Hindawi
Journal of Engineering
Volume 2023, Article ID 6038824, 11 pages
https://doi.org/10.1155/2023/6038824

Research Article

Fatigue Life Analysis of Remanufactured Radial Rolling Bearing with the Replaced Loading Zone

L. Chen,[1] D. T. Bu,[1] Z. B. Feng,[2] and H. B. Liu[1]

[1]*Henan University of Science & Technology, Luoyang 471003, China*
[2]*SKF (Shanghai) Industrial Services Co., Ltd, Shanghai 200949, China*

Correspondence should be addressed to D. T. Bu; 491421538@qq.com

Received 9 November 2022; Revised 11 September 2023; Accepted 2 November 2023; Published 6 December 2023

Academic Editor: B. Sridhar Babu

The replacement of the loading zone is not considered in the active calculation method on fatigue life of remanufactured bearings. In practical application, when the radial bearings are reinstalled after remanufacturing, it is required to replace the loading zone, which results in a large deviation between the calculated fatigue life according to the active calculation method and the actual life. In this paper, the fatigue life factors of radial bearings with different remanufacturing levels are calculated according to the actual application condition. The results of case studies show that with the improvement of the remanufacturing level, regardless of whether the loading zone is replaced or not, the remanufacturing bearing life factor is gradually increased and the maximum can reach 1. Considering the replacement of the loading zone, the life factors of remanufactured bearings with different fixed rings are also very different, among which the remanufacturing deviation of fixed outer-ring level II is the largest, reaching 11.3%. However, with the increase of the remanufacturing level, the deviation decreases gradually. The life factors by the method presented in this paper of remanufactured radial bearings with the replaced loading zone are significantly higher than those of the active calculation method. The research results of this paper provides a more accurate calculation scheme for the fatigue life of remanufactured radial rolling bearings, which is a supplement to the active calculation method and has important practical significance for the practice of bearing remanufacturing engineering.

1. Introduction

The purpose of rolling-bearing remanufacturing is to excavate the remaining life of bearings whose bearing parts (mainly the rings) are not fully used. Rolling-bearing remanufacturing has a longer history than generalized remanufacturing and has formed a series of system documents in the long process of development [1]. The concept of bearing remanufacturing was first presented in September 1974, when Stanley presented a report entitled "bearing field inspection and refurbishing" at the Symposium on Propulsion System Structural Integration and Engine Integrity, held at the Naval Post Graduate School in Monterey [2]. The U.S. Army Aviation Systems Command held a symposium named "bearing restoration by grinding seminar" in St. Louis from May 20 to 21, 1976. After the meeting, the U.S. Army Aviation Systems Command summarized these reports and issued USAAVSCOM-TR-76-27 [3], which marks the remanufacturing of rolling bearings as a systematic project. NASA released the first report on bearing remanufacturing in 1976, TM-X-73440 [4]. In the 21st century, the ecological deterioration caused by carbon dioxide emissions has attracted more and more attention. The scale of the rolling-bearing remanufacturing industry is developing rapidly. Bearing manufacturers have set up specialized remanufacturing factories one after another. The typical manufacturers include SKF [5–7], Schaeffler [8, 9], and Timken [10–12].

Due to the particularity of the raceway remanufacturing method, the rolling bearing cannot return to the original design life after remanufacturing but can only return the bearing life to the original life curve, as shown in Figure 1. The calculated rated life curve in the figure refers to the theoretical life curve established according to the bearing

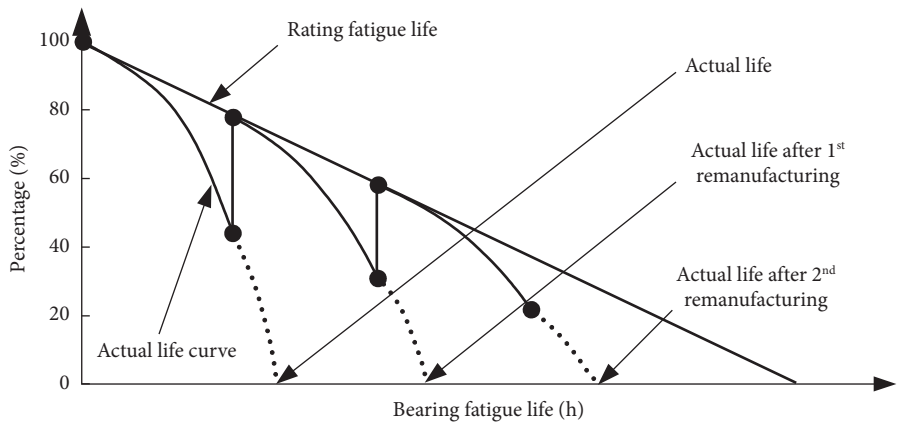


Figure 1: Life curve of remanufactured rolling bearings [13].

application condition in the process of bearing selection. In practical application, due to installation factors, environmental pollution, insufficient lubrication, and other factors, the actual life often deviates from the predicted life value. According to Timken's statistics, only 10% of the bearing used in heavy industry can reach the rated fatigue life L_{10}. Bearing remanufacturing can effectively restore its life. On the other hand, the fatigue life of remanufactured bearings can still be calculated by the statistical method after remanufacturing when a batch of bearings has reached their fatigue life. The remanufacturing level of rolling bearing varies and metal removal of the raceway varies, which will directly affect the fatigue life of bearings after remanufacturing. Many studies have focused on the fatigue life of remanufactured bearings. NASA released the life analysis report TN D-8486 of remanufactured bearing in 1977 [14]. In 1987, an analytical report TM-88871 [15] was published on the effect on fatigue life owing to metal removal on raceways by NASA. Zaretsky and Branzai [16] summarized the life calculation of remanufactured bearings again at the Society of Tribologists and Lubrication Engineers Annual Meeting and Exhibition in 2014 based on NASA TM-2005-212966 [17]. Zamzam et al. [18] analyzed the rolling contact fatigue of remanufactured bearings by polishing. Chen et al. [13] proposed a new class IV remanufacturing method based on the remanufacturing of large-size radial bearing rollers and the fatigue life of cylindrical roller bearings by the new remanufacturing method is verified by experiments. Matthew [19] studied the problem of bearing remanufacturing to prolong life and improve performance. Darisuren et al. [20] researched the relationship between the remanufacturing process and fatigue life of spherical roller bearings.

