International Journal of Applied Engineering Research
ISSN 0973-4562 Volume 10, Number 7 (2015) pp. 17729-17741

http://www.ripublication.com

Design Optimization of Large Diameter Ball Bearings Using Genetic Algorithms

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Abstract

The design of large diameter ball bearings has a fundamental influence on the performance, life and reliability of the bearings. Consequently, this also affects the operating quality and the economization of machines on which the bearings are used. This invokes the need of an optimal design methodology to achieve these objectives collectively, i.e., the multi-objective optimization. In this paper, two primary objectives for a large diameter ball bearing, namely, the static capacity (C_S) and the spinning friction (M_S) have been simultaneously optimized using genetic algorithm. The optimal design parameters namely, ball diameter (D_b) and number of balls (Z) have been obtained for the objective functions of maximizing the static capacity and minimizing the spinning friction.

Keywords: Ball bearings, Dual-objective optimization, Genetic algorithm

Introduction

The rolling bearings are classified to large diameter bearing when the diameter range varies from 0.5 m to 15 m. They are often subjected to heavy loads under relatively low operating speeds [1]. The load carrying capacity and life of the large diameter bearing is largely depends on the key design factors such as geometry, materials, hardness of the raceways etc.…. Generally, larger diameter bearings are designed according to the customer's requirements and applications. Hence there is no standard design procedure is available for the design of slewing bearings. And the large diameter bearings are expected to serve in different loading conditions such as axial, radial, moment or combination of the above. Therefore, while designing large diameter bearing the design engineer concentrates more on static load rating instead of dynamic rating. But at the mean time the fundamental requirement of any bearing is the rotation without friction. The static load rating depends on the materials chosen for rolling elements as well as raceways, internal geometry of the bearing, load distribution between rolling elements. The load distribution among the rolling elements depends on the size and number of rolling elements present in the bearing. For better performance the designer must focus on reducing the friction itself on the bearing along with high load carrying capacity. In this respect, optimization of the internal bearing geometry as well as the tribological conditions of relevant friction partners is required. In general, sliding occurs at all contact points of a rolling bearing; e.g., between rolling elements and raceway or cage. This can involve macro slip or micro slip. A differential slippage always occurs in ball bearings due to the varying distance of the individual contact area points of the axes of rotation of the bearing elements. This means that the centre section of the ball surface slides in the opposite direction of the direction of rolling and that the external sections slide in the direction of rotation. Spinning friction is caused by slippage that occurs when a rolling element turns on the vertical axis of its contact.

Large diameter bearings are widely used in engineering applications such as Nuclear reactor, wind mill, etc.… Hence the requirements for the design of large diameter bearings are different from the general bearing design procedure. There is no specific procedure is available for the design of large diameter bearing. Manufacturers design the bearing according to the requirement of customers [2]. The benefits of specialized research can be obtained when it is possible to use a standard bearing of the proper size and type. The design engineers are motivated to arise with design technology that gives long lasting, more efficient and highly reliable bearing designs. These objectives are hard to satisfy, thus making it a numerically challenging problem. There is a need to optimize them collectively warrant an application of the multi-objective optimization.

Several research works have been done on bearings, design of bearings and optimization of bearings, but the literatures on large diameter rolling element bearings are very limited. I. Prebil and P. Kaiba [3] developed a software package which is capable of producing information the designer requires. The expert system automates the design of large diameter bearings and saves considerable time. A.V.N.S. Prakasa Rao [4] developed an expert system for the selection of the bearing. R.A. Pallini and J.E. Sague [5] established a simplified computational method, which is constructed from the established design criteria and presented with minimal geometry information. Asimow [6] used Newton-Raphson method for the optimum design of the length and the diameter of journal bearings supporting a given load at a given speed, which minimize a weighted sum of the frictional loss and shaft twist. Maday [7] and Wylie and Maday [8] used bounded variable methods of the calculus of variable to determine the optimum configuration for one-dimensional hydrodynamic gas slider bearings. The design criterion was maximizing the load carrying capacity of the bearing. Changsen [9] described a design method by using a gradient based numerical optimization technique, for rolling element bearings. The objective functions proposed for rolling element bearings for optimizing the stated objectives are non-linear and also constrained in nature. Hamit Saruhan [10] used genetic algorithm for the optimization of rotor bearing systems considering system stability along with other design criteria such as fluid film thickness, power loss, film temperature, and film pressure. H. Hirani and N.P. Suh [11] described the optimum design methodology for improving the operating characteristics of fluid-film steadily loaded journal bearings by considering design variables as radial clearance, length to diameter ratio, groove geometry, oil viscosity and supply pressure to simultaneously minimize oil flow and power loss. Nenzi Wang and Yau-Zen Chang [12] developed multi-objective optimization problem for air bearing design by using genetic algorithm (GA) with the Pareto ranking.

