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Resonance Reliability Analysis for Axle Box Bearing of EMU

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Abstract

In order to study the influence of design variables on the resonance reliability of axle box bearings of electric multiple units (EMU), two methods of resonance reliability analysis of axle box bearings are proposed based on fuzzy reliability and probabilistic reliability. The randomness of the elastic modulus, Poisson's ratio, density, and speed of axle box bearings and the fuzziness of the resonance criteria are considered. The fuzzy reliability theory is introduced to analyze the resonance reliability of axle box bearings, and the resonance reliability equation is deduced and combined with the theoretical analysis of bearing vibration. Then, the resonance reliability of axle box bearings based on fuzzy theory is obtained. Based on this, the axle box bearing of EMU is parameterized by APDL language. The resonance reliability analysis of axle box bearings is carried out by using the Monte Carlo simulation (MCS) method based on the frequency interference model. The results show that the discreteness of the design variable and speed of axle box bearings have a negative influence on the resonance reliability of bearings, greatly increase the probability of resonance, and reduce the reliability of bearings. By comparing the results of resonance reliability analysis obtained by the probabilistic design method, the accuracy and practicability of the resonance fuzzy reliability analysis are verified, which provides a theoretical reference for the anti-resonance design of axle box bearings.

Keywords: axle box bearings; resonance reliability; fuzzy reliability; frequency interference; probability design

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1. Introduction

As the core functional component of the moving part of the EMU, the vibration of axle box bearings during their operation has an important influence on the running stability, safety, and carrying capacity of the train [1]. Practice has shown that with an increase in the EMU speed, the fatigue failure of the axle box bearing is becoming more and more prominent. Bearing fatigue failure caused by forced vibration is one of the most common sense for the fatigue failure [2]. Therefore, avoiding forced resonance as much as possible and improving the reliability of bearings during their operation in the axle box bearing design stage are key to ensuring the safe operation of trains.

Resonance is a form of vibration that is related to structure and material properties and cannot be completely avoided. Thus, many scholars have studied the vibration of bearings [3-5], and the research results lay a theoretical foundation for bearing fatigue strength analysis. However, the design parameters of the bearing have a certain degree of dispersion, and the resonance criterion has a certain degree of ambiguity, which makes it difficult for the traditional deterministic strength design to meet the reliability and safety of the axle box bearing fatigue strength design [6]. For that reason, the application of fuzzy reliability theory to the vibration reliability analysis of axle box bearings is of practical significance for improving the fatigue life of bearings. In order to improve the vibration reliability of mechanical parts, Bergman [7] considered the influence of random parameters on the reliability of linear vibration systems based on mechanical reliability research and promoted the development of reliability theory of dynamic random structures. Spencer [8] studied the reliability analysis of non-linear vibration systems considering random parameters, on the basis of the reliability analysis of stochastic non-linear single-degree-of-freedom systems. Shi [9] proposed the reliability design method of mechanical part vibration considering the discreteness of vibration design variables, based on the traditional vibration design method. For years, after an in-depth theoretical research and analysis by researchers, some vibration reliability models have been established and widely used in mechanical systems. With the deepening research on fuzzy reliability, in order to more accurately evaluate the vibration characteristics of mechanical parts, some scholars have introduced fuzzy reliability theory into the reliability design of mechanical vibration. Zhang [10] established the reliability model of blade anti-resonance and introduced the probability distribution of cut sets to make up for the shortcomings of common distribution. The influence of the natural frequency blur degree on the anti-resonance reliability of the blade was obtained. Song [11] used the fuzzy reliability theory to analyze the longitudinal resonance reliability of remanufactured sucker rods. The rationality of the method was verified by comparing experimental and numerical results. Wang [12] carried out the sensitivity analysis of resonance reliability on gears under thermal analysis and obtained the influence degree of each random variable on the natural frequency of the gear, which led to a new idea of gear reliability analysis.