None of the abovementioned studies on fatigue life of remanufactured bearings has paid attention to the replacement of the loading zone. According to the practical application of replacing the loading zone for radial bearing after manufacturing, the fatigue life factors of different remanufacturing levels with replacement of the loading zone are calculated in this paper. The results of case studies show that the life factors of the radial bearing with the replacement of the loading zone are increased and the increased range varies according to different remanufacturing levels, with a maximum increase of 12% according to the calculations in this paper.

2. Classification of Rolling-Bearing Remanufacturing

The method of rolling-bearing remanufacturing includes but is not limited to the scope of generalized remanufacturing. Generalized remanufacturing mainly includes additive manufacturing technology, combined with machining to restore the size and shape accuracy of the parts. Coors et al. [21] investigated the wear behavior of additively welded cladding layers on less wear-resistant base materials. Finally, he discovered that additive manufacturing processes can be used to clad less wear-resistant base materials and achieve high wear resistance, making it possible to exploit the advantages of surface coatings under severe wear conditions. But the remanufacturing of rolling bearings is different from the generalized remanufacturing, and the difference is mainly reflected in the remanufacturing of raceways. Due to the huge alternating stress between the contact pair of rolling elements and raceways in the work, the raceways remanufactured by using additive technology are difficult to meet the application needs of rolling bearings. At present, the method of removing materials is widely used to remanufacture bearings.

The object of rolling-bearing remanufacturing is the bearing that has been used or stored for a long time. Because of the different storage status, the different number of use cycles, and the different application conditions, the condition of rolling bearing to be remanufactured varies greatly. When the bearing is remanufactured, its remanufacturing level should be determined first. Different remanufacturing levels mean that there are differences in the methods and contents of remanufacturing, which has a direct impact on the fatigue life of remanufactured bearings. Therefore, the classification methods of remanufacturing used in practical applications are introduced first.

At present, there is no universally accepted standard for the classification of bearing remanufacturing. The active classification methods are based on the enterprise

documents of bearing remanufacture factories and the research report of NASA. Remanufacturing classifications from typical factories as well as NASA are listed in Table 1. The classification details are different as can be seen in Table 1. SKF divides the remanufacturing level into five levels in the form of class I–class IV [5]; Schaeffler FAG divides the remanufacturing level into four levels according to level I–level IV [8]; Timken divides the remanufacturing level into three levels according to type I–type III [11]; and NASA [17] divides the remanufacturing level into four levels according to level I–level IV.

Different remanufacturing levels involve distinct remanufacturing procedures. The following provides a concise overview of the procedures associated with each remanufacturing level based on NASA's remanufacturing classification. Level I is the remanufacturing level to inspect used bearings or bearings in long-term stock to confirm whether they still meet the requirements of drawings or if bearings with minor defects are partially polished or grinded to restore bearing performance. Level II refers to the remanufacturing level of replacing the rolling element and cage when necessary and the polishing of raceways to restore bearing performance, and the thickness of metal removal on the raceway is less than 13 μm. Level III refers to the remanufacturing level of raceway grinding and replacing of enlarged rollers to restore bearing performance, and the thickness of metal removal on the raceway is 76 μm and 300 μm for bearings with outer diameter less or greater than 400 mm. Level IV means the remanufacturing level of replacing a new ring.

3. Rolling Contact Fatigue and Replacement of the Loading Zone

In the application of rolling bearings, the external load is transferred to the rolling elements through the ring, which causes huge contact stress between the rolling elements and the raceway. Periodic alternating stress on rolling element surfaces and raceways causes rolling contact fatigue. The area which bears the load is defined as the loading zone. Due to the effect of the clearance of the radial bearing, only some area in the circumference direction of the fixed ring is subjected to alternating stress.

3.1. Effect of Loading Zone Replacement on Fatigue Life. Taking the application of deep-groove ball bearings as an example, the schematic diagram of loading zones (both original and new) and the contact profile under external load P are illustrated in Figure 2. In Figure 2(a), the outer ring of the bearing is fixed and the inner ring rotates at angular velocity ω_i. Gr is the radial clearance of the bearing. Because of the combined influence of load and motion, the whole inner raceway is the loading zone, while only the lower part of the outer raceway is the loading zone. The size of the loading zone on the outer raceway is affected by the clearance, while the larger the clearance, the smaller the loading zone is. Continuous action of periodic alternating stress will cause stressing of the metal on the raceway surface. The stressed depths of raceways are indicated as x_i and x_o on section A-A in Figure 2(b), respectively.

The replacement of the loading zone refers to the use of the raceway area which has not been stressed as the new loading zone in the next application cycle as shown in Figure 2(a). For example, the inner ring is the rotating ring and the outer ring is the fixed ring, and when the bearing is subjected to radial force, the rotating ring is stressed as a whole, but only a part of the fixed ring is stressed; the stressed part is called the loading zone, and the unstressed part is called the nonloading zone. After the bearing runs for a certain period of time, the inner ring and the outer ring are remanufactured at different levels according to the degree of damage and the nonloading area of the outer ring is used as the new loading zone when the bearing is reinstalled after remanufacturing. Ball bearings and roller bearings have the same principle; the only difference is the contact form.

The fatigue life of bearing will decrease to a certain extent after material stressing according to TM-2005-212966 [17]. The fatigue life of rolling bearings is a comprehensive characterization parameter of the life of internal and external raceways and rolling elements. A replaced loading zone means that the fixed ring raceway is not stressed and the fatigue life of the fixed ring will not decrease. Then, the fatigue life of bearing will be different. The fixed ring (the outer ring in Figure 2(a)) is rotated 180 degrees in the circumferential direction to enter a new application cycle. In the new application cycle, the life of the inner raceway decreases, but the life of the outer raceway is the same as that of the new bearing, which will lead to the increase of the life of the remanufactured bearing system, as shown in Figure 3.

3.2. Rolling Contact Fatigue of Rolling Bearings. The contact types commonly observed in rolling bearings are point contact and line contact, as illustrated in Figure 4. The contact state of deep-groove ball bearing is the typical point contact as can be seen in Figure 4(a). The contact point expands to an ellipse when applied with the external load P. When the ball contacts with the inner and outer raceways, one is in contact with the outer circle and the other is in contact with the inner circle. The difference of the coincidence degree results in the difference of the contact ellipse. In Figure 4(a), a is the half length of the contact ellipse between the inner raceway and the ball, b is the half width of the contact ellipse between the inner raceway and the steel ball, and a' and b' are the half length and half width of the contact ellipse between the outer raceway and the steel ball, respectively. The contact state of cylindrical roller bearing is the typical line contact as can be seen in Figure 4(b). a and b are the half length and half width of the contact ellipse between the outer raceway and the cylindrical roller, respectively, and b' is the half width of the contact ellipse between the inner raceway and the cylindrical roller.

