Application of advanced optimization techniques in the selection of optimal process parameters and failure prediction of anti-frictional bearings - A review

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Abstract. Engineering design generally considered as goal-oriented, controlled, conclusion making process to manufacturing a product. While designing a mechanical component, designers always consider certain objective like tensile and flexural strength, deflection, weight, wear and tear, fatigue, etc. It is very difficult to accommodate all the objectives govern by multiple variables in the design of components. For this purpose, concentration has been given on the optimization of certain components of the mechanical design specially bearing. Bearings are extensively used in machine to reduce the friction and enhance rotational motion. Any critical failure of it, would not only affect the overall systems performance but also its reliability, safety, availability and cost-effectiveness. Objectives like long fatigue life i.e. higher dynamic load capacity, rating life need to be achieved collectively in the design of the rolling element bearing. The objective of this article is to highlight influence of the advanced optimization techniques in design optimization and to determine and understand various methods of fault diagnosis of bearings to accomplish superior performance and to withstand global competitive environment.

1. Introduction

Bearing is simple, precious and of great utility member of machine system. The purpose of bearing is to provide relative motion, free movement and support to the transmission component of machine line shaft [1]. Bearings classified into two broader groups i.e. hydrodynamics bearing also known as sliding contact bearing and anti-friction or rolling element bearing. There is basic difference in two types of bearing, later is selected form the started catalogue of the manufacturer while the first is custom design. Hydrodynamic bearing design is application based and considered the parameters like higher life, rigidity, capacity and less friction. One general form of hydrostatic bearing is radial bearings finds it bid in heavy load applications like machine tools and some of the measuring devices. However, out of number of parameters, oil canal width ratio is crucial parameter to optimize the capacity [2].

State of art design of the bearing is not limited to hydrodynamic or rolling element. Advanced forms of the bearing includes the magnetic bearing, externally pressurized air bearing, thrust bearing, gas bearing and many more. Magnetic bearing is the modified form of the journal bearing in which fluid is replaced by the magnetic field. By using magnetic force, rotor is stabilized in at the center and seamlessly move without wear and lubrication [3]. Air bearing is also extended form of journal bearing in which air cushions provided to permit bearing action with minimum friction. Number of parameters like pressure of supply air, characteristics of porous pads like geometry and permeability make the optimal design of air bearing complex [4,5]. One more form of the hydrodynamic bearing known as gas bearing is also
widely used for heavy applications. Tight tolerance in the bearing clearance is the key factor for the stability of the gas bearing [6].

A wide form of bearing that used in low to medium load applications is the anti-friction or rolling element bearings. Dynamics capacity is most important objective mostly consider while selecting the rolling element from the manufacturers standard catalogue [7]. Load carrying capacity of the rolling element also depends on type of element and related geometrical parameters. With the geometrical changes in the design of the rolling element bearing the load carrying capacity of the bearing in different directions can be enhanced like radial, axial and thrust forces [8]. Allot of forms of the anti-friction bearing that widely used are deep groove ball bearing, angular contact bearing, single and double row taper roller bearing. Due to non-linear nature of the bearing it is look simple but difficult to design, any failure of the bearing may results into catastrophic breakdown in the machine or the part of the machine [9].

Every time after creating or designing a new product, designer tries to achieve the best solution for the product and therefore need to perform optimization. Though, optimization in design is not new, but it is time intense and involves systematic procedure to identify the right grouping process parameters and relevant objectives. Engineering design problems classified under several criteria’s that are number, nature and permissible values of design variables, existence of constraints, number, nature and reparability of the objective function, physics of problem, and the nature of the environment [6]. Application of optimization is wide and cover almost every application of engineering. Metal cutting process is key factor manufacturing support system which consists of allot of input-output and in process parameters [7]. Due to complexity and uncertainty in the machining process it is difficult to perform computing manually, so, soft computing techniques are prefer to applied for machining process and optimizing them [8]. Relatively very less work was carried on the design optimization of the rolling element bearing. Objective of this paper is to review the application of advanced optimization techniques to rolling element bearing design. Review has been made on the basis of design optimization of the rolling element bearing along with highlighting the scope of nature inspired optimization techniques in the field of design and fault diagnosis of the rolling element bearing. The aim of present work is to highlight the applicability of the traditional and advanced optimization techniques in the selection of optimal process parameters and to predict the failure mode of the bearings.

2. Bearings

2.1. Hydrodynamic Journal bearings

Hydrodynamics journal bearings work on the hydrodynamics lubrication theory which statuses that the two contacting surfaces to be separated thin layer of viscous material while transmitting the motion. These bearings are very well known for their characteristic features like excellent damping, minimum friction due nonphysical contact and high load carrying capacity. Various equations has been adopted in direct or in modified form like Reynolds equation and different optimization techniques. Important design variables includes length of the bearing, geometrical specification of groove and radial clearance between journal and the bearing, etc.