The works mentioned above mostly use a single method to analyze the resonance reliability of mechanical parts and fail to explain the accuracy and practicability of the method. Because there are few studies on the reliability of bearing resonance, this paper takes the EMU axle box bearing as the research object and considers the randomness of bearing design variables and the ambiguity of the resonance criterion comprehensively. Based on the theory of fuzzy reliability and vibration analysis for bearing structures, the equation for calculating the resonance fuzzy reliability of axle box bearings is derived. The influence of the coefficient of variation and the rotational speed on the fuzzy reliability of the bearing resonance is analyzed. At the same time, the MCS method is used to analyze the resonance reliability of the axle box bearing based on the frequency interference model and obtain the resonance reliability of the axle box bearing. By comparing the two resonance reliability analysis methods, it is verified that the fuzzy reliability analysis results are more in line with the actual situation, providing a theoretical reference for the reasonable structural design of axle box bearings.

2. Resonance Reliability Model of Bearing based on Fuzzy Theory

2.1. Vibration Analysis Theory of Bearing Structure

The vibration of EMU axle box bearings may be caused by external excitation, such as irregular tracks, non-circular wheels, and flat wheels, or it may be caused by their own structure and failure [13]. The main type of axle box bearing is the double row tapered roller bearing. The main vibration mode of this kind of bearing is radial bending vibration, as shown in Figure 1. Since the outer ring of the axle box bearing is in clearance fit with the box chamber and the inner ring moves with the axle, any excitation force of the bearing from the wheel can result in vibration of the natural frequency of the outer ring. The inner ring and axle have an interference fit. The higher the natural vibration frequency, the smaller the vibration. Therefore, it is very important to study the vibration characteristics of the outer ring of axle box bearings for analyzing the vibration characteristics of bearings. The bending moment on any section of the ferrule can be expressed as [14-15].

$$M = \frac{EI}{r^2}\left(\frac{\partial^2 u}{\partial \theta^2} + u\right) \tag{1}$$

Where E is the elastic modulus of the material, I is the moment of inertia of the ferrule cross section, r is the radius of the neutral axis of the ferrule cross section, u is the radial displacement, and θ is the position angle of the determined point on the centerline.

According to Equation (1), the bending potential of the ferrule is given by

$$V = \frac{EI}{2r^4}\int_0^{2\pi}\left(\frac{\partial^2 u}{\partial \theta^2} + u\right)^2 r\mathrm{d}\theta \tag{2}$$

$$\begin{aligned} &\int_0^{2\pi}\cos m\theta \sin m\theta \mathrm{d}\theta = 0 \\ &\int_0^{2\pi}\cos^2 m\theta \mathrm{d}\theta = \int_0^{2\pi}\sin^2 m\theta \mathrm{d}\theta = \pi \end{aligned} \tag{3}$$

The potential energy of the vibration ferrule can be obtained by combining Equations (2) and (3).

$$V = \frac{EI\pi}{2r^3}\sum_{i=1}^{\infty}\left(1-i^2\right)\left(a_i^{\,2}+b_i^{\,2}\right) \tag{4}$$

The kinetic energy of the vibration ferrule can be obtained by

$$T=\frac{A\rho}{2g}\int_0^{2\pi}\left(\dot{u}^2+\dot{v}^2\right)r\mathrm{d}\theta \tag{5}$$

$$\begin{aligned}u&=a_1\cos\theta+a_2\cos 2\theta+\cdots+b_1\sin\theta+b_2\sin 2\theta+\cdots\\ v&=a_1\sin\theta+\tfrac{1}{2}a_2\sin 2\theta+\cdots-b_1\cos\theta-\tfrac{1}{2}b_2\sin 2\theta-\cdots\end{aligned} \tag{6}$$

$$T=\frac{\pi rA\rho}{2g}\sum_{i=1}^{\infty}\left(1+\frac{1}{i^2}\right)\left(\dot{a}_i^{\,2}+\dot{b}_i^{\,2}\right) \tag{7}$$