The contact area between rolling elements and raceways are very small, which results in huge contact stress between rolling elements and raceways. The material of a certain depth under the effective area of the load is affected by stress. The contact area of inner and outer raceways is different, so

Table 1: Classification and details of bearing remanufacturing.

Units	SKF [11]'s classes		FAG [15]'s levels		Timken [12]'s types		NASA [22]'s levels	
Classification	0	Inspection	I	Requalifying	I	Recertify	I	Reclamation
	I	Reclassification	II	Refurbishment	II	Recondition	II	Refurbishment
	II	Refurbishment	III	Remanufacture	III	Remanufacture	III	Restoration
	III	Remanufacture 1	IV	Plus			IV	Remanufacture
	IV	Remanufacture 2						

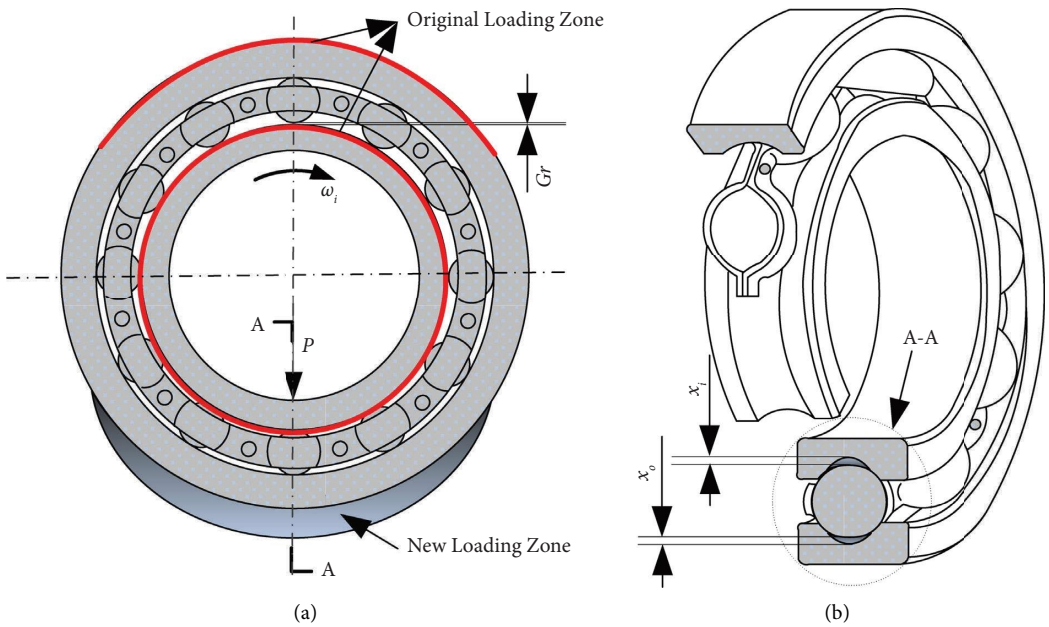


Figure 2: Loading zone of deep-groove ball bearing. (a) Loading zone. (b) Material stressed on raceways.

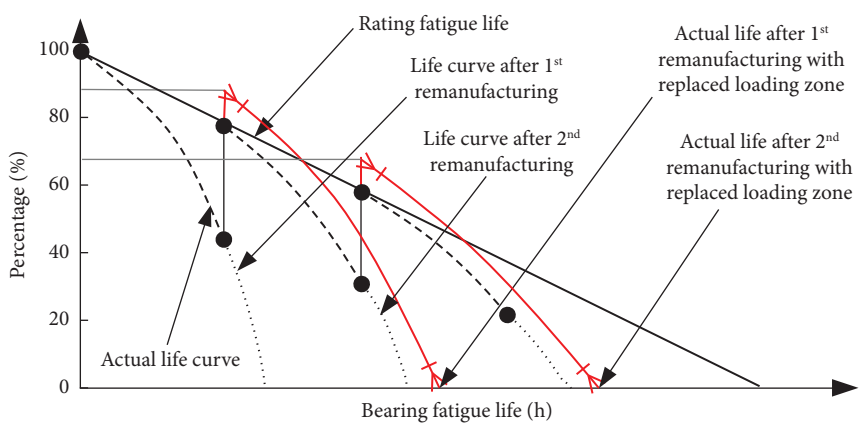
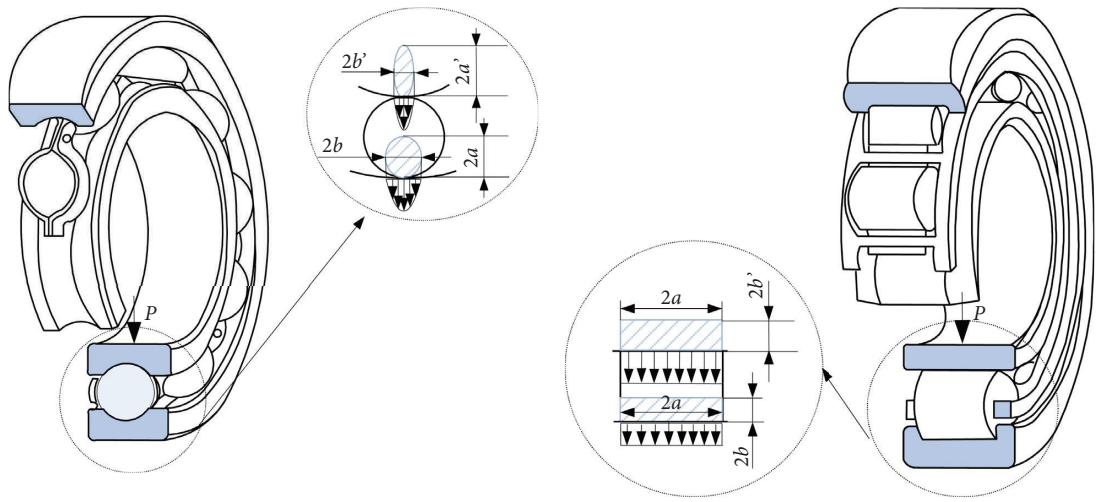


Figure 3: Life curve of remanufactured rolling bearings with the replaced loading zone.

the depth of stress on the raceway surface is different. Fatigue failure of the contact surface is a statistical phenomenon, which is related to the volume of the material under stress, so the stress depth directly affects the fatigue life of the internal parts of rolling bearings [22]. Rolling contact fatigue is characterized by metal particles falling off from the surface of the raceway or rolling elements. For a well-lubricated bearing, the exfoliation begins with a crack below the surface and then extends to the surface, eventually forming a pit or exfoliation on the surface of the loading area.