Basic principle of the hydrodynamic journal bearing i.e separation of mating surfaces by a thin layer of viscous material has been adopted in various forms which results in the modified form of the bearing like air bearing, magnetic bearing. In case of air bearing separation between two surfaces achieved by providing air film. Pressure of supply air and characteristics of porous material are important design variables to achieve optimal performance of the air bearing [5]. In case of magnetic bearings, magnetic field used to keep the rotor in concentric position in the bearing casing. Number of accountability aspects of magnetic bearing has been considered by the researchers like reduction in actuator mass and power loss and enhancement in the external static load capability of the rotor [10]. The combination of shaft with multiple discs rigidly or flexibly connected to shaft is termed as rotor. Unbalance response amplitude and stability of rotor is critical performance criteria of the bearings. In case of high-speed operations stability of rotor and controlled vibrations necessary to avoid catastrophic failures. So, higher
power-to-weight ratio is desirable [11]. Number of objective functions governed by number of parameters led the application of advanced optimization techniques in the design of the hydrodynamics journal bearings. Also, number of researchers applied traditional optimization technique to optimize the design of the above mentioned bearings. But, limited scope of traditional optimization techniques to handle number of objectives together nature inspired optimization technique replaced the prior. Table 1 shows the review of application of optimization techniques on hydrodynamics, air and magnetic bearings.

Table 1. Review of application of optimization techniques

| Author, Year | Type of the bearings | Optimization technique | Design parameters | Remarks |
|--------------|----------------------|------------------------|-------------------|---------|
| Zhang and Talke [12], 2005 | Air bearings | Combined genetic algorithm-subregion (CGS) approach | Flying height, Roll angle | Objective function shown suitable convergence in three considered cases. CGS is superior convergence rate than Genetic algorithm (GA) and less computational time than sub-region approach (SA) |
| Song et al. [13], 2005 | Journal bearings | Enhance artificial life optimization algorithm (EALA) | the radial clearance, length to diameter ratio, average viscosity | EALA shows the superior results than artificial life algorithm (ELA). EALA results shows enhancement in journal speed and radial clearance while length to diameter ratio tends to lower. |
| Cavdar [2], 2006 | Radial journal bearings | Computer aided optimization | Power ratio, width to diameter ratio, pocket length in axial direction and width ratio | Approach is suitable up to 3000 rev/sec. If the rotation is increased above limit than flow become turbulent. |
| Wang et al. [4], 2009 | Air bearings | Genetic algorithm, cluster OpenMP | pressure of supply air, width of square porous pad, distance of porous pad edge to bearing edge, and permeability | Three task used to compute the performance of the algorithm which consist of change in the grid size and air bearing models. The moderate and larger size grain tasks effective in CLOMP. |
Rao and Tiwari [3], 2009 | Magnetic bearings | Genetic algorithm | Performance parameters and the controller of the magnetic bearing highly depends on air gaps, bias currents and length of permanent magnets. GA can effectively handle optimization of multiple objectives with number of process parameters.

Wang and Cha [5], 2010 | Air bearings | hypercube-dividing method (HDM) | The new approached proposed termed as HDM found superior to produce Pareto optimal solution. If the minimum size of hypercube is defined properly, performance of the HDM can be enhanced.

Gorasso et al. [14], 2015 | Hydrodynamic journal bearings | Simulations and Artificial Intelligence Tools | Optimal value of mass flow help to restricts the temperature and enhances the maximum pressure and fluid layer thickness. Although, dimensional parameters like diameter and length of bearing not much modified by algorithm.

Zhong et al. [10], 2016 | Magnetic bearings | Genetic algorithm | Two modified forms of the genetic algorithm, NSGA-II and NCGA used and obtained results were compared with Pareto optimal solution. The temperature distribution and hot spot generation in the bearing has analyzed by FEA on 2D model.

Akbarzadeh et al. [15], 2017 | Thermodynamics journal bearings | MOPSO algorithm | Two different case of multiple optimized solved considering bearing power loss, the minimum oil film thickness, and the maximum pad temperature as objective function. Along with the effect of design variables, effect of bearing speed,
| Author(s) | Component | Type of Optimization | Design Parameters Considered | Results & Conclusions |
|----------|-----------|----------------------|------------------------------|-----------------------|
| Soorajkrishna et al. [11], 2018 | Rotor bearing | Genetic algorithm | length-to-diameter ratio, bearing load, and inlet oil temperature | Single and multi-objective optimization carry out on rotor bearing. The scaled goaled programming which is modified form of previously used Genetic algorithm shown considerable improvement to achieve optimal solution. Obtained results were validated with the FEA results. |
| Guenat and Schiffmann [6], 2019 | Gas journal bearings | Monte-Carlo method | internal diameter of the shaft, the external diameter of an element, length of an element, and density of the material | Author proposed a new methodology of multi-objective optimization to enhance the range of design parameters. Optimized results help to enhance the manufacturing tolerance in the design of the grooved journal bearing. |