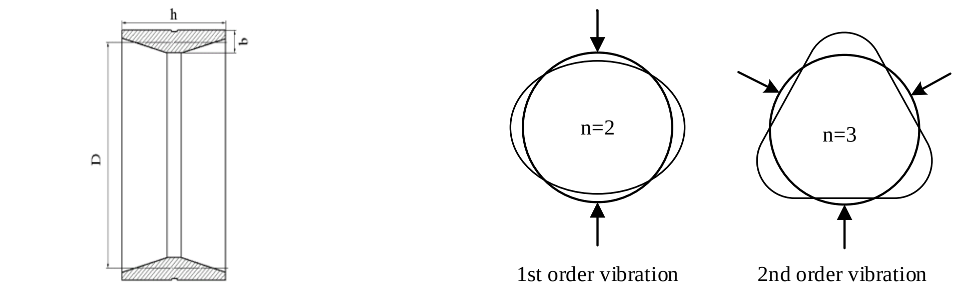
The equation of arbitrary vibration models is obtained using Equations (4) and (7).

$$\frac{\pi rA\rho}{g}\left(1+\frac{1}{i^2}\right)\ddot{a}_i+\frac{EI\pi}{r^3}\left(1-i^2\right)a_i^2=0 \tag{8}$$

The radial bending natural frequency of the axle box ferrule bearing in state free can be provided by

$$f_R=\frac{i(i^2-1)}{2\pi(D/2)^2\sqrt{i^2+1}}\sqrt{\frac{EIg}{\rho A}} \tag{9}$$

Where i is the order of resonance, D is the diameter of the neutral axis of the ferrule cross section, E is the elastic modulus of the material, I is the moment of inertia of the ferrule cross section, g is the gravity, ρ is the density of the material, and A is the longitudinal cross-sectional area of the ferrule.



(a) Cross section for axle box bearing (b) Radial bending vibration for axle box bearing

Figure 1. Cross section for axle box bearing and schematic diagram of radial bending vibration

The natural frequency of the EMU axle box bearing ferrule in state free can be calculated by Equation (9), and its natural vibration frequency is high frequency vibration, generally from thousands to ten thousands of Hertz.

2.2. Establishment of Bearing Resonance Reliability Model

For mechanical systems, resonance will occur when the external excitation frequency is equal to the natural frequency or the ratio of the two systems is λ = 1. However, in practice, the ideal resonance situation is difficult to achieve. In the conventional mechanical vibration reliability design, $f_m\in[0.95\varpi_n,1.05\varpi_n]$ is generally taken as the resonance criterion, that is, when the natural frequency is within the region where f_m is located, it is considered that resonance occurs. Otherwise, it is non-resonance, ignoring the transition state between resonance and non-resonance.

Fuzzy vibration reliability design is based on conventional reliability design. It considers the randomness of design variables and the fuzziness of resonance criteria comprehensively. It regards natural frequencies within the region of f_m as resonance generated by a certain probability, and resonance that is beyond that region is generated by a certain probability. In order to better conform to engineering practice and people's way of thinking, a membership function is introduced to accurately describe this probability. The membership function should have the following characteristics: (1) interpenetration of resonance and non-resonance; (2) in the resonance region where $f_m = \omega_n$, the degree of membership is 1 or $g(f_m) = 1$. In the resonance region where $f_m = (1 \pm 0.05)\omega_n$, the fuzziness is the greatest and the membership degree is 0.5. According to the above characteristics of membership degree, the intermediate normal membership function is selected as the membership function $g(f_m)$, as detailed in Figure 2. This function can better reflect the transition state from resonance to non-resonance.

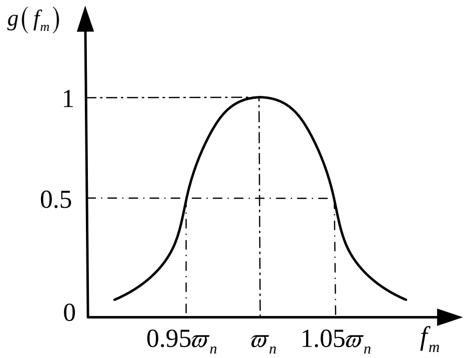


Figure 2. Intermediate normal membership function

The membership function can be expressed as

$$g(f_m) = \exp\left[-\left(\frac{f_m - \varpi_n}{\sigma}\right)^2\right],\ \sigma^2 = a\varpi_n / \sqrt{-\ln 0.5} \tag{10}$$

Where ϖ_n is the mean value of the excitation frequency and a is a constant, taken as a = 0.05.

