearing dynamic capacity and fatigue life were compared to the data in standard catalogues, an improvement was noticed.

In the study of Wei and Chengzi, a problem that would extend the bearing life by reducing the bearing friction losses was considered [29]. The multi-purpose optimisation problem was solved using NSGA-II. While macro-geometries of the bearing (bore diameter, outside diameter and width) were considered as standard, non-standard internal geometry parameters were used. It was discovered that, when the rotational friction power loss was the same as the existing design, lifetime of the optimised design was 36 % longer than the existing design.

A non-linear constrained optimisation problem was formulated by Tiwari et al. for the design of tapered-roller bearings and a procedure was described for the resolution of the optimisation problem [30]. In the study, realistic constraints were formulated based on geometric, bearing standards and durability factors. Geometric constraints were formulated from the standard boundary dimensions in bearing standards. Design problem input was selected from the bearing standards and catalogues. Design optimisation problem was optimised using real coded genetic algorithms and related dynamic load capacity demonstrated improvements in fatigue life based on the standards given in the standard catalogues. A sensitivity analysis was carried out to observe the effect of manufacturing tolerances on design variables.
Waghore and Tiwari proposed a hybrid approach to optimise the dynamic capacity of bearings [31]. Non-linear optimisation formulation was resolved using Artificial Bee Colony Algorithm (ABCA), Differential Search Algorithm (DSA), Grid Search Method (GSM) and Hybrid Method (Combination of HM, ABCA / DSA and GSM). Sensitivity analysis was conducted to see the effects of tolerance on the design variables and the dynamic capacity. The dynamic capacity of the optimised bearings was found to be higher than those specified in the bearing catalogues.

Panda et al. addressed the fatigue life, which is an important problem in the design of rolling element bearings [32]. In the study, the dynamic load capacity of the radial rolling bearing was optimised using new constraints with Sort-Based Constraint Processing method. In addition, basic design variables were illustrated together with constraints. With the method developed, a stable bearing design with lower contact stresses was obtained. A hybrid algorithm consisting of PSO and TLBO was used in the study. The convergence rate was increased while the constraints were satisfied with the hybrid algorithm developed.

In the study carried out by Eugenio Dragoni, the internal dimensions of the tapered rolling element bearings were optimised for maximum dynamic capacity [33]. The bearing system discussed comprises of two identical bearings which are formed under any combination of radial and axial forces. It was shown that the basic rating life quadratically increased more when in the cylinder and that the aspect ratio of the cylinders increased to the sixth power of the pitch diameter of the cylinder set and decreased to the third power of the radial force applied.

Dynamic load capacity of rolling element bearings was optimised by Husain Bavasab Shaikh and Avinash Gulabrao Kamble using Jaya algorithm [34]. The effect of various design parameters on a specific response parameter was analysed. The results of the Jaya algorithm were compared to the values obtained from the genetic algorithm and the optimisation technique selected yielded better results than the genetic algorithm.

Jat and Tivari used NSGA-II approach in their study, in which they optimised fatigue and wear behaviour of spherical rolling element bearings [35]. In the study, in which multi-purpose optimisation approach was used, the purpose functions were dynamic load capacity and hydrodynamic film thickness. In the study, bearing life factor and specific film thickness increased compared to the existing design. In the sensitivity analysis performed to estimate the effect of the deviation of design variables on objective functions, the tolerances of three design variables and objective functions were shown. It was observed that the life of the bearing had increased through the optimisation method.

Teaching and Learning – Based Optimization (TLBO) was used by Dandagwhal and Kalyankar for the optimisation of the dynamic capacity of rolling element bearings, which is a new optimisation technique [36]. 9 design variables were considered for the selected problems. The results obtained were confirmed to be better than the standard catalogues and manuals. Therefore, it was demonstrated in this study that the performance optimisation proposed in bearing design was applicable.

4. CONCLUSION AND DISCUSSION

In this paper, a literature study was carried out on the necessity of design optimisation techniques on rolling element bearings. As the bearing industry was out of the scope of professional studies carried out in the field of optimisation in the past, only a few studies have been carried out on rolling element bearings. In the last two decades, however, a number of scientific studies have come to the forefront for optimal bearing design using different types of optimisation algorithm techniques. In this study, studies on optimum bearing design were evaluated.

It is seen that the studies made on the subject concentrate on high bearing capacities, low weight, low friction losses and high wear resistance in rolling element bearings. Conventional optimisation approaches were used in the earlier studies performed for this purpose. As some practical problems involve objective functions that are continuous and/or non-derivatised, conventional optimisation techniques do not allow the desired results to be achieved in optimum bearing design.

Intelligent optimisation techniques that have come up in the solution of engineering design problems over the last two decades draw attention as techniques that are solid, flexible, easy to solve, and that can be the best solution in a shorter time than other conventional techniques at the same time. As seen in this literature study, studies carried out on bearing optimisation in recent years have mainly focused on intelligent optimisation approaches. Many optimisation approaches were used for this purpose. Among the approaches used, GA stands out. However, studies on optimum bearing design have been carried out using other approaches, as well. When the studies in the literature are examined, even though better results are obtained in the studies carried out in intelligent optimisation techniques, more scientific studies are needed to be carried out on the optimal design of bearings.

CONFLICT OF INTEREST

No conflict of interest was declared by the authors

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