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Internal clearance behaviour in healthy and faulty bearings

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Abstract. Internal clearance is a critical parameter in bearing design and operation because it affects the bearing's performance. It can be considered as a special type of the looseness fault. Several studies indicate that rolling bearings with large internal clearances showed a short predicted fatigue life. However, the time waveform and spectral features of bearing with internal clearances are partially studied and require further studies. To address this gap, the purpose of this paper is to study the effect of internal clearance on the dynamic response of healthy and faculty rolling bearings in both time waveform and spectral representations. Four experiments are designed and performed: (1) rigid bearing with no defect, (2) rigid bearing with bearing defect, (3) bearing with high internal clearance, (4) bearing with high internal clearance and bearing defect. The results indicate an increase in the overall vibration level with high internal clearance is introduced, however, there is an increase in the overall vibration level when high internal clearance and bearing defect are both presented. The internal clearance negatively affects the impact amplitude of the bearing defect, which also affects the spectral pattern at the natural frequency zone.

1. Introduction

Rolling bearings are critically important components in various industries, playing a crucial role in their machineries. Rolling bearings are indeed one of the main monitored components as they can provide valuable insights into the condition of the entire equipment in which they are installed. Internal clearance, also known as radial internal clearance, is an important parameter in the design and operation of rolling bearings. It refers to the space or gap between the rolling elements (balls or rollers) and the inner and outer raceways of a bearing, illustrated as Ci in Figure 1. High internal clearance in a bearing can result in higher levels of vibration, as it allows for more free movement of the rolling elements which causes vibrations, especially at high speeds or under dynamic loads.

There are several mathematical models used to estimate the effect of internal clearance on the bearing vibration response such as Tiwari et al. [1] Lioulios and Antoniadis [2], Harsha [3]. Ambro et al. [4], Changqing and Qingyu [5] Upadhyay et al. [6]. Xu et al. [7]. However, when the authors were testing bearing faults using the fault simulator rig at the University of Stavanger, a strange result was observed and motivated us to experimentally explore the effect of internal clearance on the bearing vibration response under healthy and faulty conditions. The issue was observation when we started with a set of bearings (internally rigid, almost no clearance) and later we had to use another set of bearings as we ran out of the first set of bearings. The second set of bearings was a bit internally loose which provided unexpected time wave and spectral features. Thus, the author decided to explore this issue further and perform four experiments and report the results: (1) rigid bearing with no defect, (2) rigid bearing with bearing defect, (3) bearing with high internal clearance, (4) bearing with high internal clearance and bearing defect.

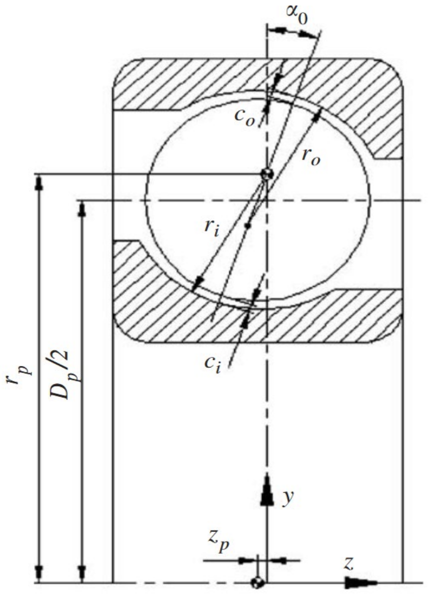

Figure 1. Bearing cross-section with internal clearance [1].

In the following section, the experimental set up is presented. In section 3, the main results of the experiments are illustrated and discussed, followed by some conclusions about the effect on internal clearance under healthy and faulty conditions and how to detect it.

2. Materials and Methods

The aim of this experiment is to study the internal clearance effect under healthy and faulty bearing conditions. Under healthy bearing conditions, two types of bearings are considered, one has high internal clearance (internally loose) and the second has no internal clearance (internally rigid), as shown in Figure 1. Under faulty conditions, the same type of bearings were used and an artificial defect was introduced to the bearing outer race, of 2 mm size.

Figure 2. Bearings used in the experiments.