The resonance reliability of axle box bearings is the probability that resonance does not occur during the operation of bearings. Assume that the natural frequencies of bearings obey the normal distribution: $f_m \sim N(\mu, \sigma)$, and its probability density distribution function is listed by

$$h(f_m) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left[-\frac{(f_m - \mu)^2}{\sigma^2}\right] \tag{11}$$

According to the probability equation of the fuzzy event, the fuzzy failure probability of the axle box bearing resonance can be expressed as

$$\tilde{P} = \int_{-\infty}^{+\infty} f(\omega_n)\int_{-\infty}^{+\infty} g(f_m)h(f_m)\mathrm{d}f_m\mathrm{d}\omega_n \tag{12}$$

$$\tilde{P} = \int_{-\infty}^{+\infty} g(f_m)h(f_m)\mathrm{d}f_m \tag{13}$$

The fuzzy resonance reliability of the axle box bearing is obtained by

$$\tilde{R} = 1 - \tilde{P} \tag{14}$$

3. Resonance Reliability Model of Bearing based on Fuzzy Theory

Taking the axle box bearing of EMU as the research object, the bearing is a type of sealed double-row tapered roller bearing, and its random variables obey the normal distribution. The diameter of the bearing outer ring is D_1 = 230mm, the width is B = 120mm, the diameter of the section is D_2 = 207.5mm, the elastic modulus is E = 207MPa, Poisson's ratio is μ = 0.3, and the density is $\rho = 7.83\times10^{-9}$ t/mm^2. The bearing speed is v = 3000r/min and obeys the normal distribution.

The resonance fuzzy reliability of an axle box bearing that is 0.999955 can be calculated by using the method mentioned above. Axle box bearings are precision components with less discrete design variables. For the convenience of research, the coefficient of variation is 0-0.7. Figure 3 displays the relationship between the fuzzy reliability R and variation coefficient δ.

It is seen from Figure 3 that when the membership degree is constant, the fuzzy reliability of bearings decreases with an increase in the variation coefficient. When the variation coefficient is between 0 and 0.2, the decrease in fuzzy reliability is small. The fuzzy reliability decreases greatly when the variation coefficient δ is between 0.2 and 0.5. When the variation coefficient is between 0.6 and 0.7, the decrease in fuzzy reliability tends to be flat. When the variation coefficient δ is equal to 0.7, the fuzzy reliability value is the smallest, about 0.99725.

Figure 4 shows the relationship between the fuzzy reliability R and the bearing speed v. As evident from Figure 4, the fuzzy reliability is higher when the bearing speed is less than 2500r/min, but it decreases with an increase in the bearing speed. This shows that when the speed of the bearing increases, the external excitation will increase and the excitation frequency will fall within the resonance region more easily.