Standard Genetic Algorithm (GA) is well suited for non-linear problems and in most cases, they can find the global optimum solution with a high probability and are naturally applicable to the solution of discrete optimization problems but with high computational expense. Choi and Yoon [13] used GA in optimizing automotive wheel-bearing unit. The method presented maximized system life of the wheel bearing. Chakraborthy et al. [14] describes the design optimization problem of rolling element bearings with five design parameters using GAs based on the requirements of long fatigue life. Rajeswara Rao and Rajiv Tiwari [15] developed a nonlinear optimization procedure based on genetic algorithm for designing rolling element bearings. The constraint contains unknown constants, which have been given ranges based of parametric studies through initial runs. Shantanu Gupta et.al., [16] developed a multi objective optimization technique by simultaneously considering the variables, such as the dynamic capacity (C_d), the static capacity (C_S), and the Elasto hydrodynamic minimum film thickness (Hmin).

The foremost importance must be given to the selection of design variables. The design objective must be either maximization or minimization within the allowable constraints. In the present study, the optimization of large diameter bearings is carried out by considering static capacity (C_S) and spinning friction (M_S) of bearing as design objectives.

Problem Formulation of Ball Bearing Design

To optimize the performance characteristics and life of a large diameter bearing, the rolling element diameter and the number of rolling elements has to be calculated accurately. In this formulation of the problem, there are two objectives present. Hence this problem can be called as a dual objective optimization problem. Any constrained multi-optimization problem is essentially composed of three components, namely, design parameters, objective functions, and constraints.

Design Parameters

The design parameter vector can be written as:

$$X = [D_b, Z, KD_{min}, KD_{max}, NZ_{min}, NZ_{max}] \quad (1)$$

D_b and Z are geometric parameters of bearings and KD_{min}, KD_{max}, NZ_{min} and NZ_{max} are part of constraints. The diameter of balls (D_b) is a discrete variable and the number of balls (Z) is a variable of the whole number type. In the optimization, both are treated as continuous variables. The constraints are usually kept constant while designing bearings, but in the present case, these secondary parameters are also considered as variables. This has been made possible due to the flexibility and the robustness offered by the adopted GA based approach. All dimensions are in millimetres (mm), angles in radians, forces in Newton (N) and spinning friction in N-mm.

A case study has been made for the optimization of large diameter bearings and the sample bearing data is given below.

1. Outer diameter of bearing, D = 4605 mm.
2. Inner diameter of bearing, d = 4416 mm.
3. Pitch diameter, Dm = 4510.5 mm.
4. Width of the ring, B_w = 94.5 mm.
5. Axial load (static) on the bearing = 5000000 N.
6. The contact angle of the bearing, $\alpha = 60^o$.
7. Inner raceway curvature coefficients, f_i = 0.52.
8. Outer raceway curvature coefficients, f_o = 0.52.
9. Co-efficient of friction, μ = 0.002.
10. Constraint constant, β = 0.85.

Problem parameters were given the strict upper and lower bounds to reduce the solution space. The following table **(Table-1)** shows the upper and lower bounds (values) for the design parameters (D_b and Z) and constraint parameters (KD_{min}, KD_{max}, NZ_{min} and NZ_{max}).

Table 1: Parametric bounds

Parameters		**Lower Bound**	**Upper Bound**
Design parameters	D_b	60 mm	80 mm
	Z	160	240
Constraint parameters	K_{Dmin}	0.2	0.6
	K_{Dmax}	0.66	1
	N_{Zmin}	0.2	0.6
	N_{Zmax}	0.66	1

Objective Functions

Two important performance measures (objective functions) considered for the bearing optimization are namely, the static capacity (C_S) and the spinning friction (M_S). The static capacity has to be maximized and the spinning friction has to be minimized simultaneously, for getting the best performance of the bearing. These performance parameters are discussed below.