The bearing fault simulator rig at the University of Stavanger, shown in Figure 3, is used to run four experiments. The bearing fault simulator is a simple rotating set-up where a motor is driving a shaft carried by two bearings. Each bearing housing is monitored with three accelerometer sensors to collect vibration measurements. The sensors are connected with the SKF IMX8 monitoring module and connected to SKF cloud and @ptitude software for getting time waveform and frequency plots. All experiments are performed at a rotating speed of 20 Hz.

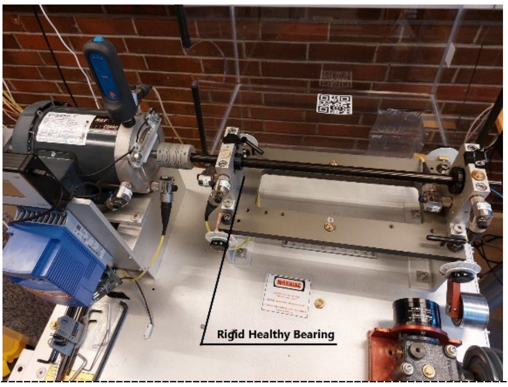

Figure 3. Bearing fault simulator rig with healthy rigid bearing (no internal clearances).

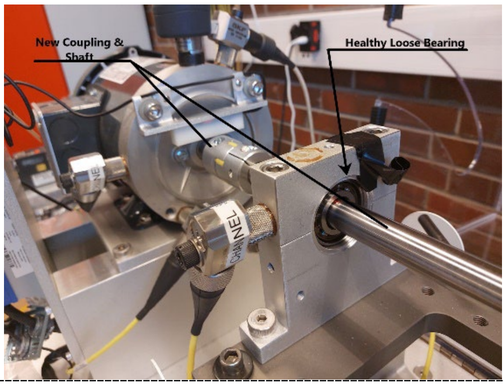

Figure 4. Bearing with high internal clearance.

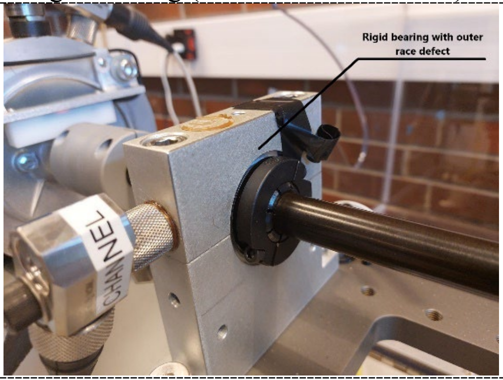

Figure 5. Rigid bearing with defect.

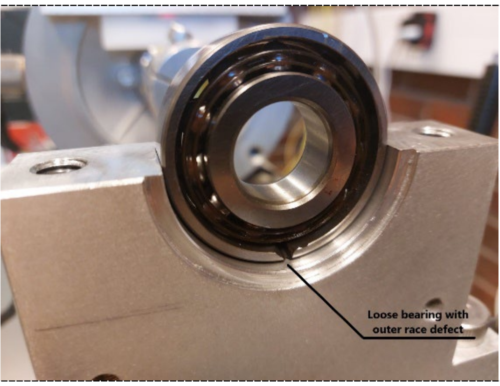

Figure 6. Bearing with high internal clearance and defect.

Table 1. Experiment setup

	Experiment 1	Experiment 2	Experiment 3	Experiment 4
Rotating speed in Hz	20	20	20	20
No. rolling elements	8	8	11	11
Clearance effect			Yes	Yes
Bearing fault		Yes		Yes
Overall description	Rigid bearing without internal clearance or defect	Rigid bearing with defect	Bearing with high internal clearance and without defect	Bearing with high internal clearance and defect

3. Results and discussion

In this section, three results categories are presented: the overall vibration level in g, time waveform plots and spectral plots for each experiment. The overall vibration values, presented in Table 2, indicate the effect of internal clearance under healthy and faulty conditions. First, the overall vibration value for the internally loose bearing (experiment 3), which is 0.275 g, is clearly higher than the overall vibration value for the internally rigid bearing (experiment 1), which is 0.084g. Second, comparing the overall vibration values for experiment 2 (0.726 g) and experiment 4 (0.389 g), interestingly indicates that internal clearance diminishes the effect of the bearing defect. This diminishing impact phenomenon of bearing defect can be explained as the space between rolling elements and races being internally loose, the chance and impact severity are getting lower and therefore the overall vibration values are getting lower as well.

Table 2. Overall vibration value for the performed experiments.