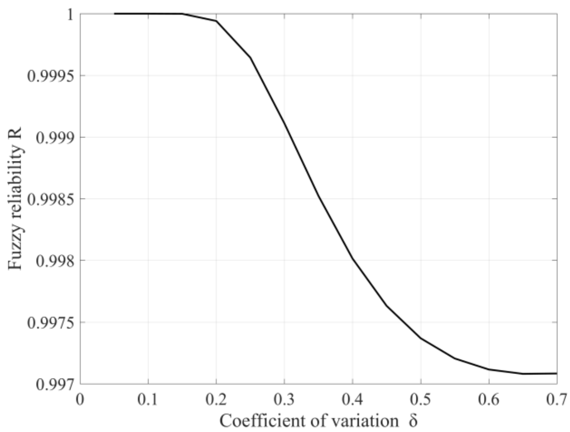


Figure 3. The relationship between fuzzy reliability and variation coefficient

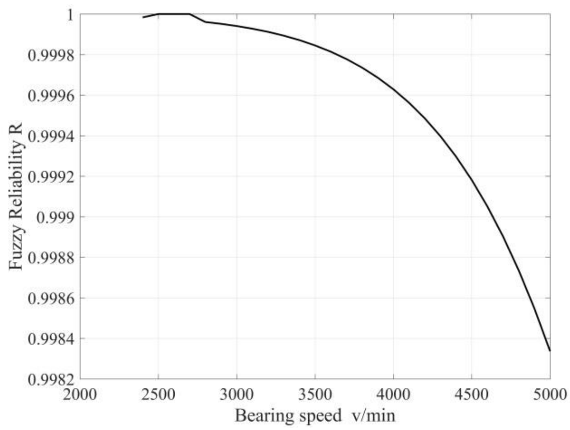


Figure 4. The relationship between fuzzy reliability and bearing speed

The value of fuzzy resonance reliability of bearings is higher according to the results of fuzzy reliability analysis of EMU axle box bearings, which indicates that the probability of resonance of the axle box bearing during its operation is relatively low. This is consistent with the characteristics of the bearing as a high-precision component. However, the discreteness of the random variables of the bearing has a certain influence on the resonance reliability, which indicates that improving the manufacturing process level of the bearing has a good promotion effect on reducing the occurrence of bearing resonance. As the bearing speed increases, the probability of the bearing resonance increases, indicating that when improving the operating speed of the EMU, attention should be paid to the resonance of the bearing.

4. Probability-based Resonance Reliability Model of Bearing

4.1. Basic Principles of Resonance Reliability Analysis for Bearing

The reliability design of mechanical parts is based on the stress-intensity distribution interference theory. This theory is based on a stress-intensity distribution interference model that can clearly reveal the causes of mechanical part failures with a certain probability and the nature of mechanical strength reliability design [16-17]. Therefore, the resonance frequency interference model of the axle box bearing is established according to the stress-strength interference theory, as illustrated in Figure 5. Figure 5 visually reflects the possible failure areas of interference between two probability distribution curves.

The natural frequency expression of the axle box bearing is given by

$$f_i = \xi\left(x_1, x_2, \cdots, x_n\right),\ i = 1, 2, \cdots, m \tag{15}$$

Where x_1, x_2, $\cdots$, x_n are the number of design variables that affect the natural frequency of bearing and i is the i^{th} natural frequency of the bearing.

In order to accurately describe the closeness of the natural frequency and the excitation frequency, the limit state equation for the resonance frequency of the axle box bearing is established.

$$Z^* = |f_a - f_b| = \begin{cases} = 0, & \text{Failure state} \\ \neq 0, & \text{Reliable state} \end{cases} \tag{16}$$

Where f_a is the natural frequency that is closest to the excitation frequency and f_b is the excitation frequency of the axle box bearing.

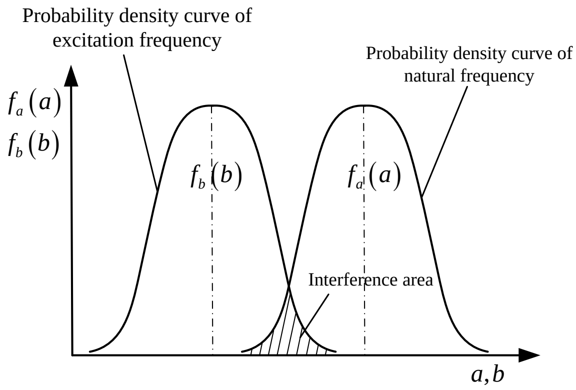


Figure 5. Schematic diagram of frequency interference model

The resonance reliability of axle box bearings is provided as follows:

$$Z = \frac{Z^*}{f_b} = \frac{|f_a - f_b|}{f_b} \tag{17}$$

Where $Z > 0.09$ is the reliability range of the bearing resonance.

4.2. Establishment of Finite Element Model and Modal Analysis

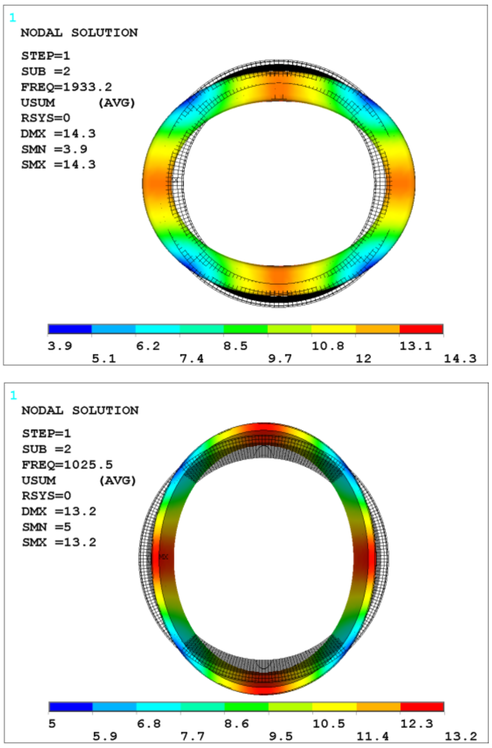
The APDL language is used to parametrically model the axle box bearing ferrule of the EMU. The element type is hexahedral SOLID185 element, the total number of elements is 89,798, and the total number of nodes is 108,128. The Block Lsnczos modal extraction method is used to extract the radial bending mode of the bearing ring from 1 to 4, as listed in Figure 6.

