Cylindrical Roller Bearing Modal Frequency Analysis for Early Failure

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Abstract. The objective of this study was to investigate the dynamic behaviour of healthy and defective cylindrical roller bearings to understand the response of these bearings to various operating conditions as a non-destructive diagnostic tool that is the modal analysis. The frequency and phase responses have been measured using a Coco-80 FFT analyser and repeated tests have shown that the values are reliable. The experimental and Finite Element (FE) simulated responses were compared and good agreement was obtained overall with some differences in natural frequencies. The differences were explained due to modelling and measurement procedures, non-linearity and small geometric differences between the measured and modelled bearings. Defective bearings showed less amplitude of acceleration in natural frequencies and harmonics and phase angle deviations at certain frequencies. These changes are associated with defects like cracks, voids, notches and/or material impurities which interfere with the continuous propagation of vibration energy. The results validate the effectiveness of using frequency response analysis, along with validated Finite Element (FE) simulations, for early fault detection and predictive maintenance of rotating machinery. This paper presents the results of the modal analysis carried out on a cylindrical roller bearing using the Frequency Response Function (FRF) for early fault detection and predictive maintenance.

Keywords: Modal Analysis, Frequency Response Function (FRF), Cylindrical Roller Bearings, Early Fault Detection, Prédictive Maintenance

1 Introduction

Mechanical parts made for rotating machinery, including bearings, play an important role in the smooth transmission of power and the reduction of friction. The breakdowns of these components can cause unforeseen shutdowns, huge monetary losses, and safety risks.

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Therefore, the timely detection of any defects in these components is crucial to ensure reliable equipment operation and extend its service life. Modal analysis has become a very useful non-destructive method for analysing the dynamic characteristics of mechanical systems. A component's frequency response can change due to changes in its structural characteristics, for which modal analysis can provide insights, possibly as the result of defects or damage. The method consists of exciting the component, measuring its response, and determining its natural frequencies, damping ratios and mode shapes. The faulty component's differences in these modal parameters to the healthy component can be a diagnostic parameter of fault.

In recent years, a number of studies have been conducted on the use of frequency response analysis for the detection of defects in rolling element bearings and other mechanical components. [14] showed amplitude peak differences between healthy and defective bearings and [1] used harmonic excitation to detect cracks in beams using the frequency response characteristics. Based on these studies, this research uses an FFT analyser (Coco-80) to study the frequency response of healthy and faulty cylindrical roller bearings. The goal was to compare the dynamic behaviour of the bearings, to compare the results of the simulations and to highlight the potential of the modal analysis for the early detection approach in rotating machines. Cylindrical Rolling bearings play a vital role in rotating machinery, as they bear the radial load and axial load, and reduce friction between moving parts. Early Fault Detection and Condition Monitoring become crucial because bearing failures can result in catastrophic damage to the equipment, significant downtime, and safety risks [11]. A dynamic understanding of bearings is essential to creating effective maintenance strategies and achieving systems reliability.

One of the important methods for understanding mechanical components' dynamic response is modal analysis. It offers useful information about the natural frequencies, mode shapes and damping properties, parameters that depend on defects or variations in structural integrity. Experimental modal analysis has been heavily used to validate finite element models and to investigate the real-world behaviour of mechanical systems [2], [5]. A change in the modal parameters, such as frequency shifts or variations in damping, can be caused by defects like cracks, misalignment, or wear [4].

Local defects like pitting or dents on the bearing raceways can have a profound effect on the vibration response of rolling element bearings. [8] showed that such defects cause observable changes in the dynamic characteristics, including shifts in natural frequencies and changes in mode shapes. The results show the potential of experimental modal analysis to condition monitoring and early fault detection. Experimental validation is important although finite element analysis (FEA) gives predictions of the dynamics of bearings. [6] noted that using FEA in conjunction with experimental modal analysis enables a true characterization of bearings in operation. This integration enhances the reliability of condition monitoring strategies and contributes to the development of predictive maintenance approach.