Lundberg and Palmgren [23] considered that orthogonal shear stress τ_0 was the origin of fatigue crack and put forward an equation for calculating the fatigue life of bearings. Chalsma and Zaretsky [24] revised Lundberg's life calculation equation by using maximum shear stress τ_{45}



(a) (b)

Figure 4: Contact form of ball bearing and roller bearing. (a) Point contact. (b) Line contact.

instead of orthogonal shear stress τ_0, as shown in the following equation:

$$\ln \frac{1}{s} \sim \tau_{45}^{ce} N^e V. \tag{1}$$

In equation (1), S is the survival probability and c is the stress life index, e is the slope of Weibull distribution, N is the bearing life counted by the number of stress cycles, and V is the volume of being stressed. According to the study of Lundberg and Palmgren [23, 24], e is equal for the point contact and for the line contact.

The fatigue life of the raceways can be obtained as follows:

$$\begin{aligned} L_{i/o} &= N \\ &= A\left(\frac{1}{\tau_{45}}\right)^c \left(\frac{1}{V}\right)^{(1/e)}. \end{aligned} \tag{2}$$

In equation (2), L_i and L_o are the lives of inner and outer raceways, respectively, and A is the life factor influenced by the raw material.

4. Life Factors of Remanufactured Raceways in Rolling Bearing

Different remanufacturing levels correspond to different techniques in the remanufacturing process, and the fatigue life of the remanufactured raceway will be influenced by different techniques directly. Then, the life factors of raceways after remanufacturing are discussed separately according to whether the stressed surface material is removed or not.

4.1. Life Factor of the Remanufactured Raceway without Metal Removing. The used times of rolling bearings which will be remanufactured are various. For convenience, L_{10} is chosen as the used time for bearings which will be remanufactured in the following discussion. According to the definition of rating life, when a batch of bearings work for a certain time, 10% of the bearings fail, while the remaining 90% of the bearings do not fail; then, the certain time is defined as rating life L_{10}.

The remaining 90% bearings are remanufactured and there is no metal which will be removed from the raceway. Based on the definition of rating life, the new L_{10} of remanufactured batch bearings is equivalent to L_{19} of original batch bearings, namely,

$$F = 10\% + 90\% \times 10\% = 19\%. \tag{3}$$

In equation (3), F is the failure probability.

Then, the survival probability is

$$S = (1 - F) = 0.81. \tag{4}$$

In equation (4), S is the survival probability.

Then, the new L_{10} (original L_{19}) of remanufactured batch bearings can be obtained by the Weibull theory [25] as follows:

$$\ln \frac{1}{S} = kL^e. \tag{5}$$

In equation (5), k is the material-related life impact factor.

The life factor of the remanufactured raceway without metal removing can be expressed as follows:

$$LF_p = \frac{L_{19} - L_{10}}{L_{10}}. \tag{6}$$

In equation (6), LF_p is the life factor of the remanufactured raceway without metal removing (polish only).

The reliability involved in calculating the life factor by equation (6) is 90%. Reliability requirements of rolling bearings vary under different application conditions. Zaretsky and Branzai [17] calculated life factors of rolling bearing with different reliability as listed in Table 2. The

Table 2: Life factors of the remanufactured raceway with different reliability.

	L_5	L_{10}	L_{15}	L_{20}	L_{30}	L_{40}	L_{50}
Life factors	0.88	0.87	0.84	0.82	0.79	0.76	0.74

calculation method of the data in Table 2 is the same as the method mentioned in this paper, so the data in Table 2 can be directly quoted in calculating fatigue life of raceways.

4.2. Life Factor of the Remanufactured Raceway with Metal Removing. It is necessary to remove some metal on the surface of the raceway in levels II, III, and IV remanufacturing, as discussed in Section 1. Removals of the strengthened material have an impact on fatigue life of the raceway. Schematic of normalized maximum shearing stress τ_{45} as a function of normalized depth below the raceway surface showing the effect of metal removal in redistributing stress is shown in Figure 5. According to Figure 5, the stress distribution state is changed by polishing or grinding. τ_{45} in the figure is normalized and is equal to 1 when the depth of the stressed material is the same as the position of the maximum shear stress.

Assuming the depth of material removal is x and it is further assumed that the metal at depths greater than Z_{45} are not stressed. Therefore, after material removal, metals have not been subject to stress cycles which can be expressed as follows:

$$\begin{cases} V_x = a l_L x Z_{45}, & \text{(a)}, \\ V_x = l_t l_L x Z_{45}, & \text{(b)}. \end{cases} \tag{7}$$

In formula (7), (a) is the calculation formula of point contact type bearings and (b) is the calculation formula for linear contact type bearings. a is the major semiaxis of the contact ellipse, l_L is the equivalent width of the contact region, and l_t is the length of the raceway contact area.

After material removal, metals have a stressed volume of

$$\begin{cases} V_{1-x} = a l_L (1-x) Z_{45}, & \text{(a)}, \\ V_{1-x} = l_t l_L (1-x) Z_{45}, & \text{(b)}. \end{cases} \tag{8}$$

In equation (8), (a) and (b), respectively, represent the stress volume under the raceway for point contact type bearings and linear contact type bearings after removing metal materials.

Each of the stressed volumes contributed to the life of the entire raceway having a stressed volume defined in the following equation:

$$\begin{cases} L_x = \left(\dfrac{1}{x}\right)^{(1/e)} L, & \text{(a)}, \\ L_{1-x} = (LF_1)\left(\dfrac{1}{1-x}\right)^{(1/e)} L, & \text{(b)}. \end{cases} \tag{9}$$

In equation (9), (a) and (b), respectively, represent the life of the stressed part and the unstressed part.