The natural frequency of the bearing outer ring is lower than that of the inner ring under the same mode of vibration according to the results of modal analysis. This is consistent with the theory of structural vibration analysis for bearings, so only the bearing outer ring is analyzed. To ensure the accuracy of the resonance reliability analysis results, the finite element model must be verified. The natural frequency of the bearing outer ring is calculated according to the theoretical Equation (9) of bearing vibration. Table 1 gives a comparison of the theoretical and numerical solutions of the natural frequency of the bearing outer ring.

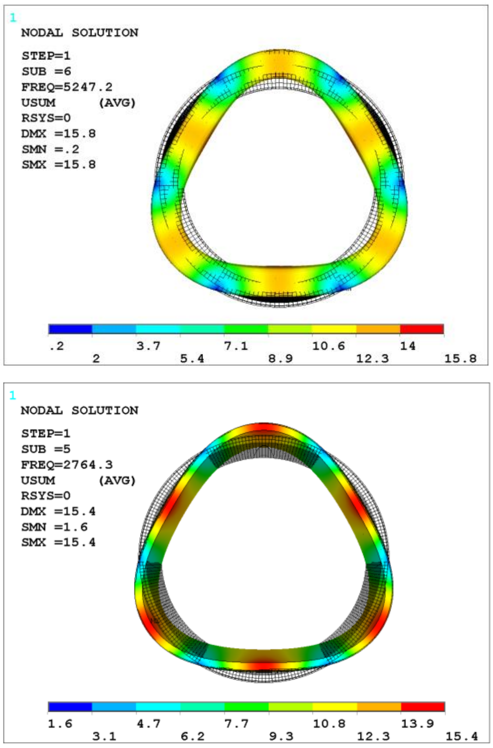
Since the bearing ferrule is simplified by the hexahedral solid element during its modeling, there is an error between the theoretical solution and the numerical solution. It can be seen from Table 1 that the relative error is small, and the model can be used for resonance reliability analysis.

Table 1. Comparison of natural frequencies of radial bending for bearing outer ring

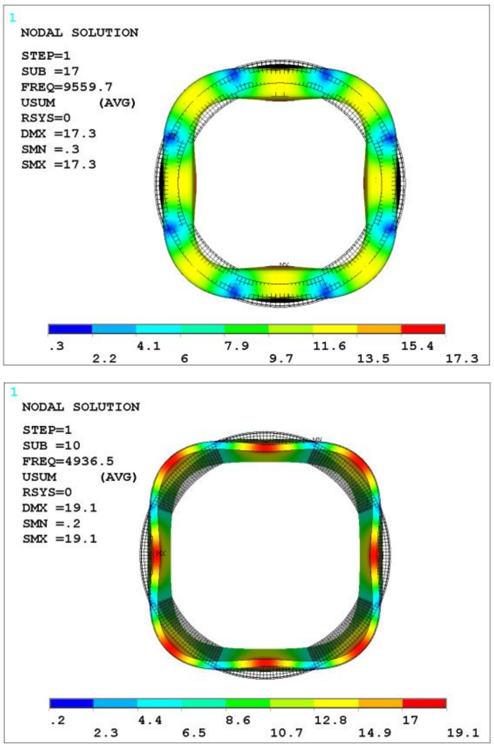
Order of resonance (n)	$n = 2$	$n = 3$	$n = 4$	$n = 5$
Theoretical solution (Hz)	996.2	2817.6	5085.5	7709.2
Numerical solution (Hz)	1025.5	2744.3	4934.5	7337
Error (%)	2.8	-2.6	-3.0	-4.8



