ROLLING BEARING DAMAGE DETECTION AT LOW SPEED USING VIBRATION AND SHOCK PULSE MEASUREMENTS

Zainal Abidin[1], Andi Isra Mahyuddin[2], and Wawan Kurniawan

Mechanical Engineering Department, FTMD Institut Teknologi Bandung,
Bandung, Indonesia, e-mail: [1]zapauitb@gmail.com, [2]aim@ftmd.itb.ac.id

Received Date: August 18, 2014

Abstract

This paper describes a study on damage detection of a rolling bearing at low speed. In this study, an NTN N204 cylindrical roller bearing with an artificial local damage was tested under various operating speed and load levels. During the testing, two methods of measurement are employed to detect the damage. The first method is vibration measurement while the second is shock pulse measurement. For vibration data, RMS (Root Mean Square) and CF (Crest Factor) values are utilized to evaluate the bearing condition. For shock pulse data, dBc (dB carpet), dBm (dB maximum), LR (Low Rate), HR (High Rate), HDm (High Definition maximum), HDc (High Definition carpet) are utilized to evaluate the bearing condition. The results show that the shock pulse measurement is capable of detecting local bearing damage at lower speed than vibration measurement. For shock pulse measurement, HDm/HDc method of analysis is capable of detecting bearing damage at lower speed than either dBm/dBc or LR/HR method. For vibration measurement, the CF value is a better parameter for detecting bearing damage at low speed than the RMS value.

Keywords: CF, dBc, dBm, HDc, HDm, HR, LR, RMS, Rolling bearing, Shock pulse, Vibration

Introduction

Rolling bearing is a vital element for rotating machines dedicated to support rotors against static and dynamic forces. Any damage to the bearing must be detected in advance before it causes a catastrophic failure since the damage may lead to production losses or even a total loss. Unquestionably, many methods of early bearing damage detection have been developed to solve this problem [1, 2].

As has been widely known, the damage of a rolling bearing develops in four stages [3]. The first stage is the microcrack which is not visible to human eyes and could only be seen using a microscope. This kind of damage is very difficult to detect even using ultrasonic measurement method. The damage then progresses to the second stage where ultrasonic and shock pulse measurement methods proof to be beneficial. When the damage enters the third stage, a local damage may be seen clearly using naked eyes. In this stage, vibration measurement using a spectrum analyzer is widely used to detect the damage. During this stage of the damage, certain unique frequency appears in the vibration spectrum, such as BPFO (Ball Pass Frequency Outer), BPFI (Ball Pass Frequency Inner), BSF (Ball Spin Frequency), and FTF (Fundamental Train Frequency) [4]. When the bearing enters the third stage of damage, it is recommended to remove it from service. When the damage could not be detected and the bearing continue to be in service, then the local damage could progress to the fourth stage in a form of a distributed damage. Since the damage is already distributed around the bearing raceway, the temperature of the bearing rises and the lubricant (grease or oil) contains a lot of metallic debris causing the vibration and noise to increase dramatically. This stage of damage could usually be detected manually by an experience operator without the aid of any instrument. However, detecting bearing damage at this stage is almost not viable since the bearing may break at any time causing the machine to stop.

Thus detecting bearing damage in stage three or preferably at stage two is crucial since it would provide the industry with plenty of lead time to order the spare parts. It should be noted that a special bearing or a general bearing with the outer diameter of more than 150 mm may need 3 months of delivery time, especially when the location of the industry is in a remote area. However, detecting bearing damage even at stage three is not easy, especially in rotating machines running at low speed. This is because when the speed is low, the impact momentum is so small that the vibration as well as shock pulse signals becomes very weak. Unfortunately, several machines, such as those in paper machinery or chemical processes, have rotational speed as low as 1 rpm or even less.

This work is motivated by the need to investigate current capability of the measurement and analysis methods to detect the local damage at stage three under various operating speed. To demonstrate the capability of vibration and shock pulse analysis, an NTN N204 roller bearing with an artificial local damage was tested at 1000 rpm. When vibration as well as shock pulse analysis succeeds in detecting the damage then the rotational speed is reduced gradually down to 24 rpm. In addition to the speed variation, the load was also varied from 5 kgf to 15 kgf. For each vibration and shock pulse analysis, several parameters were employed to indicate the severity of the damage.