Experiment setup	Vibration level (RMS value) [g]
Rigid bearing without internal clearance or defect	0.084
Rigid bearing with defect	0.726
Bearing with high internal clearance and without defect	0.275
Bearing with high internal clearance and defect	0.389

3.1. *Time waveform analysis*

To explain further the effect of internal clearance under healthy and faulty conditions, the time waveform analysis is required. The time waveform shows what physically happened during each experiment. In Figure 7, the time waveform for experiment 1 is presented, where hardly a specific pattern can be captured, and amplitudes are of low values (g values between 0 and 0.35). Comparing the time waveform of experiment 2 (Figure 8) with experiment 1 (Figure 7), a clear increase in the amplitudes can be observed (g values between 0 and 3) and a clear impact pattern is observed (impact pulses with almost fixed time interval between them). There are around 60 impact pulses that appeared in one second of the time wave presented in Figure 8. Comparing the time waveform in Figures 7 and 8 provides a good understanding of the effect of bearing defects, especially when the bearing is internally rigid.

To understand the effect of internal clearance, the time waveforms from experiment 1 (Figure 7) and experiment 3 (Figure 9) shall be compared. The time waveform in Figure 9 shows a clear increase in the amplitudes, i.e. the g values are between 0 and 1 compared to the g values in Figure 7 which are between 0 and 0.35. Moreover, there are impact pulses, even though, there is no bearing defect. It can be physically explained as the internal clearness offers a space for the rolling element to vibrate and then hit the race surfaces. However, the hits are not strong like the hits between the rolling element and the defect surface. It can be concluded that internal clearance generates impacts pulses even under healthy bearing conditions.

To understand the effect of internal clearance under faulty bearing conditions, the time waveforms of experiment 3 (Figure 9) and experiment 4 (Figure 10) shall be compared. The time waveform in Figure 10 shows a clear increase in the amplitudes, i.e. the g values are between 0 and 1.5 compared to the g values in Figure 9 which are between 0 and 1. Moreover, the duration of the length of the impact pulses is longer in Figure 10 compared to Figure 9. However, the amplitudes of impact pulses due to the bearing defect are much weaker compared to amplitudes in experiment 2 (Figure 8), which indicates that internal clearance diminishes the effect of the bearing defect. There are around 20 impact pulses that appeared in one second of the time wave presented in Figure 10, compared to 60 impact pulses that appeared in Figure 8. Therefore, it can be concluded that internal clearance affects the impact force severity and passing frequency (rolling elements are not picking the shaft speed as expected).

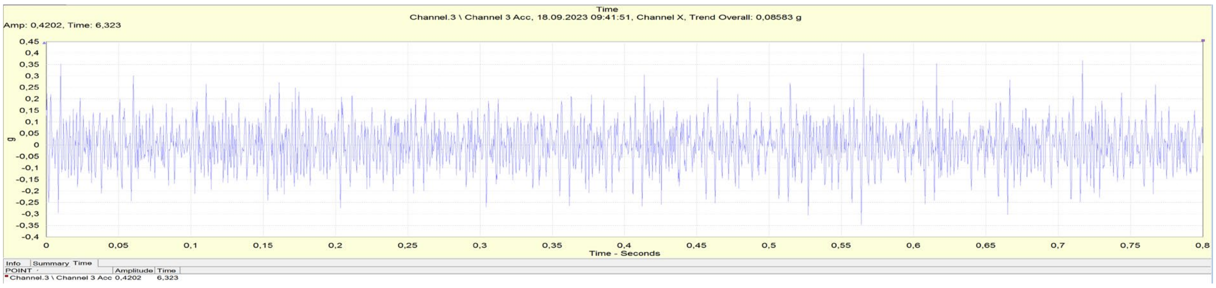

Figure 7. Time waveform for Experiment 1: rigid bearing without defect.

