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Design optimization of an angular contact ball bearing for the main shaft of a grinder

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ABSTRACT

A conventional trial and error approach toward the design of non-standard bearings takes a significant amount of time to obtain an adequate design. In this study, a non-standard angular contact ball bearing for the main shaft of a grinder was optimized using design automation and optimization techniques. To manufacture a product as precisely as possible with a grinder, the radial and axial stiffness values of the grinder bearing must be selected as objective functions. To treat two objective functions, this study employed a global criterion method as a multi-objective optimization methodology. Eight constraints on the manufacturing, film thickness, friction, and fatigue life were imposed. Six geometric variables and an axial preload were selected as design variables. All design variables were regarded as discrete because they should have manufacture-possible dimensions. Quasi-static analysis taking dynamic effects into account was employed to analyze bearing performance. For efficient discrete optimization, this study proposed a hybrid method in which a micro-genetic algorithm and regression-based sequential approximate optimizer were both employed. Optimization results revealed that both stiffness values were enhanced while satisfying all design constraints.

1. Introduction

Rolling bearings are important rotating elements in a variety of mechanical systems and are standardized by different types and sizes. The requirements of rolling bearings include long lifetimes, high stiffness, and low torque; requirements have become more stringent due to the sophisticated demands of mechanical systems such as weight reductions, miniaturization, and high reliability [1,2]. However, the existing standardized rolling bearings for general use purposes have failed to meet these requirements. If the boundary dimensions (the bore diameter, outer diameter, and bearing width) of a rolling bearing were changed to satisfy a set of requirements, the redesign of a correspondingly-sized grinder would be demanded and would likely be costly. Accordingly, the development of non-standard rolling bearings that fulfill requirements without any change to their boundary dimensions has increased. With the rising development of non-standard rolling bearings, engineers have developed CAE tools to predict the performance of rolling bearings in order to improve their design efficiency, and have conducted analysis-based designs [3]. However, depending on the expertise of the engineer and through the process of trial and error, adequate designs were made that met target requirements. As a result, the design of rolling bearings is time consuming. Therefore, increased research with regard to non-standard bearings based on optimization techniques has been performed to achieve design optimization and shortened design times.

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Changsen [4] introduced design problem formulation methods for deep groove ball bearings and tapered roller bearings by applying design optimization concepts. Choi and Yoon [5] optimized the system life of an automotive wheel bearing by performing a static analysis of the ball bearings. Chakraborthy et al. [6] performed a design optimization of deep groove ball bearings to maximize their dynamic load rating. Building on Chakraborthy's research, Rao and Tiwari [7] additionally took into account bearing widths and other constraints related to the thicknesses of the inner and outer raceways in design optimization. Gupta, Tiwari, and Nair [8] chose the dynamic capacity, static load capacity, and elastohydrodynamic minimum film thickness as objective functions and used NSGA II (non-dominated sorting based genetic algorithm II) as a multi-objective evolutionary optimizer to obtain Pareto optimal fronts of the deep groove ball bearings. Kumar, Tiwari and Reddy [9] performed a design optimization of cylindrical roller bearings to maximize their dynamic capacity. Kumar, Tiwari, and Prasad [10] maximized the fatigue life of crowned cylindrical roller bearings. Wei and Chengzu [11] selected the rating life and spin frictional power loss as objective functions and used NSGA II to obtain Pareto optimal fronts of the high-speed angular contact ball bearing subjected only to an axial load. Lin [12] implemented design optimizations for deep groove ball bearings to maximize their dynamic load rating and used differential evolution combined with real-valued genetic algorithms as an optimizer, comparing its performance with those of existing binary-code genetic algorithms. Tiwari, Sunil, and Reddy [13] obtained optimum designs to maximize the dynamic load capacity for tapered roller bearings. Waghole and Tiwari [14] maximized the dynamic capacity of needle roller bearings and used an artificial bee colony algorithm (ABCA), a differential search algorithm (DSA), a grid search method (GSM), a hybrid method combining the ABCA and GSM, and a hybrid method combining the DSA and GSM as optimizers. This study performed a design optimization of an angular contact ball bearing for the main shaft of a grinder.