Experimental Setup

The experimental setup and the instruments used in this work to measure vibration and shock pulse signals are shown in Figure 1. In the setup, the tested bearing was placed inside a bearing housing. The inner race of the bearing is rotated by a shaft which is driven by an electric motor through a pulley. The outer ring of the bearing is fixed to the housing. The bottom side of the housing is connected to a static load with weight which could be varied. On the other sides of the housing, two accelerometers are installed to measure vibration in horizontal and vertical directions. The accelerometers are connected to a three-channel signal conditioning. The output channels of the signal conditioning are connected to a Picoscope data acquisition. Near the vertical accelerometer is the shock pulse sensor that is connected directly to the Leonova Diamond manufactured by SPM Instrument AB. In addition to these sensors, an optical keyphasor sensor that produces signal of one pulse per revolution is also installed to measure the rotational speed of the bearing.

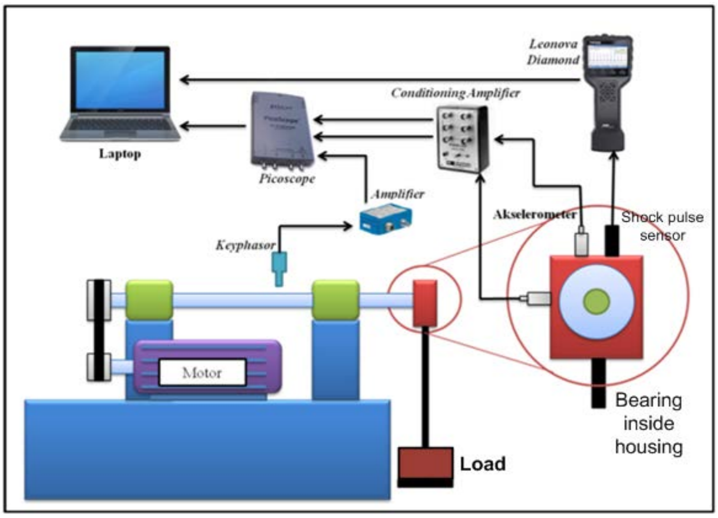

Figure 1. The experimental setup and measurement instruments

The roller bearing used for this study is an NTN N204 with dimension as shown in Figure 2 [6]. This type of bearing has a dynamic basic load rating of 25.7 kN and a static basic load rating of 22.6 kN. The size of the artificial damage at the outer ring is 2 mm x 14 mm with a depth of 1 mm. During the testing, the damage is always positioned on the top so that it coincides with the maximum pressure at the bearing load zone. With such arrangement, it is expected that an impact always occurred every time the roller ‘fall’ into the ditch.