Static capacity (C_S)

The basic static load rating or static capacity (C_S) of a ball bearing was defined as the load applied at a non rotating bearing that will result in permanent deformation of

0.0001D at the weaker of the inner or outer raceway contacts occurring in the position of the maximum loaded rolling element. Some bearings, such as extra-large bearings, control bearings in aeroplanes, etc., work at low speed. For given sizes of the bearing outline, the static load rating (C_S) should be maximizing objective.

$$C_s = f_c \times Z \times D_b^{\,2} \times \sin\alpha \times J_a(\varepsilon) \tag{2}$$

$$f_c = 13.87 \times \sqrt{\frac{2 f_i \times (1-\gamma)}{2 f_i - 1}} \tag{3}$$

$$\gamma = \frac{D_b \times \cos\alpha}{D_m} \tag{4}$$

Spinning Friction (M_S)

A significant portion of total ball-bearing friction results from friction due to spinning. For thrust-loaded angular-contact ball bearings, the ball spins about an axis perpendicular to the contact area on either the inner or the outer race depending on ball control [17]. Friction moment (M) is an important dynamic performance of rolling bearings. The friction in rolling bearings is dependent on several factors, of which the most important are the bearing load, the properties of the lubricant and the rotational speed. The friction moment of the bearings is formed upon spinning (M_S), micro-slip (M_Y), elastic hysteresis (M_R), etc. [12]. Hence the friction moment is taken as an objective function whose expression is

$$\min(M) = \min(M_S + M_R + M_Y). \tag{5}$$

Spinning friction (M_S),

$$M_s = \frac{(3 \times \mu \times Q_{\max} \times a_i \times \varepsilon_i)}{8} \tag{6}$$

$$Q_{\max} = \frac{F_a}{Z \times \sin\alpha} \tag{7}$$

$$F_a = \frac{BearingLoad}{J_a(\varepsilon)} \tag{8}$$

$$a_i = 0.0236 \times a_i^{*} \times \left[\frac{Q_{\max}}{\sum \rho_i}\right]^{(1/3)} \tag{9}$$

$$\sum \rho_i = \left[\frac{1}{D_b}\right] \times \left[4 - \left(\frac{1}{f_i}\right) + \left(\frac{2\gamma}{1-\gamma}\right)\right] \tag{10}$$

$$\varepsilon_i = \frac{\left(b_i^{*}\right)^3 \times \pi \times K_i}{2} \tag{11}$$

$$K_i = \left(\frac{a_i^*}{b_i^*} \right) \tag{12}$$

Constraints

In engineering problems, the value of a design parameter must lie in a certain limited region. In order to complete the formulation of the optimization problem, some restrictions must be imposed on the values of the design parameters. These restrictions are called constraint conditions. Constraints reduce the parameter space to the feasible parameter space. This section summarizes the five problem constraints. The ball diameter gets an upper and lower bound, through following constraints

Constraint 1:

$$(2 \times D_b) - (K_{D\min} \times (D - d)) \geq 0 \tag{13}$$

Constraint 2:

$$(K_{D\max} \times (D - d)) - (2 \times D_b) \geq 0 \tag{14}$$

Constraint 3:

Furthermore, an additional constraint, which limits the maximum allowable diameter of the ball is

$$\beta \times \{(D - d)/2\} - D_b \geq 0 \tag{15}$$

The number of balls should be within certain limited region, through following constraints

Constraint 4:

$$Z - \{N_{Z\min} \times \pi \times (D_m / D_b)\} \geq 0 \tag{16}$$

Constraint 5:

$$\{N_{Z\max} \times \pi \times (D_m / D_b)\} - Z \geq 0 \tag{17}$$

Dual-Objective Optimization

The optimization is a key word in most of engineering applications. An engineering design optimization problem is generally composed of two or more than two objectives, associated with a constrained parameter space, thereby getting the name as (constraint) multi-objective optimization. The objective vector can be denoted by

$$f(p) = \{f_1(p), f_2(p), \ldots\ldots f_n(p)\}, \text{ subjected to } c(p) \geq 0;\ n \geq 2. \tag{18}$$

Here, p – the parameter vector,
f(p) – the objective vector,
c(p) – the constraints vector.