Harris [22] derived the relationship between individual component life and system life. The life of the entire volume from equation (9) can be further defined from the Lundberg–Palmgren equation, equation (6), where

$$\frac{1}{L_{i/o}^e} = \frac{1}{L_x^e} + \frac{1}{L_{1-x}^e}. \tag{10}$$

It is uncertain which ring is fixed in bearing application. The inner and outer rings are described by fixed and rotating rings. According to the abovementioned analysis, the fatigue life of the fixed ring will be the same as that of the new ring after replacing the loading zone and the fatigue life of the rotated ring will be changed. Then, equation (10) becomes

$$\frac{1}{(L_v')^e} = \frac{1}{L_x^e} + \frac{1}{L_{1-x}^e}. \tag{11}$$

In equation (11), L_v' is the fatigue life of the rotated ring.

The life factor of the remanufactured raceway with metal removing can be defined as follows:

$$LF_g = \frac{L_v'}{L_v}. \tag{12}$$

In equation (12), LF_g is the life factor of the remanufactured raceway with metal removing (polish and grinding), and L_v is the original fatigue life of the rotated ring.

4.3. Fatigue Life of Remanufactured Bearing with Replacement of the Loading Zone. A bearing is a system of multiple components each with a different life, and the life of the system is different from the life of an individual component in the system. The relationship between rolling bearing system and rings can be expressed as in the following equation:

$$\frac{1}{L_R^e} = \frac{1}{L_\mu^e} + \frac{1}{(L_v')^e}. \tag{13}$$

In equation (13), L_R is the fatigue life of the bearing system after remanufacturing and L_u is the fatigue life of the fixed ring.

The life factor of the remanufactured bearing can be defined as follows:

$$LF_R = \frac{L_R}{L}. \tag{14}$$

In equation (14), LF_R is the life factor of the remanufactured bearing system.

The calculation process of life factors of bearings with different remanufacturing degrees can be clearly described by the flowchart shown in Figure 6.

The above describes the calculation methods of the life factors of bearings at different remanufacturing levels. The life factor can intuitively reflect the difference between the fatigue life of the bearing considering the replacement of the loading zone and the fatigue life obtained by the active calculation method, and the difference comes from whether the fixed ring is stressed or not after the bearing is remanufactured. The method proposed in this paper can improve

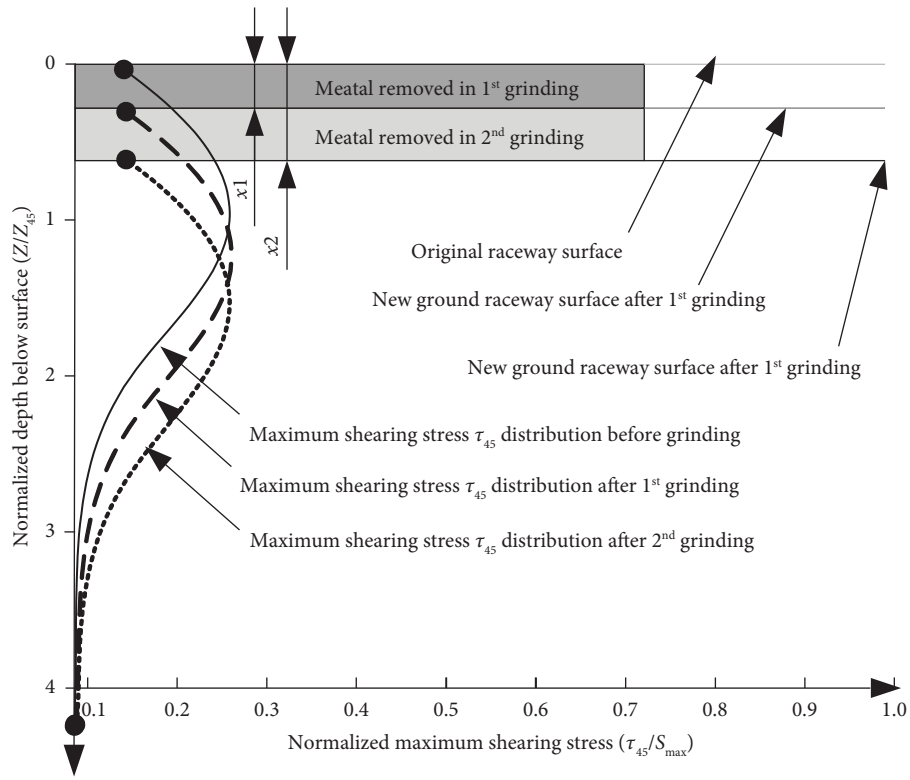


Figure 5: Schematic of normalized maximum shearing stress τ_{45} as a function of normalized depth below the raceway surface showing the effect of metal removal in redistributing stress.

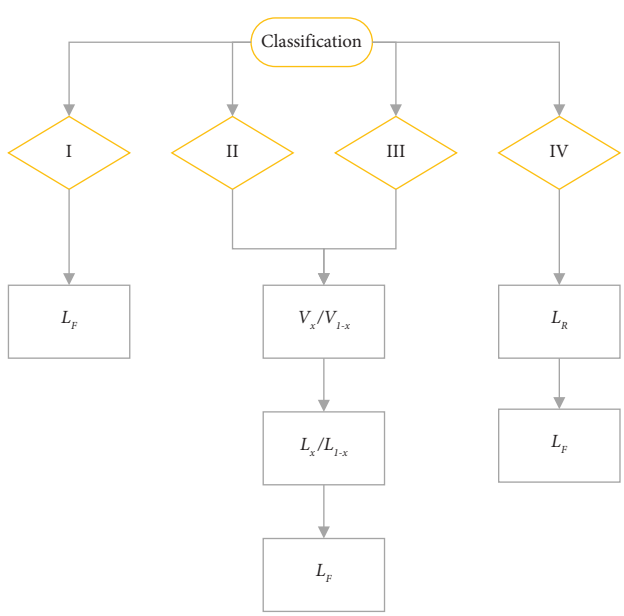


Figure 6: Life factor calculation process.

the coincidence between the theoretical life and the actual life of the bearing.

5. Case Studies

The analysis in this paper is a theoretical research of fatigue life for remanufactured bearings. The fatigue life of rolling bearings is a statistical problem, so it is difficult to verify the research results of this study by using experimental methods. Therefore, the following selected cases are calculated theoretically and compared with the results of previous calculation methods to verify the results.

5.1. Life Factors of Different Remanufacturing Levels. Assuming that there are 1000 sets of bearings of various types, the life of the inner ring L_{10i} is 1400 hours and that of the outer ring L_{10o} is 3000 hours; the fatigue life of the bearing systems can be calculated by the Lundberg–Palmgren equation [23], and it is equal to 1,000 hours. Assuming that the bearing works well, 10% of the bearings (100 sets) will fail after 1,000 hours according to the definition of fatigue life.