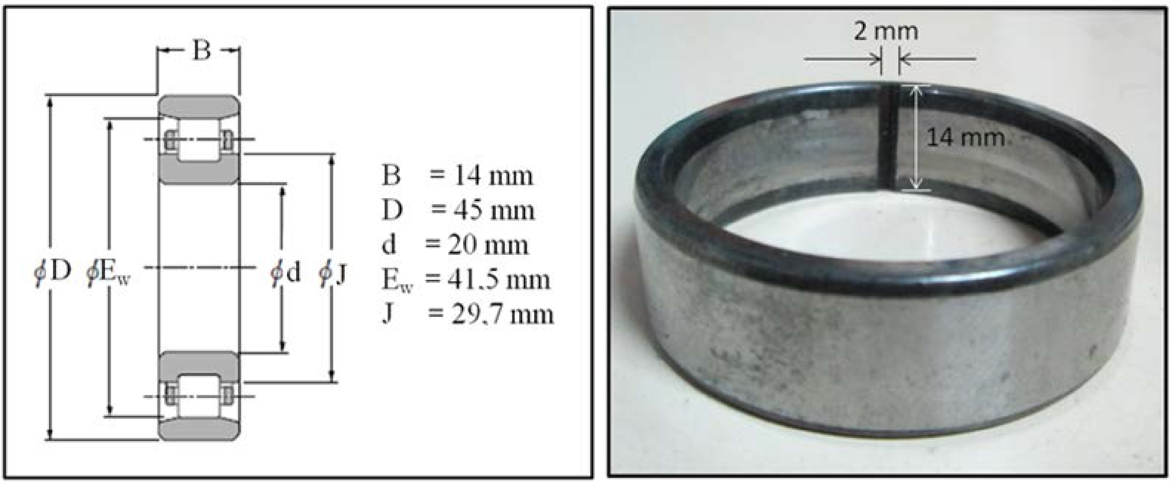

Figure 2. Dimensions of the NTN N204 bearing and the artificial damage

Frequencies of Bearing Defect

If any component of a bearing suffered from local damage, either outer ring, inner ring, ball/roller, or cage, bearing will produce specific signal with a certain unique frequency. This frequency is called bearing damage frequency. Based on the bearing dimensions, the bearing damage frequencies may be calculated based on the following equations [4]:

$$BPFO = f\left(\frac{N}{2}\right)\left(1 - \frac{d}{D}\cos\alpha\right),$$

$$BPFI = f\left(\frac{N}{2}\right)\left(1 + \frac{d}{D}\cos\alpha\right).$$

$$FTF = \frac{f}{2}\left(1 - \frac{d}{D}\cos\alpha\right).$$

$$BSF = f\left(\frac{D}{2d}\right)\left(1 - \left(\frac{d}{D}\cos\alpha\right)^2\right).$$

where BPFO is the frequency of outer ring damage (Hz), BPFI is the frequency of inner ring damage (Hz), FTF is the frequency of cage damage (Hz), and BSF is the frequency of ball damage (Hz). In the above equations, $f = n/60$ is the rotational frequency (Hz), n is the rotating speed (rpm), N is the number of ball or roller, d is the ball diameter (mm), while D is the pitch diameter (mm) and α is the contact angle. For a given rotational speed, the BPFO, BPFI, FTF, and BSF could be calculated directly once the dimensions of the bearing are known. Bearing damage produces signals which could be detected using ultrasonic, shock pulse, vibration, or even sound measurements.

Results of Vibration Measurement and Analysis

The easiest way to investigate the effect of rotational speed reduction on the vibration signals is by looking at the shape and the magnitude of vibration signals under various speeds and load. Figure 3 shows the shape and magnitude of vibration signals when the load is 5 kgf. It may be seen from this figure that at 1017 rpm, the impact signals could be observed clearly. However, as the rotational speed decreases, the vibration signals also decreases and the impact signals become less visible and mixed up with random vibration. At rotational speed of 123 rpm or lower, the vibration signal does not contain any impact anymore.

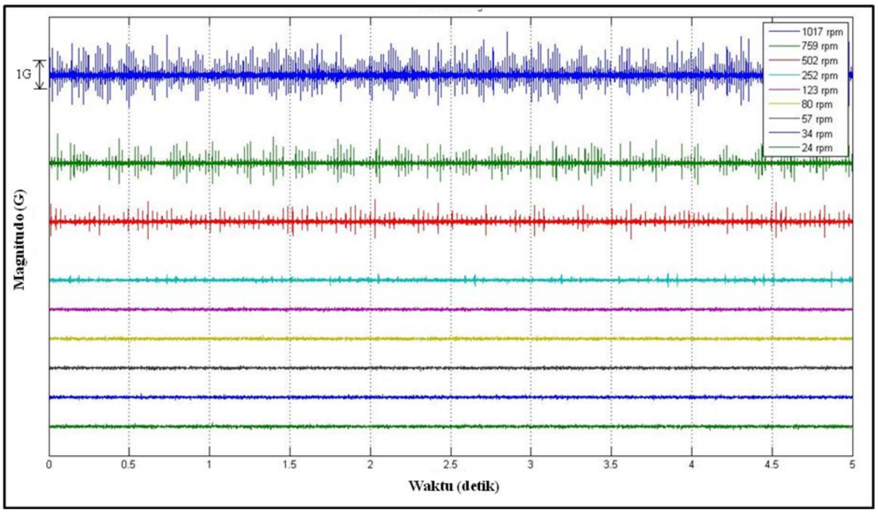

Figure 3. The shape and magnitude of vibration signals at various speeds for a 5 kgf load

Similar results are presented in Figure 4 for a 15 kgf load. Note that the results are almost similar to those in Figure 3 for 5 kgf load, except that the impact signals occurrences are more prominence. In order to observe these signals in more detail, plots of the signals for shorter time duration are depicted in Figures 5–7.