Formally, the multi-objective optimization refers to the solution of problems with two or more objective functions, which are normally in conflict with each other. In this paper, static capacity (C_S) and spinning friction (M_S) are the two objectives, which are in conflict by maximum static capacity and minimum spinning friction. In order to avoid this situation, normalization [0, 1] is necessary. 1 is allocated to best value and 0 to worst. In normalization, the objective values which are in different range (in this case C_S is in terms of 1,00,00,000 and M_S is in terms of 100) are transformed into a range between 0 and 1. That is,

For maximizing objectives

$$r_{sk} = \frac{(Z_{sk} - Z_{k\min})}{(Z_{k\max} - Z_{k\min})} \tag{19}$$

For minimizing objectives

$$r_{sk} = \frac{(Z_{k\max} - Z_{sk})}{(Z_{k\max} - Z_{k\min})} \tag{20}$$

Where,

r_{sk} = transformed value of the s^{th} individual and the k^{th} objective,

Z_{sk} = original (simulated) value,

Min = Smallest value and

Max = Larger value of the S ($0 \leq s \leq S$) individuals

The advantage of this normalization is that transformed data have comparable values. While optimizing the normalization encounters a drawback in a dynamic environment because of the modified normalized values obtained. Hence the normalization procedure has to be performed recursively.

Implementation of Genetic Algorithm

Genetic Algorithm (GA) was used as an optimization engine. Genetic algorithms are computerized search and optimization methods that work very similar to the principles of natural evolution. GA's intelligent search procedure finds the best and fittest design solutions, which are otherwise difficult to find using other techniques. GA is attractive in engineering design and applications because they are easy to use and they are likely to find the globally best design or solution, which is superior to any other design or solution.

The **figure 1** shows basic GA flow chart. The population size, the generation count, the crossover and mutation probabilities are determined after multiple runs of the algorithm with the aim of obtaining the best solutions.

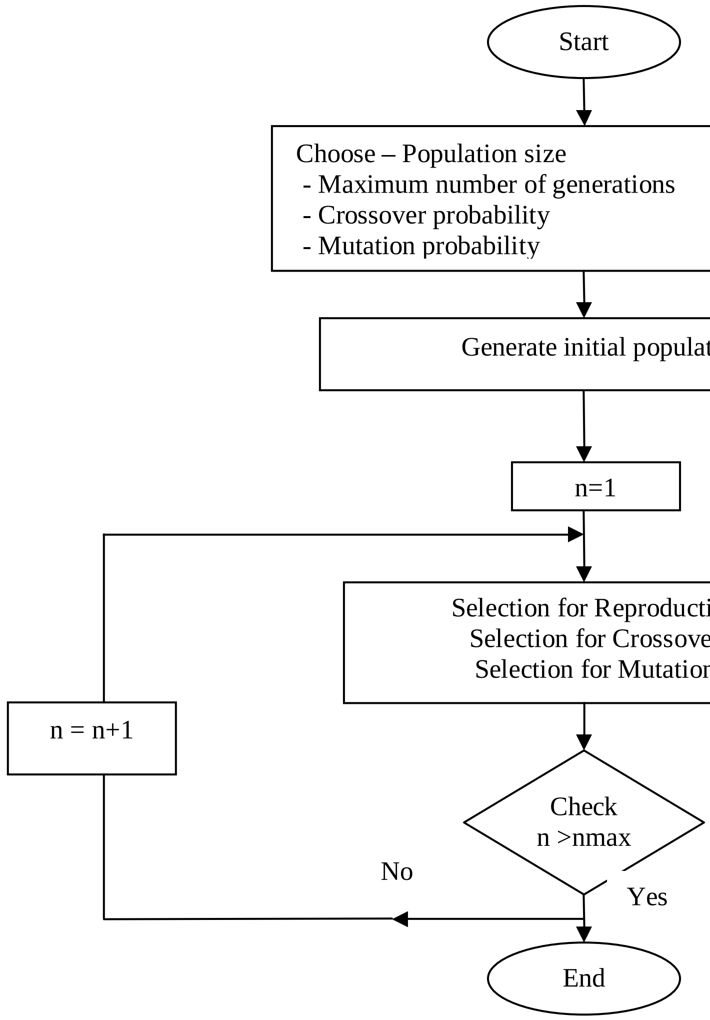

Figure 1: Flow chart of basic GA

The population size is set as 25 for all the runs. The crossover probability is varied from 0.45 to 0.6 and the mutation probability is ranged from 0.03 to 0.05. The objective values are converged in the range of 500 – 600 iteration for the crossover probability of 0.55 and mutation probability of 0.03.