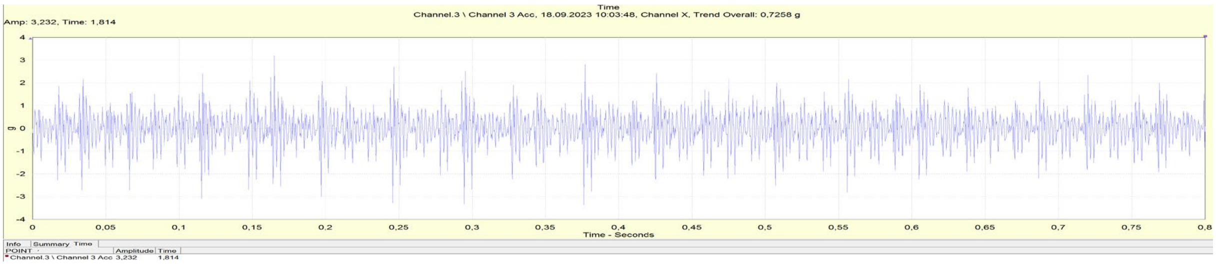

Figure 8. Time waveform for Experiment 2: rigid bearing with outer race defect.

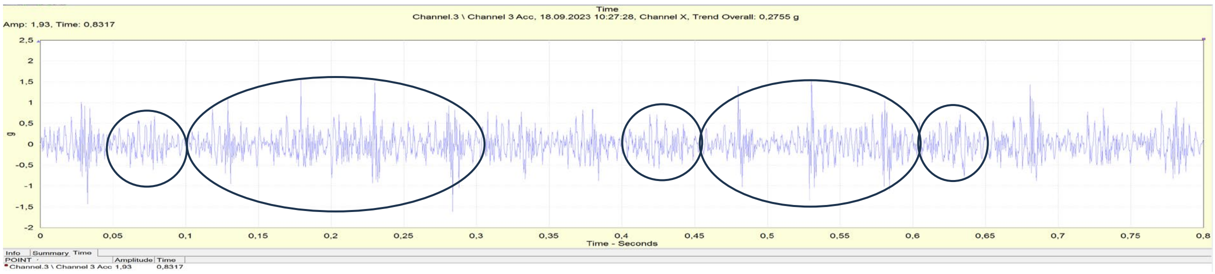

Figure 9. Time waveform for Experiment 3: loose bearing without defect.

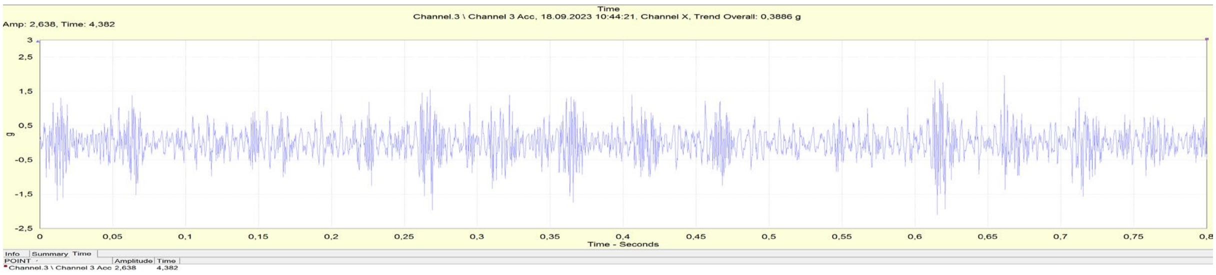

Figure 10. Time waveform for Experiment 4: loose bearing with bearing fault.

3.2. *Spectral Analysis*

The internal clearance made the task of detecting bearing fault using time waveform much harder as the impact and rolling element passing frequency were reduced. Frequency domain analysis might provide a better understanding of what happened from a spectral point of view. In Figure 11, the frequency plot for all four experiments is illustrated. There are three main frequency zones that we are going to study to understand the effect of internal clearance on the spectral features: (1) Fundamental frequency zone which is related to the rotating speed (1X) and its harmonies (2X,3X, etc.), (2) bearing fault frequency zone, which is related to the passing frequency of rolling element, (3) bearing natural frequency zone. At the fundamental frequency zone, in the first and second experiments, which are for the internally rigid bearing, there were no bins or peaks shown. However, tiny peaks at 1x (20Hz), 2x (40Hz), 3x(60Hz), and 4x(80Hz) can be seen for experiments 3 and 4, where the internally loose bearings are tested. Having peaks at the fundamental frequency zone might indicate that internal clearance generates shaft imbalance and misalignment. At the bearing fault frequency zone, the internal rigid bearing with fault (experiment 2), shows high amplitude peaks compared to all other experiments. Interestingly, in experiment 4 where a bearing defect exists like in experiment 2, the amplitudes of the peaks are much weaker. At the bearing natural frequency zone, the internal rigid bearing with fault (experiment 2), shows high amplitude peaks compared to all other experiments. It is clear that internal clearance excites the natural frequency of around 800-1000 Hz, however, the excitation is very weak. A closer look into these frequency zones has been given in Figure 11.