900 of the 1000 sets of bearings that have not failed can be remanufactured. Depending on the conditions of the bearings after application, it is possible to remanufacture the bearings in level I, II, III, or IV. The life factor is calculated according to different remanufacturing levels as shown in the following section.

5.1.1. Life Factor of Level I Remanufactured Bearings. If the bearing is remanufactured at level II, the fatigue life of the rotating ring can be obtained by equation (6) and the fatigue life of the bearing system can be obtained by equation (13). When the inner and outer rings are fixed rings, respectively, the life factor of the remanufactured bearing by level I is

calculated by using equation (14) and the results are listed in equation (15).

$$\begin{cases} LF_{\mathrm{I}-Rvi} = 0.92, \\ LF_{\mathrm{I}-Rvo} = 0.96. \end{cases} \tag{15}$$

In equation (15), the subscript I means level I remanufacturing, the subscript *Rvi* means the fixed outer ring and rotated inner ring, and *Rvo* means the fixed inner ring and rotated outer ring.

5.1.2. Life Factor of Level II Remanufactured Bearings. Assuming that the bearing needs to be remanufactured of level II, part of the metal on the raceway is removed. Each of the stressed volumes contributed to the life which can be obtained by equation (9). For the convenience of subsequent comparison, the material removal rate of the following calculation is 5% as in the literature [23].

Assuming that the inner ring is a rotating ring, then

$$\begin{cases} L_{xvi} = 20751 \quad \text{(h)}, \\ L_{(1-x)vi} = 1349 \quad \text{(h)}. \end{cases} \tag{16}$$

In equation (16), the subscript *xvi* means the unstressed volume of the rotated inner ring and the subscript $(1-x)$ *vi* means stressed volume of the rotated inner ring.

The life of the inner ring is derived from equation (11) as follows:

$$L_{vi} = 1283 \text{ (h)}. \tag{17}$$

In equation (17), the subscript *vi* means the rotated inner ring and the fixed outer ring.

When the inner ring is a rotating ring, the life of the bearing can be obtained from equation (13) as follows:

$$\begin{aligned} L_{\mathrm{II}-Rvi} &= \left(\frac{1}{L_{\mu}^{1.11}} + \frac{1}{L_{vi}^{1.11}} \right)^{-0.9} \\ &= 947 \text{ (h)}. \end{aligned} \tag{18}$$

In (18), the subscript II means level II remanufacturing and the subscript *Rvi* means the fixed outer ring and the rotated inner ring.

Similarly, when the outer ring is a rotating ring, the life of the bearing can be obtained from equation (13) as well, as follows:

$$\begin{aligned} L_{\mathrm{II-Rvo}} &= \left(\frac{1}{L_{\mu}^{1.11}} + \frac{1}{L_{vo}^{1.11}} \right)^{-0.9} \\ &= 991 \text{ (h)}. \end{aligned} \tag{19}$$

In equation (19), the subscript *Rvo* means the fixed inner ring and the rotated outer ring.

Then, the life factor of the remanufactured bearing by level II is calculated as follows:

$$\begin{cases} LF_{\mathrm{II}-Rvi} = 0.947, \\ LF_{\mathrm{II}-Rvo} = 0.991. \end{cases} \tag{20}$$

5.1.3. Life Factor of Level III Remanufactured Bearings. Calculation procedure for level III remanufacturing is the same as level II, but the material removal rate of level III is more than that of level II. For the convenience of subsequent comparison, the material removal rate of the following calculation is chosen 20% as the same in reference [17]. Then, the life factor of the remanufactured bearing by level III is calculated as follows:

$$\begin{cases} LF_{\mathrm{III}-Rvi} = 0.993, \\ LF_{\mathrm{III}-Rvo} = 0.995. \end{cases} \tag{21}$$

In equation (21), the subscript III means level III remanufacturing.

5.1.4. Life Factor of Level IV Remanufactured Bearings. The life factor of the remanufactured bearing by level IV is calculated as follows:

$$\begin{cases} LF_{\mathrm{IV}-Rvi} = 0.993, \\ LF_{\mathrm{IV}-Rvo} = 1. \end{cases} \tag{22}$$

In equation (22), the subscript IV means level IV remanufacturing.

The bearing life is assumed reasonably and the life factor is calculated by the method proposed in this paper. It is found that the bearing life factor increases with the increase of the remanufacturing level and gradually approaches 1. This is because both the removal of stressed materials and the replacement of new parts have a positive impact on bearing life. At the same remanufacturing level, the life factor when the inner ring is a fixed ring is greater than that when the inner ring is a rotating ring.

5.2. Comparison with Endurance Data of Different Bearings. Harris analyzed endurance data of 7935 bearings in reference [26]. The data are from 2 helicopter manufacturers, 3 aircraft engine manufacturers, and the U.S. Government agency-sponsored technical reports [27]. The data comprised deep-groove radial ball bearings, angular-contact ball bearings, and cylindrical roller bearings of 62 rolling bearing sets. These data are plotted in Figure 6 using the number of bearings failed rather than the number of bearings in a set. Vlcek et al. [28] established a simple algebraic relation for the upper and lower L_{10} life limits considering the number of bearings failed and the limits are also plotted in Figure 7.

The actual life of most bearings is much greater than the upper L_{10} life as can be seen in Figure 7. 47 sets of bearings would result in lives that would statistically be no different than that of new bearings if subject to levels I–III rework. The 4 sets of deep-groove ball bearings in the border can be subject to level IV rework to bring them into an acceptable range. Also, the life factors with the replaced loading zone are listed in Table 3. The data in Table 3 show that the life factors of remanufactured bearing which subject to levels II–IV rework will be near 1 if we replace the loading zone in application.