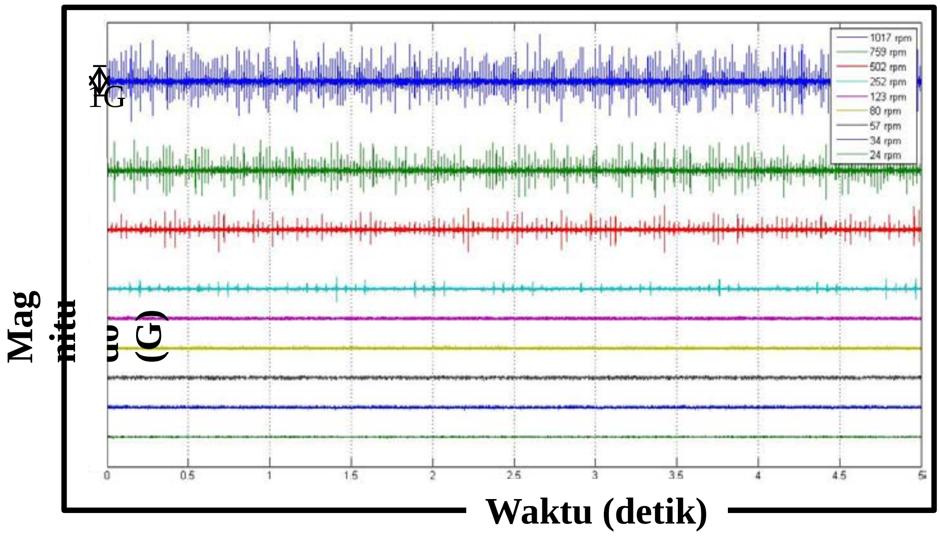

Figure 4. The shape and magnitude of vibration signals at various speeds for a 15 kgf load