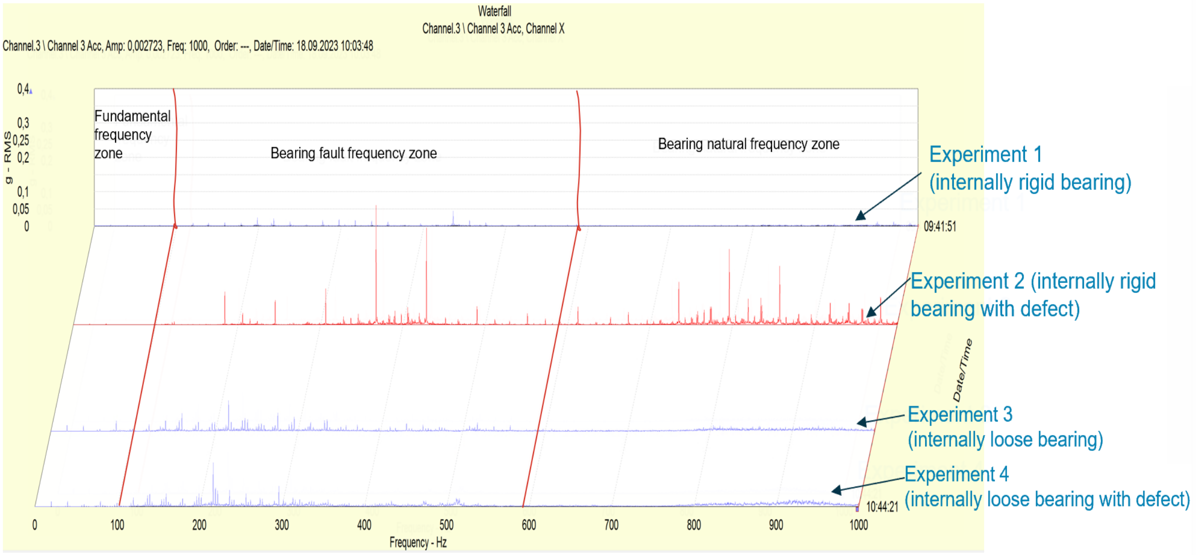

Figure 11. Waterfall plot for the performed experiments.

At the fundamental frequency zone, the internally rigid bearings (experiments 1 and 2) show no bins or peaks up to 100 Hz, as shown in Figure 12. The clear bins appear at 180 and 240 Hz for experiment 2 which might be related to the bearing defect. Remember, we have an outer race-bearing defect, its passing frequency can be theoretically estimated as (rotating speed*number of rolling elements) which is in this case equal to 160 Hz (20 Hz*8). This equation assumes that the rolling elements pick totally the shaft speed, which is not true. There is a relative speed factor for outer race fault of 40-100%. Thus, the practical bearing fault frequency can be estimated to range between 64 Hz and 160 Hz. However, the observed peaks are not within this estimated range. Looking at the time waveform of the impact pulses, a clear amplitude modulation exists, which is usually responsible for generating harmonics and sidebands.

The internally loose bearings (experiments 3 and 4) show bins or peaks up at fundamental frequency (20Hz) and its harmonics 40, 60, 80, 100, 120, 140, 160, 180, 200, 220, and 240 Hz. However, the highest amplitude is at 220 Hz. The estimated outer race fault frequency for bearings in experiments 3 and 4 is a range of 88-220 Hz (20 Hz*11 rolling elements). It can be concluded that internal clearance generates spectral peaks from 2x to 12x. The only difference between an internally loose bearing and an internally loose bearing with a defect is the amplitude of these frequency peaks, as shown in Figure 13.