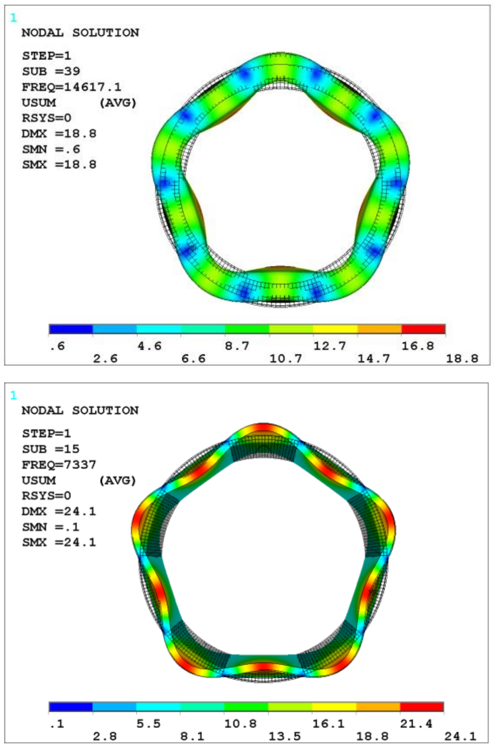
1st order radial bending



2nd order radial bending



3rd order radial bending



4th order radial bending

Figure 6. The mode of outer or inner ring for bearing

4.3. Resonance Reliability Analysis of Bearing

For the resonance fuzzy reliability analysis of axle box bearings, the probability distribution characteristics of $Z > 0.09$ are obtained under the condition of considering the randomness of each design parameter. Then, the influence of design parameters on the natural frequency for bearings is analyzed. Finally, the influence of randomness of design parameters on resonance reliability for bearings is evaluated. This paper only considers the influence of random variables, such as material properties and the speed of bearings, on its natural frequency or resonance reliability. The statistical characteristics of each random variable are shown in Table 2.

Monte-Carlo Latin hypercube sampling can avoid the overlap of sample points caused by repeated sampling, and the simulation accuracy will increase with the increase in simulation times, which is more accurate than the response surface method. The random variables in Table 2 were sampled 500 times, and the output variable is the mean value of *Z*.

Table 2. Random variables and distribution characteristics

Random variables	Symbol	Distribution type	Mean value	Standard deviation
Rotating speed (r/min)	N	GAUSS	3000	600
Poisson's ratio	NUXY	GAUSS	0.3	0.003
Elastic Modulus (MPa)	EX	GAUSS	207000	4140
Density (kg·m^{-3})	DENS	UNIFORM	7830	0

The historical curve of the mean value for resonance reliability can closely reflect the accuracy of simulation. If the historical curve of sampling tends to be stable, the number of sampling is sufficient to meet the requirements of simulation accuracy. It can be seen from Figure 7 that after 500 MCS, the mean value for the resonance reliability tends to be horizontal, and the bandwidth that satisfies the accuracy requirement is narrow. The longitudinal coordinate is 0.6930 when the curve tends to be horizontal, which shows that the resonance reliability of the axle box bearing at the 95% confidence level is Z = 0.6930 > 0.09, that is, within the reliability range defined by Equation (17). This indicates that the non-resonance reliability of the axle box bearing is 1.

As an important function in probability design, the cumulative distribution function represents the probability that the value of any point is below itself. Figure 8 shows the cumulative distribution function curve for resonance reliability.

As can be observed from Figure 8, the minimum value of the resonance reliability is 0.6904, and the probability value at this point is 0. This indicates that the probability of resonance occurrence is 0 when the resonance reliability is less than 0.6904, or the probability of resonance reliability is 0 when $Z \leq 0.09$. This indicates that the resonance reliability of the axle box bearing is 1 when $Z > 0.09$.