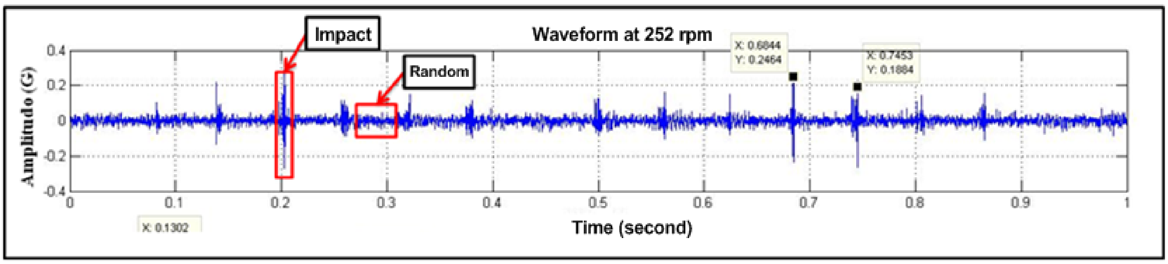

Figure 5. Vibration signal at rotational speed of 252 rpm for a 15 kgf load

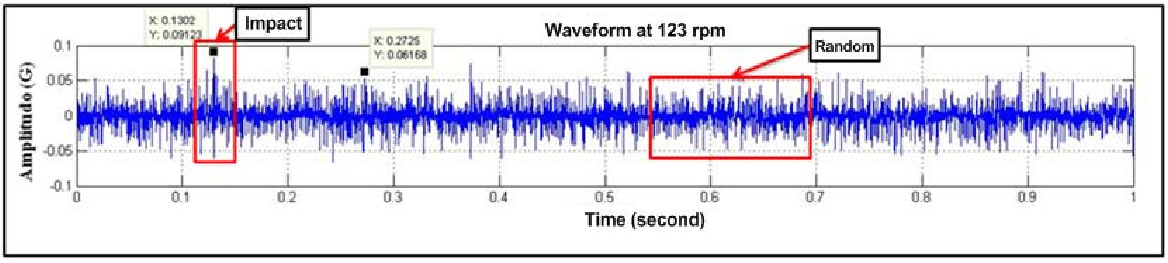

Figure 6. Vibration signal at rotational speed of 123 rpm for a 15 kgf load

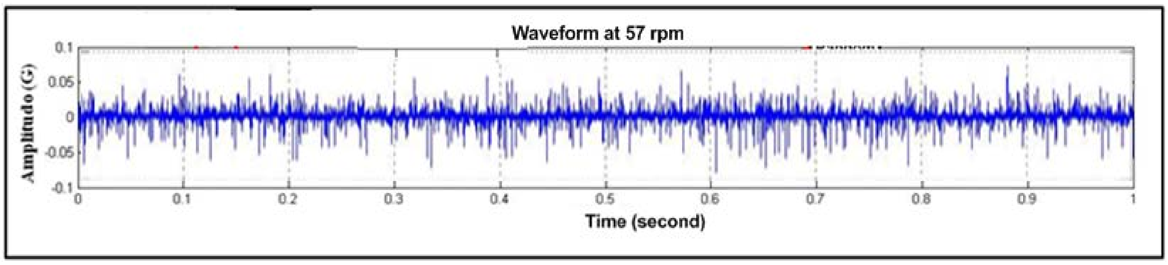

Figure 7. Vibration signal at rotational speed of 57 rpm for a 15 kgf load

Figure 5 is the plot of the vibration signal at 252 rpm at load of 15 kgf for 1 second time duration. As shown in this figure, the impacts could be clearly identified in this signal. Furthermore, the elapse time between two consecutive impacts corresponds to the period of frequency of outer ring damage (BPFO). This will be clear when spectrum analysis is performed.

When the rotational speed is reduced, less evident of impacts occur as clearly shown in Figures 6 and 7. Figure 6 shows the vibration signal when the speed is 123 rpm while Figure 7 shows similar signal at 57 rpm. Please note these three figures have different vertical scale. The range of vertical scale is chosen to enable visual inspection to the shape of the signal. In Figure 6, the impacts are not clearly visible since the random vibration has already dominated the signal. In Figure 7, no more impact is visible within the vibration signal.

Based on the vibration signals, it would be interesting to evaluate several parameters which describe the level of vibration and the impact content within the vibration signals. The level of vibration signal may be described by RMS (Root Mean Square) value while the quantity of impact signal buried within the vibration signal may be described by CF (Crest Factor). CF is defined as the ratio between the peak (maximum) value and the RMS value. A smooth sinusoidal signal has a CF equal to 1.41. A signal with a CF higher than 6 is considered as impulsive signal.

Figure 8 shows graphs relating the RMS values with the rotational speed for three load levels. It may be seen that the RMS level increases as the rotational speed increases. Furthermore, the level of load does not significantly influence the RMS value. Since the

RMS value decreases as the rotational speed decreases, even for the same level of bearing damage, the RMS value is then not suitable to be used as a parameter to indicate bearing damage at low speed.