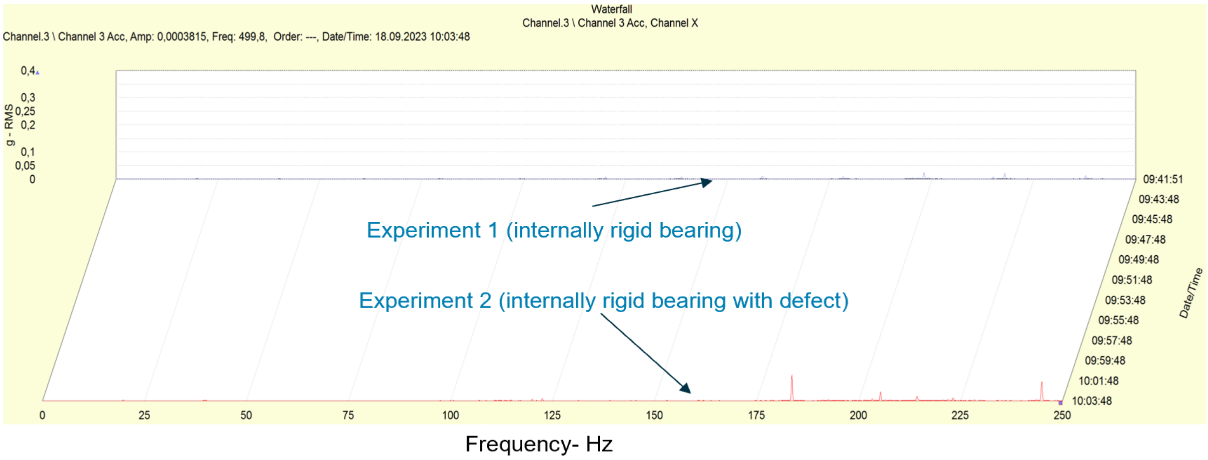

Figure 12. Waterfall plot for the fundamental and bearing fault frequencies zones, rigid bearing with and without bearing fault.

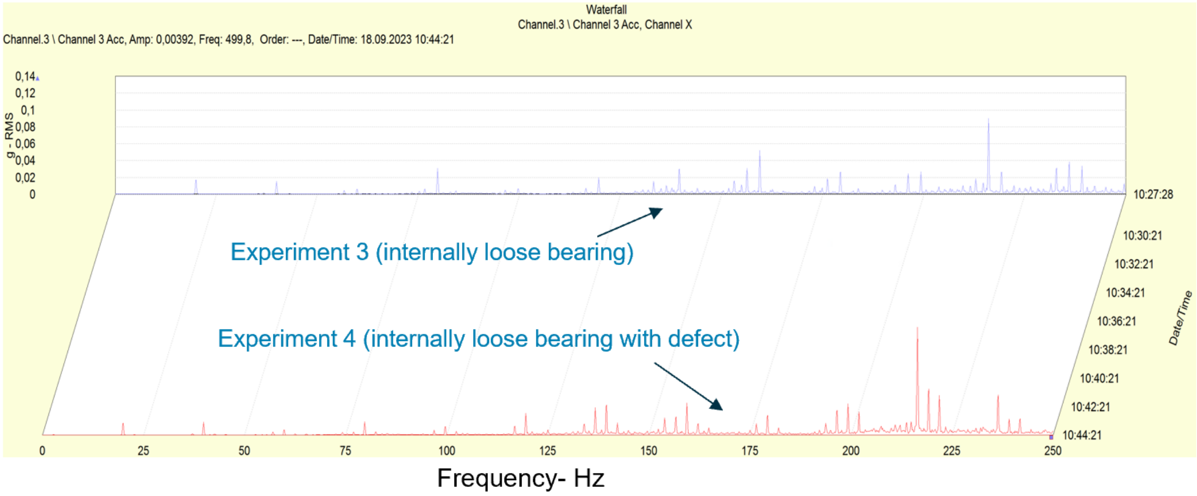

Figure 13. Waterfall plot for the fundamental and bearing fault frequencies zones, loose bearing with and without bearing fault.

At the bearing natural frequency zone (700-1000 Hz), the internally rigid bearings (experiments 1) show no bins or peaks, as shown in Figure 14. However, there are clear bins at the natural frequency zone in the case of experiment 2 (Figure 14), as the impacts of the bearing defect on the bearing defect area excited the bearing natural frequency. For internally loose bearing (experiment 3), it is expected to have no excitation at the natural frequency zone, same as the case of experiment 1. However, there is a clear excitation in Figure 15, from 750 Hz to 1000 Hz. It physically means that the rolling element vibration due to the internal clearances generates minor impact events that lightly excite the bearing natural frequency. In the case of experiment 4, the excitation at the natural frequency zone (750-1000 Hz) is a bit higher compared to the one in experiment 3, however, it is much lower compared to the one in experiment 2. It physically means that bearing defect under internally loose conditions excites the natural frequency, however, the effect of bearing defect is much higher under internally rigid conditions.