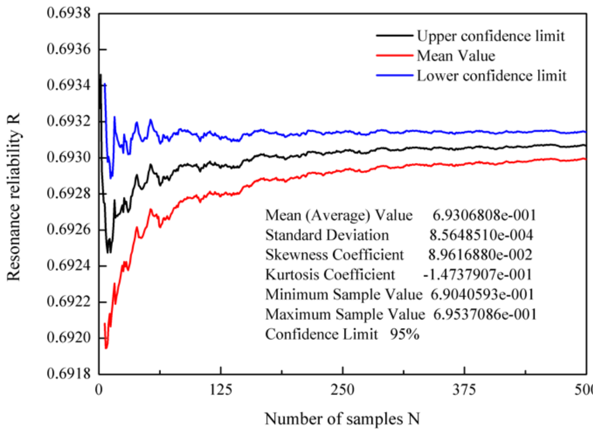


Figure 7. The mean history of resonance reliability

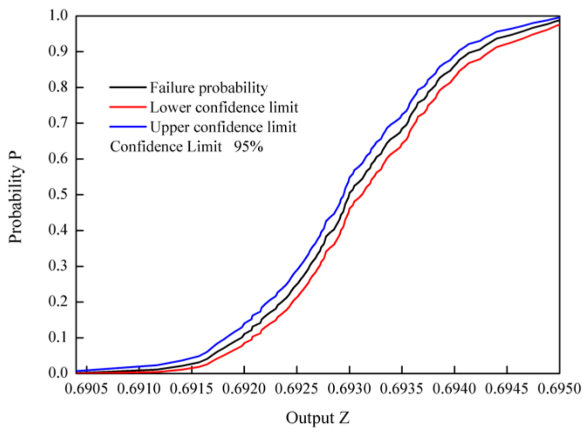


Figure 8. Cumulative distribution function of resonance reliability

Figure 9 presents the sample history of natural frequency fluctuations caused by random variable changes in axle box bearings.

It can be identified from Figure 9 that during the 500 simulations, each change in the random variable causes a change in the natural frequency. The square point in the figure indicates the value change in the natural frequency. The maximum natural frequency value is 1032 Hz, and the minimum natural frequency value is 1015Hz. It can be found that the variation of the random variable has a great influence on the natural frequency, which is possibly caused by the bearing resonates due to the randomness of the design variables, resulting in a decrease in bearing reliability.

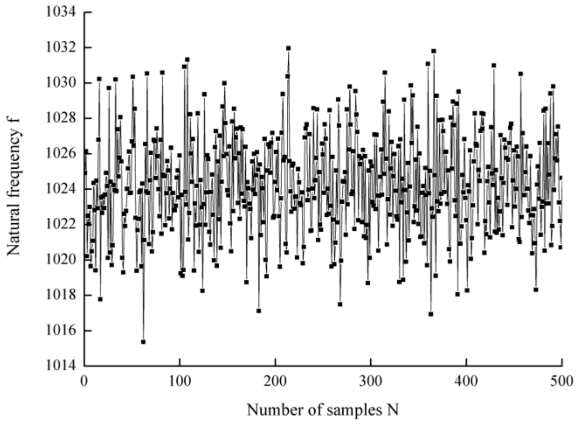


Figure 9. Sample history of natural frequencies

In summary, both methods can predict the resonance reliability of the axle box bearing, but the results of the fuzzy resonance reliability calculating method are more conservative. This is because the fuzziness of the resonance criterion is considered, which is safer and closer to the actual axle box bearing operation compared with the calculation results based on the frequency interference model.

5. Conclusions

In this paper, two different calculation methods are used to evaluate the resonance reliability of axle box bearings. The following conclusions can be obtained:

(1) By calculating the fuzzy resonance reliability of axle box bearings, the relationship curves between the fuzzy resonance reliability and the variation coefficient and the bearing speed are obtained. Fuzzy reliability decreases in varying degrees with the increase in the variation coefficient and bearing speed.

(2) MCS of the axle box bearing is carried out based on the frequency interference model, which obtains the resonance reliability of the bearing and the influence of random variables on the natural frequency of the bearing. Changes in the random variables make the natural frequency fluctuate to varying degrees, likely in the resonance region of the bearing, leading to its resonance. Therefore, the discreteness of the design variables should be controlled as much as possible during the design process.

(3) The results of fuzzy resonance reliability are more in line with the engineering practice because the randomness of design variables and the fuzziness of the resonance region are considered comprehensively, which provides a strong basis for the design of axle box bearings.

Acknowledgments

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