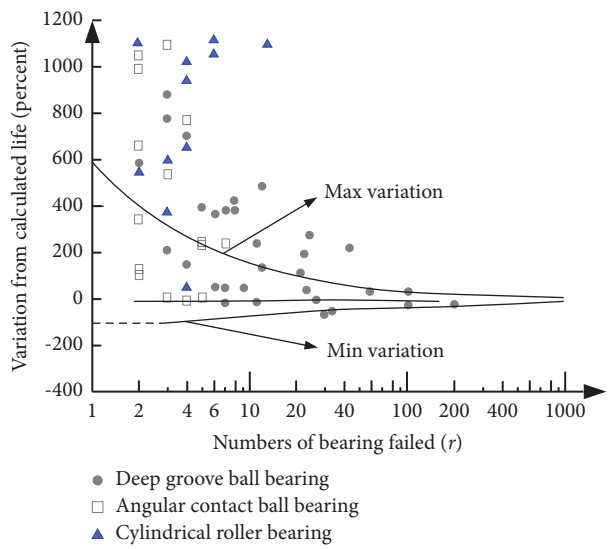


Figure 7: Variation between actual and calculated L_{10} for 62 sets (7935 pieces) bearings [15].

Table 3: Life factors of different remanufactured bearings.

Bearing type			Remanufacturing level			
			I	II	III	IV
Life factor L_F	Deep-grove ball bearing	Fixed inner ring (*vo*)	0.92	0.95~0.99	>0.99	>0.99
		Fixed outer ring (*vi*)	0.96	>0.99	>0.99	1
	Angular-contact ball bearing	Fixed inner ring (*vo*)	0.92	0.97~0.99	>0.99	>0.99
		Fixed outer ring (*vi*)	0.96	>0.99	>0.99	1
	Cylindrical roller bearing	Fixed inner ring (*vo*)	0.92	0.95~0.99	>0.99	>0.99
		Fixed outer ring (*vi*)	0.96	>0.99	>0.99	1

The resultant L_{10} life should fall between the maximum and minimum values if the rework life is no different from the calculated life. If, however, the L_{10} life is greater than the maximum variation L_{10} life, then the true life is probably greater than the calculated. However, it can be found from Figure 7 that the actual L_{10} of a large number of bearings is greater than the theoretical maximum L_{10}. This indicates that the life of the bearing after remanufacturing may be greater than the theoretical life because the loading zone needs to be replaced when the bearing is reinstalled after remanufacturing.

6. Results and Discussion

The life factors of remanufactured bearings whether the loading zone is replaced or not are shown in Figure 8. The life factors according to different calculating methods and different fixed rings can be seen in Figure 8(a). The life factors of the bearings without replacement of the loading zone are from reference [17], while the life factors' replacement of the loading zone is from this paper. The deviation between the calculation method proposed in this paper and the active calculation method can be seen in Figure 8(b). According to the data comparison in the figure, the following results are obtained:

(1) With the increase of the remanufacturing level, the life factor of remanufacturing improves step by step regardless of whether the loading zone is replaced or not. This growth trend is determined by the classification method of remanufacturing. The higher the remanufacturing level, the more stressed materials removed and the more new parts replaced, which has a positive impact on bearing life.

(2) Regardless of whether the fixed ring is the inner ring or the outer ring, the bearing life factor after considering the replacement of the loading zone is higher than that obtained by the active calculation method. This is because after remanufacturing, the loading area needs to be replaced and the fixed ring is not stressed at this time, so its life should be the same as the life of the new ring. This is the most critical part of this paper and also the core theoretical content that is different from the existing research results. Considering that the bearing fatigue life after changing the loading zone is closer to the actual situation, the life factor calculation method proposed in this paper is better than the active calculation method.

(3) The life factors of remanufactured bearings with different fixed rings are also quite different when the loading zone is replaced. The cause of this difference lies in the difference of the coincidence degree between the rings and the rolling element as analyzed in part 3.2.

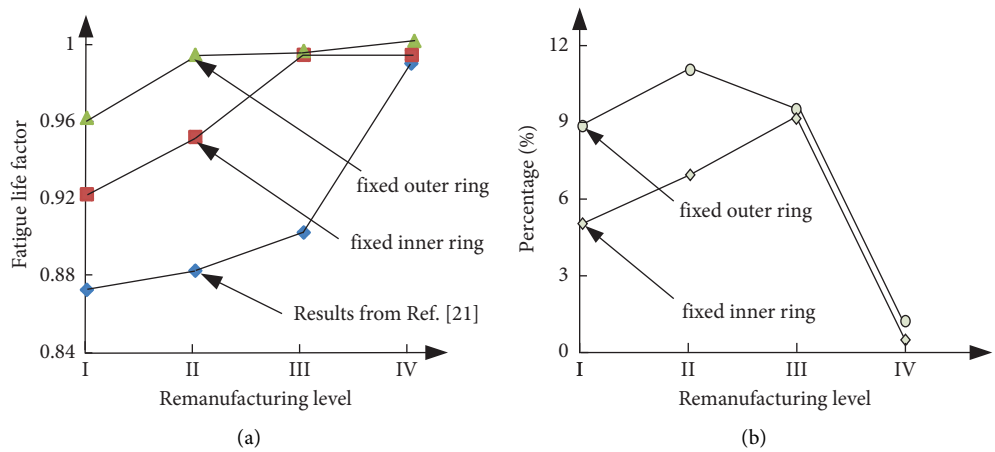


Figure 8: Comparison of life factors. (a) Different life factors according to different methods. (b) Deviation of life factors of different fixed rings.

(4) The deviations between the life factors obtained by different calculation methods are volatile. As can be seen in Figure 8(b), the biggest deviation in case studies is level II remanufacturing with the fixed outer ring, which is 11.3%. The smallest deviation in case studies is level IV remanufacturing with fixed inner rings, which is 0.3%. The mean deviation of various remanufacturing levels is 6.55%. This is the result of the combined effect of the remanufacturing level and the coincidence degree.

(5) For level I and II remanufactured bearings, whether to consider replacing the loading zone has a great impact on the bearing life, but for level III and IV remanufactured bearings, whether to consider replacing the loading zone has almost no impact on the bearing life because a large number of stress materials are removed, which has a positive impact on the bearing life.

7. Conclusion

(1) The research object of this paper is radial bearing. For thrust bearings or thrust-radial bearings, the whole circumferential direction of both fixed and rotating rings is the loading zone, so the results of this paper are not applicable.

(2) In this paper, the life of inner and outer raceways of bearings is assumed, and the life of the bearing system is calculated through this assumed life; thus, the life coefficient of remanufactured bearings is obtained.

(3) Radial bearings are widely used in various rotating machinery, but there is a lack of research on the life of remanufactured bearings by replacing the loading zone, which leads to a huge deviation between the actual life and the theoretical life, which is not conducive to the application of bearings in engineering practice. The research results of this paper are a supplement to the active calculation method of bearing life and can reduce the deviation between the actual life and the theoretical life of the bearing. The research results of this paper are a supplement to the active calculation method of bearing life and can reduce the deviation between the actual life and the theoretical life of the bearing.