The roulette wheel selection method is used for selecting the chromosomes for reproduction. The single point crossover has been implemented for crossover operation. The complete replacement strategy is adopted for replacing the initial population for the next generation. In this work, number of iterations is fixed as the termination criteria. A simple C program has been developed for GA. **Table 2** shows the best optimization result of dual objective optimization, i.e. static capacity C_S & spinning friction M_S.

Table 2: Optimum Static Capacity Cs And Spinning Friction Ms

Design parameters		**Converged Constraint constants**				**Static capacity (C_S) and Spinning friction (M_S)**	
D_b (mm)	Z	K_{Dmin}	K_{Dmax}	N_{Zmin}	N_{Zmax}	C_S (N)	M_S (N-mm)
60.627451	233	0.3569	0.756	0.4353	1	47223355.95	161.337425

The **figure 2** shows the relation between the objective functions (Static Capacity and Spinning Friction) and the number of generations.

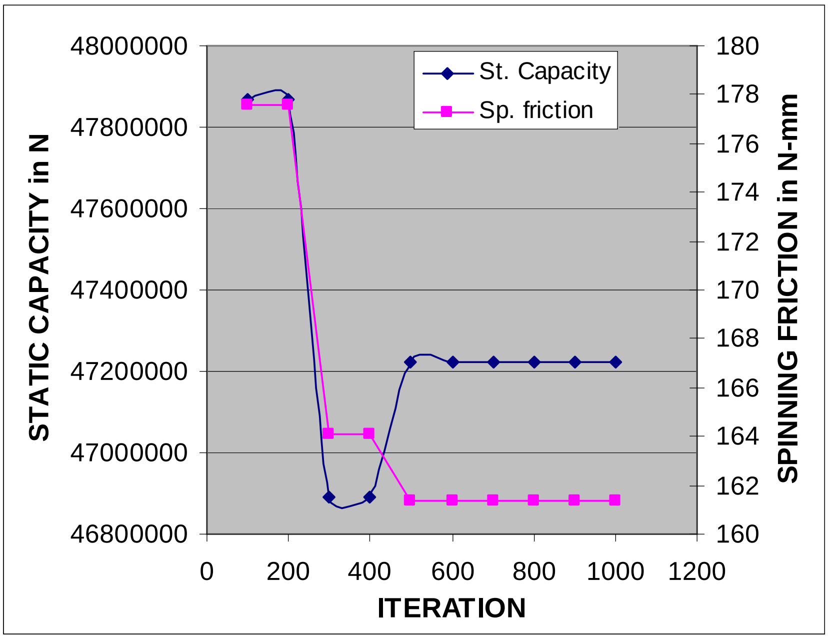

Figure 2: Static Capacity (C_S) And Spinning Friction (M_S) Curve

The **figure 2** shows the relation between the objective functions (Static Capacity and Spinning Friction) and the number of generations.