2 Methodology

A specially excited impact hammer was used to measure the modal frequencies of the roller bearing under free-free boundary conditions. The free-free boundary conditions used in the FE simulations were simulated by hanging the roller bearing with an elastic rubber band. The impact force was then generated in the bearing by exciting the bearing with an impact

hammer from Brüel & Kjær with a calibrated sensitivity of 22.23 mV/N. The decision to use an impact hammer rather than a modal shaker was based on the benefits this would offer in terms of speed, convenience and cost, and both methods perform equally well for non-complex systems [2].
The response of the impact on the motion of the roller bearing was recorded using an accelerometer from Brüel & Kjær that was mounted on the bearing with sensitivity of 97.96 mV/g. The processed signals were recorded in a 4-channel data recorder (CoCo-80 meter) and the frequency response function (FRF) between the input and output points of the bearing was calculated. The experimental setup used for the modal testing is shown in a schematic in Figure 1.

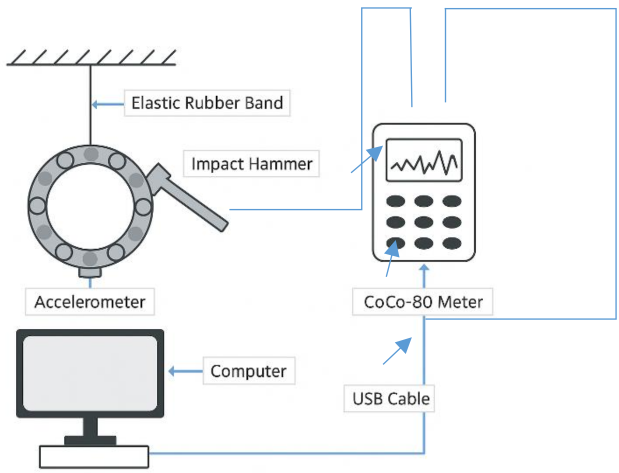


Figure 1. Schematic of the experimental setup.

The impact hammer's tip plays a key role in exciting the required vibration modes, with harder tips producing a wider frequency range. An exponential window was applied in the CoCo-80 meter to reduce leakage and improve FFT analysis accuracy. In a temperature-controlled laboratory, roller bearings (healthy and unhealthy) were suspended with elastic rubber bands and impacted at a fixed point using a metallic-tip hammer. A miniature accelerometer, attached with beeswax, measured the response, and a 4-channel CoCo-80 meter recorded and computed the Frequency Response Function (FRF). Channels 1 and 2 were used for the hammer and accelerometer, respectively, with sensitivity and trigger conditions configured for optimal results. Each bearing was lightly struck five times to ensure repeatability. Two main challenges suspending the bearing effectively and minimizing external interference were overcome by using elastic bands and performing the test in an enclosed area, ensuring the bearing was stable before impact. Figure 2 illustrates the experimental setup.

Figure 2. Experimental setup for frequency response testing [5]

The frequencies obtained from the experiment were extracted using the Engineering Data Management (EDM) software for post-processing and shown as the roller bearing frequencies. The CoCo-80 meter was used to create modal parameter files which were downloaded in atfx format and plots were made to analyse the actual frequencies. The vibration of the roller bearing is displayed as time domain responses, and the magnitude responses are displayed in the frequency domain. This procedure provided adequate linearity and good FRF results. The post-processing setup of the CoCo-80 meter and EDM software is shown in figure 3. Repeated measurements were performed to get the right frequency response curve for the component. The coherence function was applied to evaluate the data quality, to identify the noise contaminated frequencies and to check the accuracy of the measurements; values near to unity throughout the frequency range showed that the measurements were very accurate over the entire frequency range.