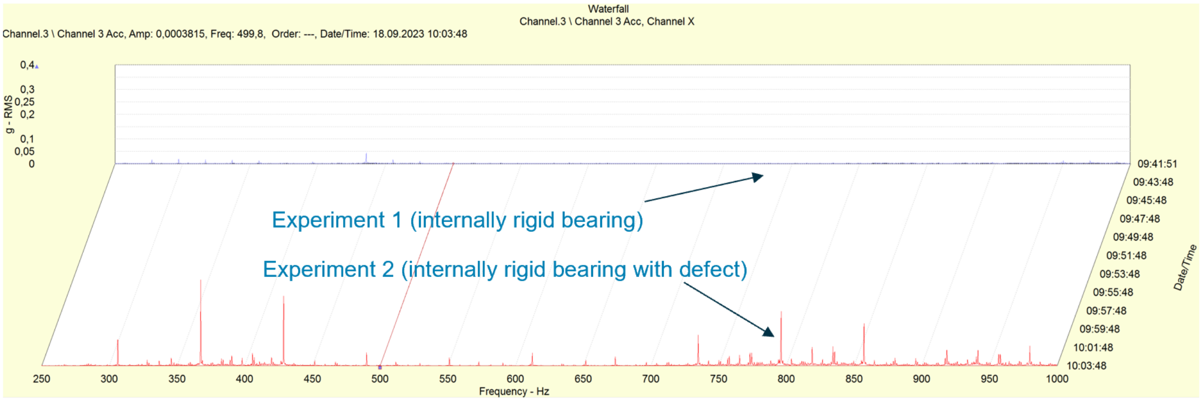

Figure 14. Waterfall plot for the natural frequencies zones, internally rigid bearing with and without bearing fault.

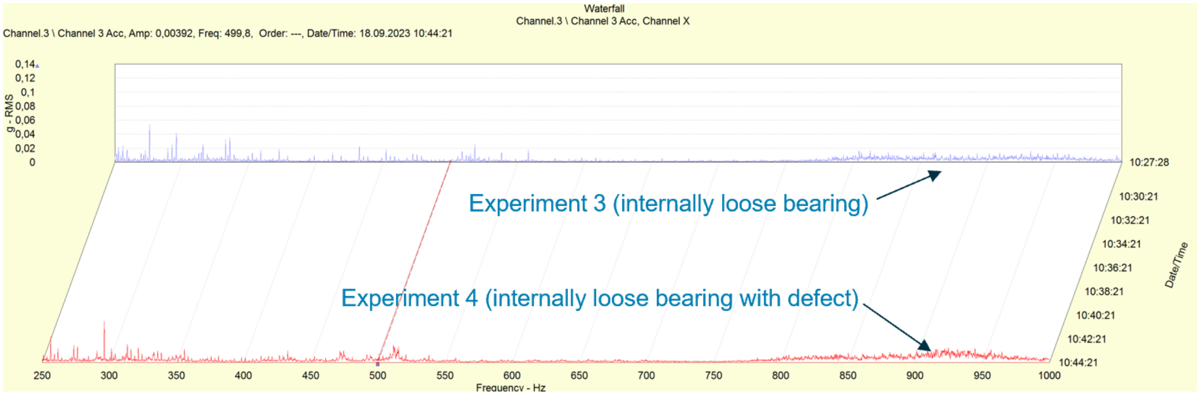

Figure 15. Waterfall plot for the natural frequencies zones, internally loose bearing with and without bearing fault.

4. Conclusion

The performed experiment in this paper shows the effect of internal clearance on the bearing vibration, its time wave and spectral features. Moreover, it explains the effect of internal clearance on bearing defect detection. The internal clearance generates impacts that vary in their amplitudes and interval (time between impacts), several peaks from 2x-12x and wide peaks at the natural frequency zone. The internal clearance diminishes the impact of bearing defects and makes them harder to detect. This effect of internal clearance acts as a smoothening agent for the defect impact, especially since the overall vibration values are much lower compared to the internally rigid bearing. It will be interesting to study the effect of internal clearance over time and observe if the bearing is going to deteriorate faster than the internally rigid bearing.

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