Compared to the aforementioned studies, contributions of this study toward the advancement of applying optimization techniques to the design of non-standard rolling bearings consisted of: (1) the use of an efficient hybrid optimization method taking into account a relatively long quasi-static analysis time for the angular contact ball bearing under radial and axial loads, (2) the use of a comprehensive design problem formulation including stiffness, manufacturability, film thickness, friction, and fatigue life, and (3) the treatment of all design variables as discrete variables taking manufacturability into account.

Objective functions and constraints of all the aforementioned studies can be expressed through explicit functions of design variables, and thus no analysis procedures were necessary except for the design of an automotive wheel bearing [5] and angular contact ball bearing [11]. In the case of the automotive wheel bearing, static analysis was employed, and in case of the angular contact ball bearing, quasi-static analysis was employed. Although quasi-static analysis procedures were used for the angular contact ball bearing in Wei and Chengzu [11], the bearing was only subjected to an axial load; thus, all balls had equivalent inner and outer contact angles. However, the high-speed angular contact ball bearing for the main shaft of a grinder in this study was subjected to both radial and axial loads; thus, each ball had different inner and outer contact angles, resulting in longer times to obtain converged analysis solutions compared to the case of the bearing only subjected to an axial load. It took an average of 10 s (CPU: Intel Core i7 960, RAM: 24GB) to carry out one quasi-static analysis. If one of the genetic algorithm (GA) or meta-heuristic algorithm frequently used in the aforementioned bearing design optimization studies were applied, it would require considerable design time. Therefore, this study proposed a hybrid method using both a micro-genetic algorithm (MGA) [15] and progressive quadratic response surface method (PQRSM) [16] implemented in PIAnO (process integration, automation, and optimization) [17], a commercial PIDO (process integration and design optimization) software. The MGA that required fewer function evaluations than GA was first used to obtain near global optima in the feasible region; these were then used as multi-starting initial points of a function-based local optimizer (PQRSM) to obtain the best optimum solution.

All the aforementioned studies commonly accounted for the life and manufacturability of rolling bearings in their design problem formulations. Additionally, [5,9,10,13,14] included contact stress, [8] included film thickness, and [11] included friction. However, a comprehensive design problem formulation of this study took into account the radial stiffness and axial stiffness due to simultaneously imposed radial and axial loads in addition to all of the design requirements considered in prior studies. Note that the contact stress was implicitly accounted for when maximizing stiffness values.

Other than the number of balls or rollers, all the aforementioned studies treated all design variables as continuous variables except for the design of an automotive wheel bearing [5] and cylindrical roller bearing [9,10], where only the roller diameter was treated as a discrete design variable. In practice, however, design variables must be selected from sets of specified discrete values. The sets of this study are listed in Table 2. The treatment of all design variables as discrete variables of this study resulted in optimum discrete design variable values that could be directly adopted in practice without further discretization. Post-optimally discretized solution yielded deteriorating design results compared to those of the discrete optimization in this study.

This paper is comprised of the following: Section 2 for bearing design problem formulations explains a design object, design variables, objective functions, and constraints in detail; Section 3 briefly introduces quasi-static analysis; Section 4 describes the proposed design optimization procedure; Section 5 shows the results of multi-objective discrete design optimization; Section 6 presents the conclusions of this study.

2. Bearing design problem formulation

2.1. Design object and components

A grinder is a machine with which to grind surface structures with a rapidly-rotating grindstone. In order for the ground surface to be more precise than that of a surface cut by a regular bite, the stiffness of the grinder is of great significance. Insufficient stiffness can result in deformations at the main shaft of the grinder during operation, leading to imprecise fabrication. To improve