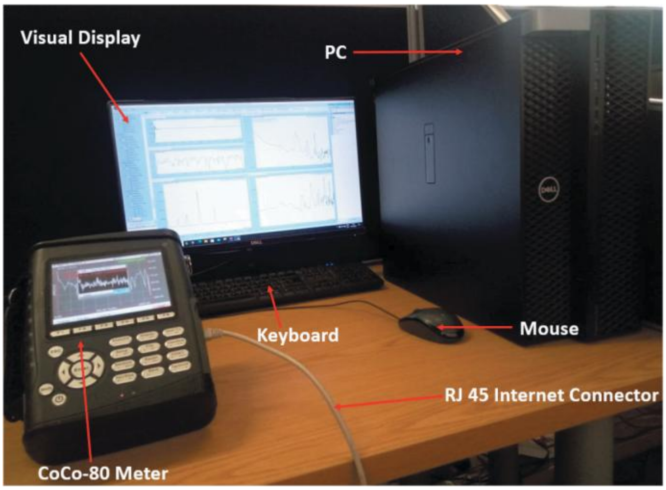


Figure 3. Experimental results postprocessing setup [5]

3 Results & Discussion

Each experiment was repeated five times and the frequency response for both healthy and defective cylindrical roller bearings were measured with the Coco-80 FFT analyser for reliability and reproducibility. The corresponding frequency response plots (Figure 4) indicate that the amplitude peaks at the natural frequencies are higher in the healthy bearing than in the defective bearing. Defective Bearing, on the other hand, shows that the amplitude of acceleration at the same mode frequencies and their harmonics is significantly reduced. This reduction is due to defects that cause a loss of smooth flow of the vibration energy through the bearing, thus reducing the vibration response.

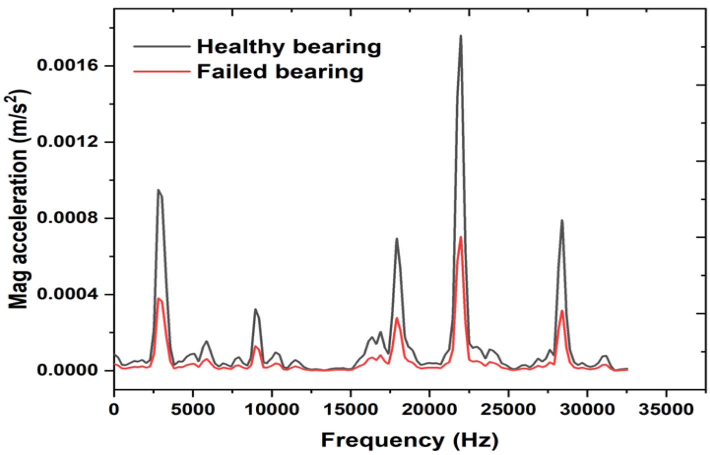


Figure 4. Comparison of the experimental frequency response of healthy and unhealthy cylindrical roller bearing

The phase angle plots of healthy and faulty bearings are shown in figure 5. The phase behavior was found to be similar for all frequencies, except for significant deviation at the peaks for some frequencies, and for other frequencies, the phase behavior was similar for both bearings. These deviations are caused by the presence of defects that may have occurred during manufacture or during operation, such as cracks, inclusions, voids or any notches. These irregularities change the dynamic response of the bearing and result in observable changes in the phase angle at certain frequencies.

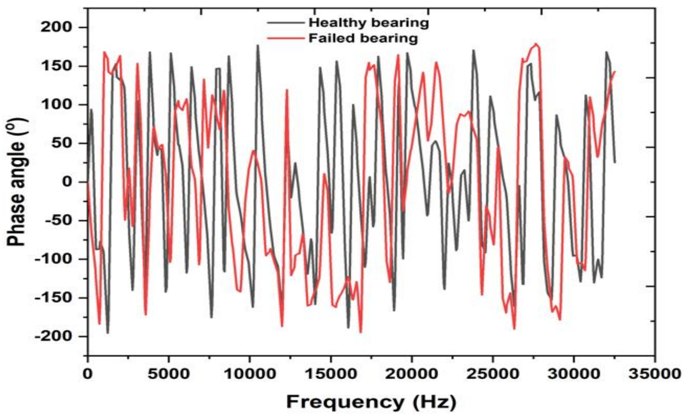


Figure 5. Comparison of the phase angle of healthy and unhealthy cylindrical roller bearing