2.2. Rolling element bearings

Application of optimization in design is bounded into certain space and process with single or multiple goals. Common objectives in the design of mechanical components consist of aspects of strength, deflection, weight, wear, corrosion, etc. depending on the requirements. However, design optimization of complete mechanical system is complicated with number of objectives governed by number of design variables [16]. So, application of optimization technique considering single component is always better to reduce the complexity. For this purpose, concentration has been given on the optimization of certain components of the mechanical design specially bearing. To understand the current state of application of optimization in gears and bearings, a literature review has been presented. As discussed, bearing is one of the important component of the mechanical system and early detection of faults is crucial requirement to avoid catastrophic failure of the whole system. On other hand, design of the bearing depends on the dynamics capacity of the rolling element bearing which depends on number of design variables [17].

Number of researchers concentrated on various objectives related to enhancement in efficiency of rolling element bearings like fatigue life, corrosion resistance, reduction in overheating, friction, vibration and noise. But in normal operating conditions, the main failure that most of the rolling bearings face is contact fatigue. For the longer life of the bearings, it is necessary to increase fatigue life which is directly proportional to the dynamics load capacity. A standard rolling element bearing consists of inner ring, outer ring and the rolling element. Rolling element is sphere in case of ball bearings while cylindrical roller in case of roller bearings. However, design seems to be simple of the rolling bearing but non-linear behaviour and inner geometry only responsible for the deflection and load distribution [18]. As
explained above section, fatigue life is function of the dynamic load rating. Table 2 consists of review of application of optimization techniques in rolling element bearings.

**Table 2. Review of application of optimization techniques**

| Author, Year | Type of the bearings | Optimization technique | Remarks |
|--------------|-----------------------|------------------------|---------|
| Rao and Tiwari [19], 2007 | Rolling element bearing-Ball bearings | Genetic Algorithm | Maximization of fatigue life considered as objective while number of parameters measured were pitch dia of the bearing, sphere i.e. rolling element diameter and there number with inner and outer race curvature. Convergence of the parameters studied and the fatigue life considerably improved. |
| Gupta et al. [17], 2007 | Rolling element bearing-Ball bearings | Genetic Algorithm | A multi-objective optimization problem in which dynamics, static capacity and electrodynamic minimum film thickness considered as objectives. Non-dominated sorting based genetic algorithm (NSGA-II) used to obtain Pareto Optimal solution considering eight geometrical parameters. |
| Kumar et al. [20], 2008 | Cylindrical roller bearings | Genetic Algorithm | Considered dynamic fatigue failure as objective function. Number of geometrical parameters were more in cylindrical roller bearings which makes the system non-linear and complex. Genetic algorithm is capable to deal with number of parameters. Obtained results were superior and compared with standard results available in catalogue. |
| Wei and Chengzu [21], 2010 | High speed Angular Contact ball bearings | Non-dominated sorting based genetic algorithm (NSGA-II) | Considered two objectives i.e. frictional loss in rotation and longer serving life with five process parameters. A high speed angular ball bearing (AC 7007) optimized in which 7.5 superior results obtained than standard values. Stiffness can be consider as another objective function. |
| Mendi et al. [8], 2010 | Deep groove ball bearing | Genetic Algorithm | Reduction in volume consider as objective of a gear box which consists of reduction of volume of gear, shaft and bearings. Genetic algorithm used to perform said optimization in which obtained results shown a superiority than analytic method results. |
| Dragoni [22], 2013 | Radial cylindrical roller bearings | Linear optimization | Focused on maximization of static and dynamic rating life considering multiple size constraints. Dynamic load rating depends on five geometrical parameters whereas static load rating depends on two geometrical parameters. For the dimensionally unconstrained condition, roller diameter and pitch diameter helps to enhance dynamic load rating. |
After certain permissible range of pitch diameter, dynamic load rating start decreasing due to abrupt changes in curvature diameter.