7.1. Recommendations and Future Directions

(1) Reference 14, reference 21, and this paper all calculate the bearing life factor by assuming the bearing life and metal removal rate, which lacks test verification. However, bearing life is a complicated statistical problem, and bearing researchers should verify their conclusions through experiments as much as possible. The life curves of remanufactured bearings considering the replacement of load zones also need to be supplemented by life tests to facilitate practical engineering applications.

(2) Raceway fatigue of rolling bearings (especially industrial bearings under heavy load conditions) is an unavoidable problem in its application practice, and it is also the root problem that causes the big difference between bearing remanufacturing and general remanufacturing. For heavy and large bearings, the material that needs to withstand the alternating periodic stress only accounts for a small part of the whole bearing material; if the raceway is separated from the bearing as a whole, it provides great convenience for the bearing remanufacturing.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Acknowledgments

This work was supported by the Doctoral Foundation of Henan University of Science and Technology (grant no.: 13480075).

References

[1] L. Chen, *State and Review of Remanufacturing Industry on Rolling Bearing*, Bearing, 2019.

[2] D. C. Stanley, "Bearing field inspection and refurbishing," *Symposium on propulsion system structural integration and engine integrity*, Naval Post Graduate School, Monterrey, Mexico, 1974.

[3] H. Hanau, R. J. Parker, and E. V. Zaretsky, "Bearing restoration by grinding[R]. U.S. Army Aviation Systems Command," 1976, https://apps.dtic.mil/sti/tr/pdf/ADA025420.pdf.

[4] R. J. Parker, E. V. Zaretsky, and S. M. Chen, *Evaluation of ball and Roller Bearings Restored by Grinding*, Glenn research center, Cleveland, OH, USA, 1976.

[5] P. Franck, "Remanufacturing bearings," *SKF Evolution*, vol. 03, no. 3, pp. 3–5, 2018.

[6] S. Heike, "The benefits of remanufacturing rolling bearings," *SKF Evolution*, vol. 03, no. 3, pp. 5–9, 2012.

[7] Skf, "Aircraft engine service [N/OL]," 2018, http://www.skf.com/cn/zh/industry-solutions/aerospace/services/aeroengine-services/index.html.

[8] Schaeffler, "Repair and Recondition of rolling bearings," *Schaeffler Technologies, TPI*, vol. 207, no. 2, pp. 8–12, 2017.

[9] Schaeffler, "Repair, diagnosis & training of aerospace bearing," 2018, https://www.schaeffler.com.au/content.schaeffler.au/en/products-and-solutions/industrial/industry_solutions/aerospace/refurbish-ment/index.jsp.

[10] J. Alexander, *Using Bearing Repair to Extend Bearing Life: For Heavy Industries*, TIMKEN Bearing Repair For Heavy Industries Technical White Paper, New York, NY, USA, 2016.

[11] J. Alexander, *A Case for Bearing Repair: Bearing Repair Provides a Valuable Alternative to Replacement for Aggregates Producers*, TIMKEN Bearing Repair Technical White Paper, New York, NY, USA, 2012.

[12] Timken, "Leaders in aerospace bearing services," 2008, https://www.bearinginspectioninc.com.

[13] L. Chen, X. T. Xia, H. T. Zheng, and M. Qiu, "Rework solution method on large size radial roller bearings," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 38, no. 4, pp. 1249–1260, 2016.

[14] J. J. Coy, E. V. Zaretsky, and G. R. Cowgill, *Fatigue Life Analysis of Restored and Refurbished bearings*, Glenn research center, Cleveland, OH, USA, 1977.

[15] E. V. Zaretsky, *Effects of surface removal on rolling-element fatigue*, Glenn research center, Cleveland, OH, USA, 1987.

[16] E. V. Zaretsky and E. V. Branzai, "Rolling-bearing service life based on probable cause for removal – a tutorial," *Society of Tribologists and Lubrication Engineers Annual Meeting and Exhibition*, vol. 02, no. 2, pp. 739–744, 2014.

[17] E. V. Zaretsky and E. V. Branzai, *Effect of Rolling Bearing Refurbishment and Restoration on Bearing Life and reliability*, Glenn research center, Cleveland, OH, USA, 2005.

[18] G. Zamzam, S. Farshid, and W. Aditya, "Experimental and analytical investigation of effects of refurbishing on rolling contact fatigue," *Wear*, no. 393, pp. 190–201, 2017.

[19] R. E. Matthew, "Repair as an option to extend bearing life and performance [EB/OL]," *SAE Technical Paper*, vol. 01, 2007.

[20] S. Darisuren, A. Amanov, and J. Kim, "Remanufacturing process and improvement in fatigue life of spherical roller bearings," *Journal of the Korean Society of Tribologists and Lubrication Engineers*, vol. 30, no. 30, pp. 350–355, 2014.

[21] T. Coors, M. Y. Faqiri, and F. Saure, "Wear of tailored forming steels," *Advanced Engineering Materials*, vol. 25, 2023.

[22] T. A. Harris, *Rolling Bearing Analysis*, CRC Press Inc, New York, NY, USA, 2006.

[23] G. Lundberg and A. Palmgren, "Dynamic capacity of rolling bearings," *Journal of Applied Mechanics*, vol. 7, no. 3, 1947.

[24] J. Chalsma and E. V. Zaretsky, "Design for life, plan for death," *Machine Design*, vol. 66, no. 66, pp. 55–59, 1994.

[25] W. Weibull, *A Statistical Theory of the Strength of Materials*, Generalstabens Litografiska Anstalts Förlag, Stockholm, Europe, 1939.

[26] T. A. Harris and J. I. Mccool, "On accuracy of rolling bearing fatigue life prediction," *ASME Journal of Tribology*, vol. 118, no. 2, pp. 297–310, 1966.

[27] E. V. Zaretsky and E. V. Branzai, *Model Specification for Rework of Aircraft Engine, Poser Transmission, and Accessory/auxiliary ball and Roller Bearings*, Glenn research center, Cleveland, OH, USA, 2007.

[28] B. L. Vlcek, R. C. Hendricks, and E. V. Zaretsky, "Determination of rolling-element fatigue life from computer generated bearing tests," *Tribology Transactions*, vol. 46, no. 4, pp. 479–493, 2003.