Modal parameters including the natural frequencies of the different bearing modes, the corresponding mode shapes of the bearing components, and the qualitative descriptions of these mode shapes extracted from the FE simulation—are presented to aid in understanding the dynamic behaviour of the bearing. In this study, the eigenfrequencies were obtained from the FE model of a healthy cylindrical roller bearing. Each mode was considered without repeating any natural frequency, since the asymmetrical nature of the mistuned roller bearing prevents frequency duplication. Table 1 presents the first sixteen natural frequencies of the bearing. These modes were selected because higher modes are repetitions of the existing mode shapes and therefore add no new information.

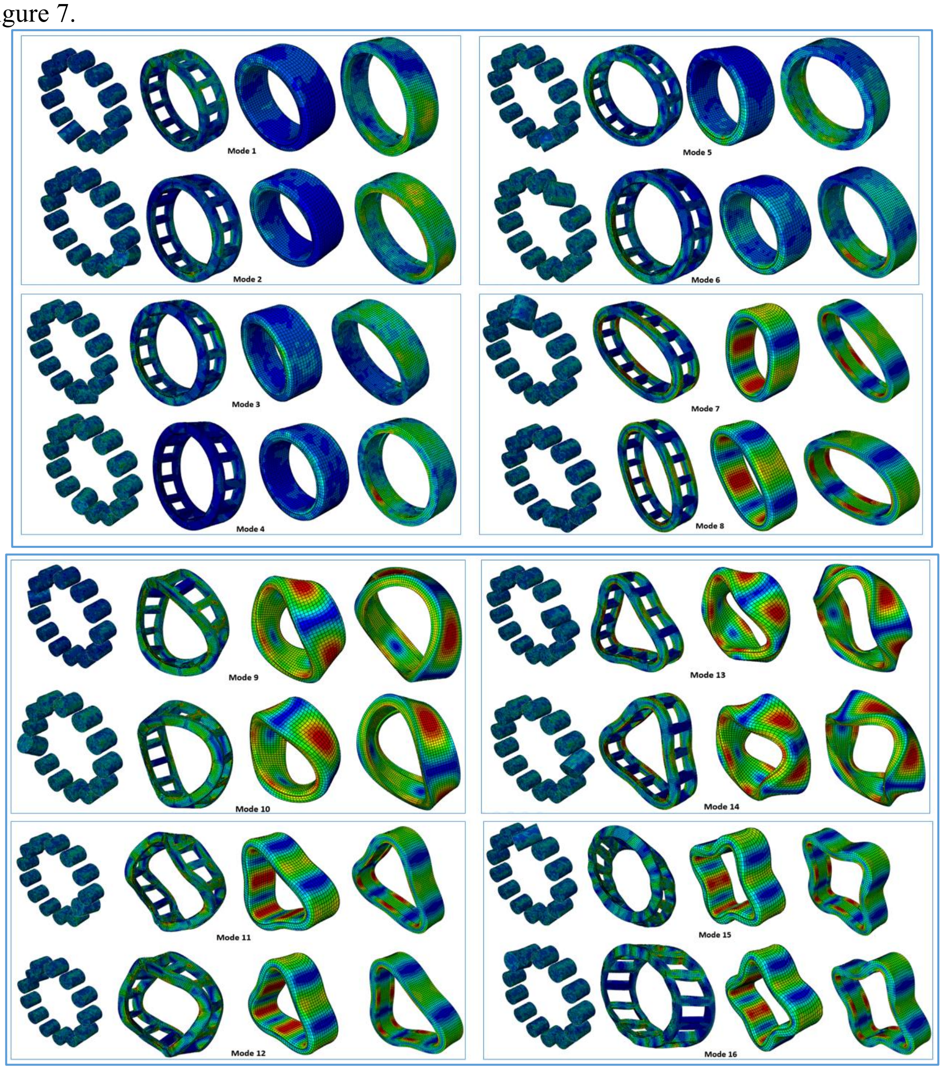
Table 1. FEA natural frequency and mode shapes of the healthy cylindrical bearing components