| Authors            | Bearing Type            | Optimization Method                        |
|--------------------|-------------------------|--------------------------------------------|
| Thoriya et al.     | Rolling contact bearing| Teaching learning based optimization       |
| [23], 2015         |                         | A review has been carried out on the design optimization of rolling element bearing using TLBO algorithm in which single and multi-objective conditions considered. In most of design problem of rolling contact bearings, dynamic capacity considered as objective which defines the life of the bearing. |
| Lostado et al.     | Double row taper roller bearing | Multiple response optimization and FEM | A new methodology implemented to optimizes the life of double row taper roller bearing considering Preload, radial load, axial load and torque as the performance parameters. Three parameters value obtained from the Finite element modeling obtained results had shown considerable improvement as compared to available standard results. |
| Kim et al. [25], 2016 | Angular contact ball bearings | Multi-objective discrete optimization | A hybrid approach in which genetic algorithm and regression optimizer used for efficient discrete optimization. Angular contact ball bearing in the application of the shaft of grinder used for the optimization. Constraints considering film thickness, friction, manufacturing and fatigue life while six other geometrical variables selected as design variables. Optimized results of stiffness shown considerable improvement. |
| Shaikh and Kamble [18], 2018 | Deep groove ball bearings | Jaya Algorithm | A newly developed advanced optimization technique named as Jaya Algorithm used for design optimization of deep groove ball bearing which consists of number of design variables. Considered algorithm shown superior performance over the other advanced optimization and traditional techniques. |
| Martinez et al. [26], 2018 | Taper roller bearings | Data mining classification technique | For the proper work prediction of the taper roller bearing an optimal relation need to define considering contact stresses, fatigue spalling and pitting. A finite element models followed by design of experiments synchronized in such a way that the overall simulation cost to be reduced. All the FE model validated with good accuracy. |
| Dandagwhal and Kalyankar [9], 2019 | Deep groove ball bearing and teaching learning based algorithm | Two different models of rolling contact bearing i.e. deep groove ball bearing and cylindrical roller bearing has been considered. Both the models have different geometrical specification which consists |
3. Discussions on current limitations and future trends
Hydrodynamic bearing and rolling element bearings has basic difference in the design and the process parameters which leads to use different type of optimization approach while find out optimal values of respective parameters. Hydrodynamic bearings available in number of forms like air bearing, magnetic bearing, journal bearing, gas journal and rotor bearing. All types have same basic working principles but as the lubricant replaces by magnetic field or air or gas, we need to consider respective parameters for optimization. Power loss, mass flow, temperature rise, maximum pressure and minimum lubricant film thickness are few general objective functions optimized by various researchers. Still number of process and design parameters related to traditional form of journal bearing and of advanced or modified form need to be analyses properly. Various researchers focused on design optimization of the rolling element bearings due to quite simple structure as compared to hydrodynamic bearings. Still non-linear relations of inner and outer race with rolling element i.e. sphere or roller makes optimization problem complex. A common objective function, dynamic capacity of the bearing used by many researcher as the life of the bearing directly proportional with it. Still, various objective functions like lubrication film thickness, heat generation due to friction need to be explored along with fatigue life. Certain factors like preload and material properties of the bearing material need to be considered in the process of optimization.

Also, predictive maintenance of the bearing is prime concern to avoid the catastrophic failure of the system. Early detection of faults is also emerging area for the application of advanced optimization technique [27]. Normally envelope analysis used demodulation technique which provided very little flexibility and it is very difficult to vary the working conditions. Advanced optimization technique like genetic algorithm has strong ability to optimize the optimal resonance demodulation in which initial estimates provided by kurtogram. Li et al. [28] used the support vector machine with ant colony optimization to predict the failure of the bearings. Best and worst solution updated for the pheromone trails density. Results of optimization were validated by experimentation and superior than SVM-GA combination. In another study, Xi et al. [29] used neural network modified by glowworm swarm optimization (GSO) used to determine six different faults features. Initial weight and threshold values of neural network optimized using GSO. ANN found good scope in the fault detection in the bearings. Same principle used by Unal et al. [30] to diagnose the faults in bearing, fitness value validated by experimentation. Recent use of artificial intelligence and machine learning tool also shown the potential of technique in soft computing [31]. Kolodziejczyk et al. [32] used the AI and ML to correlate the working conditions with the mating bodies and to explain the impairment mechanisms.

4. Conclusion
From the review of studies on the design optimization of the rolling element bearings, it is seen that emphasis is on the maximizing life of the bearing. Although, literature available for design optimization for multiple objectives likes dynamic capacity, the static capacity and the elasto-hydrodynamic minimum film thickness, dynamic capacity have drawn the attention of a greater number of researchers. Relatively less work has been carried out in the area of design optimization of the rolling element
bearings and further application of optimization techniques required particularly for the objectives of maximum wear life, the maximum static load rating, the minimum frictional moment and the minimum spin to the roll ratio along with maximum dynamic capacity. The generic framework for application of design optimization in rolling element bearing attempts to provide a single, unified, and systematic approach to determine optimal or near-optimal design parameters. Also, scope of optimization techniques in the fault diagnosis of the rolling element bearing had been discussed. With the continuous research in the field of optimization, no doubt the quest to pursue better and improved rolling element bearing design optimization will continue.

5. References

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