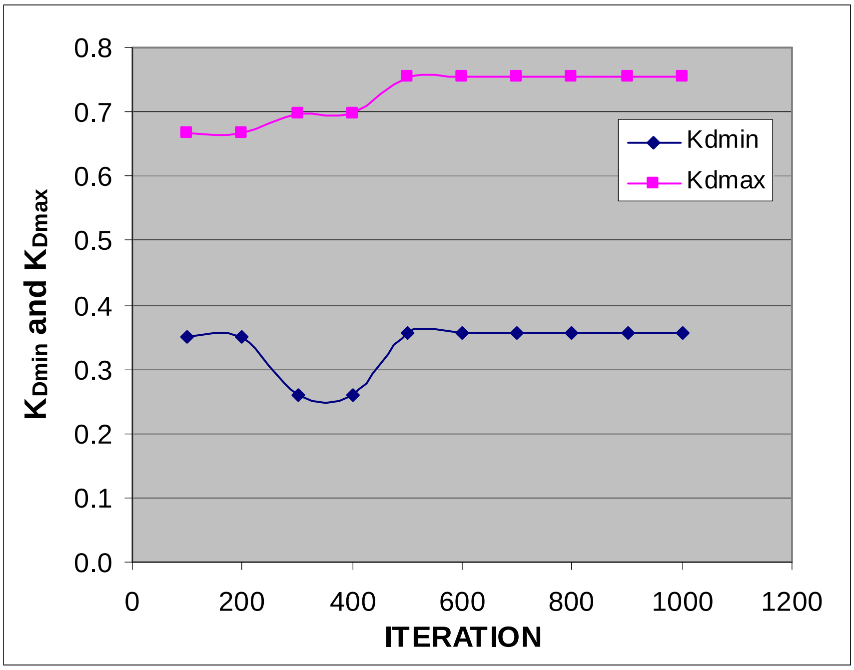

Figure 3: K_{Dmin} and K_{Dmax} Curve

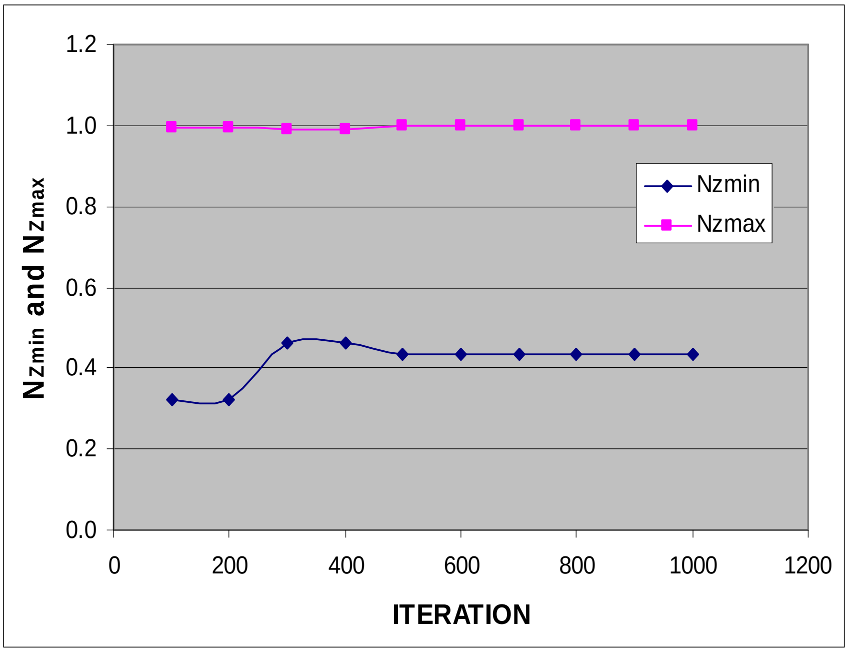

Figure 4: N_{Zmin} and N_{Zmax} Curve

The **figure 3 and 4** shows the relation between constraint parameters (K_{Dmin}, K_{Dmax}, N_{Zmin} and N_{Zmax}) and the number of generations.

Conclusion

In this paper, a procedure for the optimization of large diameter ball bearing design has been developed. The optimization problem has non-linear characteristics with dual-objectives. Generally the large diameter ball bearings are optimized based on the static capacity. In this study, Static load (C_S) and spinning friction (M_S) have been taken as objective functions to optimize the design parameters (D_b and Z).

From the study it is observed that

- Bearing rolling element size and number of rolling elements are optimized based on the static capacity and spinning friction.
- The parameters K_{Dmin}, K_{Dmax}, N_{Zmin} and N_{Zmax} used in the constraints are converged to a very closer range.
- Parametric study can be performed to find out the variation in the trade-off with the changing operating conditions.

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Nomenclature

D	Outer diameter of bearing, mm.
d	Inner diameter of bearing, mm.
D_m	Pitch diameter of bearing, mm.
B_w	Bearing width, mm.
D_b	Diameter of ball, mm.
Z	Number of balls.
f_i	Inner raceway curvature coefficient.
f_o	Outer raceway curvature coefficient.
r_i	Inner raceway curvature radius.
r_o	Outer raceway curvature radius.
C_S	Static Capacity, N.
M_S	Spinning Friction, N-mm.
K_{Dmin}	Minimum ball diameter limiter
K_{Dmax}	Maximum ball diameter limiter
N_{Zmin}	Minimum number of balls limiter
N_{Zmax}	Maximum number of balls limiter
f_c	Load rating factor.
α	Contact angle, in radians.
$J_a (\varepsilon)$	Axial load integral.
μ	Co-efficient of friction.
Q_{max}	Maximum load capacity, N.
F_a	Axial load, N.

a_i	Semi major axis inner raceway contact.
b_i	Semi minor axis inner raceway contact.
a_i^*	Non-dimension semi major axis inner raceway.
b_i^*	Non-dimension semi minor axis inner raceway.
$\Sigma\rho_i$	Curvature sum of inner raceway.