Mode	Natural Frequency of Bearing (Hz)	Mode Shape			
		Balls	Cage	Inner Ring	Outer Ring
1	246	Bend	Bend	Bend	Bend
2	492	Bend	Bend	Bend	Bend
3	748	Bend	Bend	Bend	Bend
4	1 220	Bend	Bend	Bend	Bend
5	1 642	Bend	Bend	Bend	Bend
6	2 922	Bend	Bend	Bend	Bend
7	4 714	Bend	Bend	Bend	Bend
8	5 738	Bend	Bend	Bend	Bend
9	7 018	Bend	Bend+Twist	Bend+Twist	Bend+Twist
10	7 786	Bend	Bend+Twist	Bend+Twist	Bend+Twist
11	8 810	Bend	Bend+Twist	Bend	Bend
12	1 0746	Bend	Bend+Twist	Bend	Bend
13	12 026	Bend	Bend	Bend	Bend+Twist
14	16 634	Bend	Bend	Bend	Bend+Twist
15	17 146	Bend	Twist	Bend	Bend
16	18 170	Bend	Twist	Bend	Bend

From Table 1, it is evident that the Finite Element (FE) results show reasonably good correlation with the experimental values presented in Table 2, thereby confirming the integrity of the developed FE model. Although the absolute magnitude of modal stress distribution in FE analysis has no physical meaning, it is useful for identifying potential hot spots in the structure (Booysen, 2014; Qin, 2015). Accordingly, the modal stress distribution for the first vibration mode of the roller bearing is shown in Figure 6. The results indicate that the maximum stress occurs at the outer bearing, corresponding to the hot spot location. This suggests that failure of the bearing is most likely to initiate at the outer raceway.

Figure 6. Modal stress distribution of mode 1

Mode shape is a key modal parameter that illustrates the deformation pattern of the FE model at different natural frequencies (modes of vibration). Figure 7 presents the mode shapes for the first twenty-four vibration modes, since higher-order modes are simply repetitions of these patterns and provide no additional insight. Visualising the mistuned roller bearing is important for understanding its dynamic behaviour. In FE analysis, modal stress visualisation is commonly used to identify hot spots or regions of stress concentration (Booysen, 2014). In this study, the visualisation was enhanced by adjusting the deformation scale of the FE model to improve the clarity of the mode shapes. Bending vibration modes are often the most destructive because of the large bending moments they induce. Since the resonance characteristics of the roller bearing are strongly influenced by the lower modes, only these are considered in the dynamic analysis. Accordingly, the first twenty-four mode shapes representing a symmetrically mixed deformation pattern of the roller bearing are shown in Figure 7.



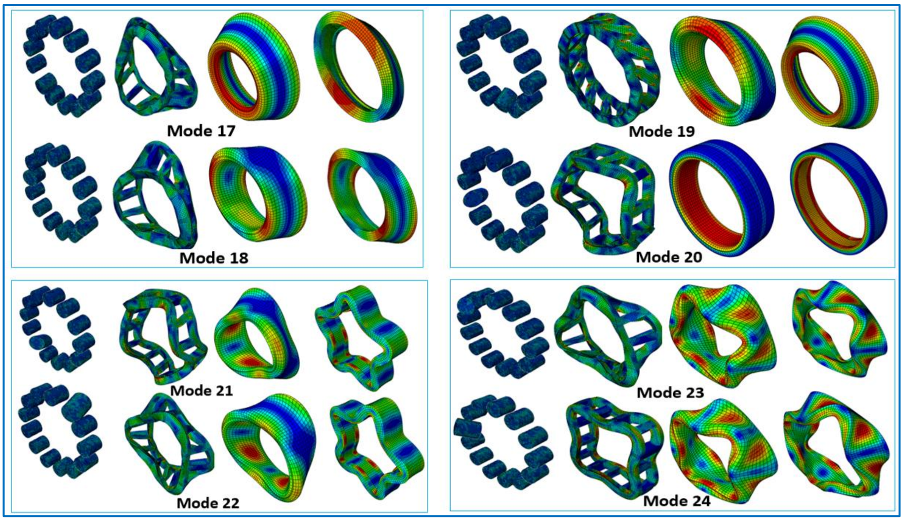


Figure 7. First twenty-four mode shapes of vibration of the components of a cylindrical roller bearing

Figure 8 compares the experimental and FEA frequency responses of healthy bearing. The results show good agreement, providing partial validation of the numerical model. A slight deviation was observed between the simulated and experimental responses, which can be attributed to bearing manufacturing and assembly tolerances. Differences in the natural frequencies may also arise from modelling and measurement processes (Lieven & Ewins, 1988), non-linear effects, and slight geometric discrepancies between the real bearing and the FE model (Talai, 2016).

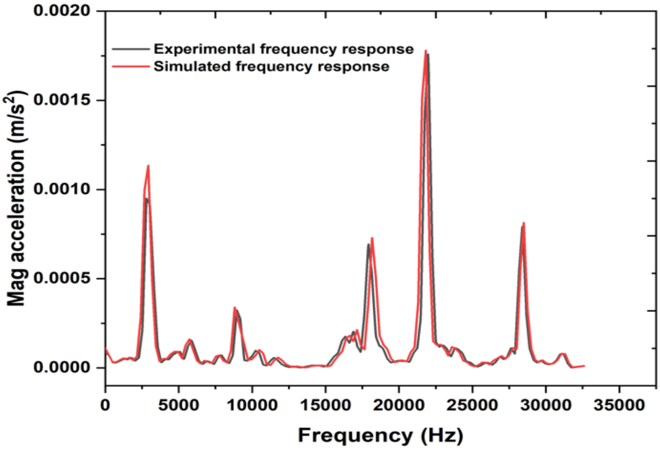


Figure 8. Comparison of the experimental and simulated frequency response plots of a healthy bearing

Table 2 presents a comparison between the simulated and experimental natural frequencies of the first sixteen modes of the cylindrical roller bearing, along with the corresponding percentage deviations.

Table 2. Comparison of the first sixteen experimental and simulated natural frequencies of a healthy cylindrical roller bearing

Natural Frequency

Mode	Experimental	Simulated	% Deviation
1	246	256	3.52
2	492	512	3.91
3	748	768	2.60
4	1 220	1 280	4.69
5	1 642	1 596	2.88
6	2 922	2 816	3.76
7	4 714	4 652	1.33
8	5 738	5 888	2.55
9	7 018	7 168	2.09
10	7 786	7 680	1.38
11	8 810	8 960	1.67
12	10 746	10 496	2.38
13	12 026	11 776	2.12
14	16 634	16 940	1.81
15	17 146	16 896	1.48
16	18 170	17 920	1.40

4 Conclusion

The frequency and phase responses of healthy and faulty cylindrical roller bearings in this study were determined using modal analysis, using a Coco-80 FFT analyser. The results indicated that defects like cracks, voids, notches, or material impurities have a significant impact on the dynamic behaviour of bearings. Defective bearings showed decreased acceleration amplitudes at the natural frequency and harmonics, and phase angle deviations at certain frequencies. Experimental frequency responses were shown to be in good agreement with the simulated frequency response, and this validated the FE model and confirmed that it can capture the dynamic characteristics of both healthy and defective bearings. Given these results, the authors believe that frequency response analysis should be incorporated into regular predictive maintenance programs. A baseline frequency and phase profile for healthy bearings would enable deviations from these profiles to become an early warning sign of a fault and help prevent unexpected failures, reduce downtime and enhance the reliability of rotating machinery.

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