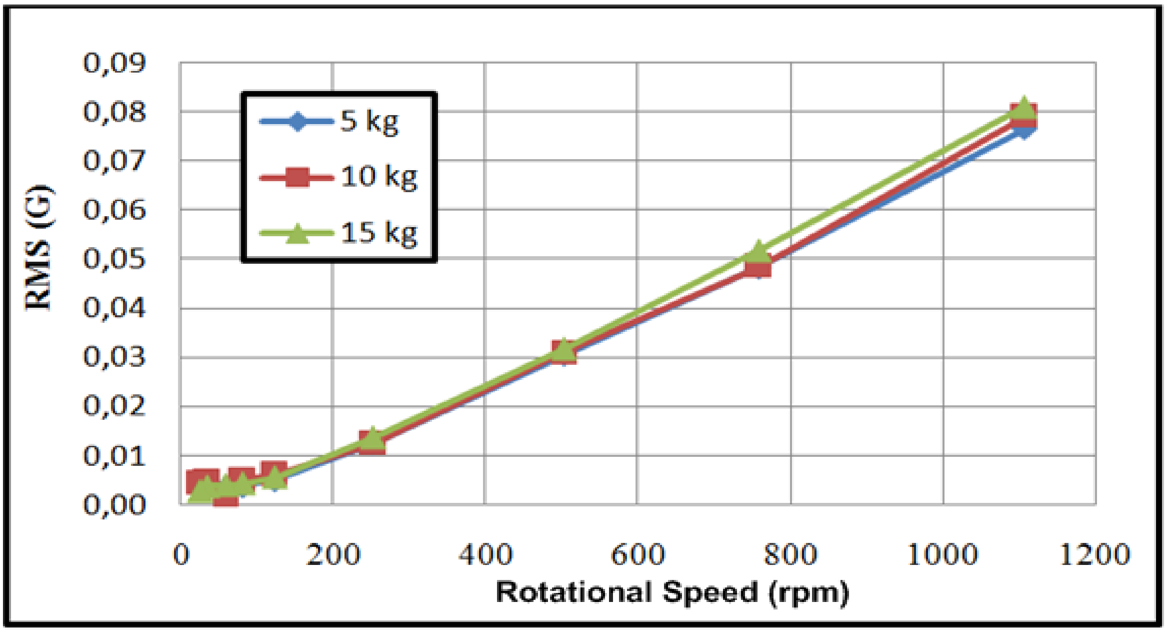

Figure 8. The RMS value as a function of speed at three level of load

As an alternative to the RMS value, Figure 9 shows the graph of CF values against speed for the three levels of load. As clearly shown in this figure, the CF value does not decrease as the speed decreases. In fact, the CF value stays almost constant with value above 16 irrespective of the rotational speed. Thus, the CF value is a much better parameter to indicate bearing damage than the RMS value.

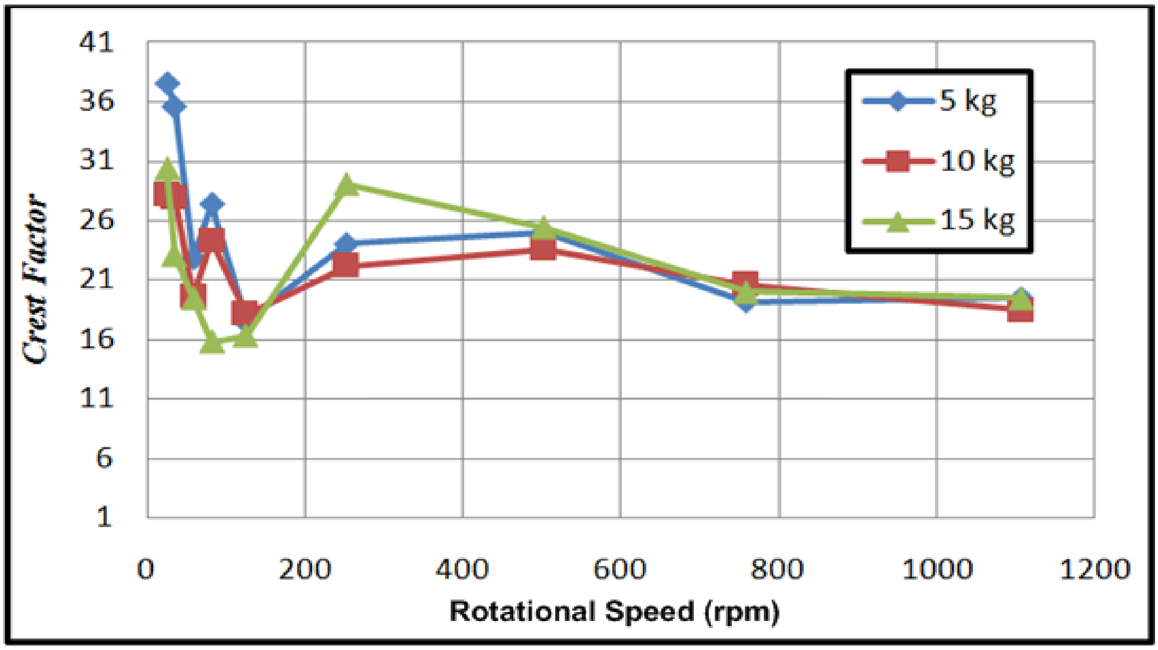

Figure 9. The CF value as a function of speed at three level of load

The most common method employed to identify the existence of local damage in rolling bearings is by vibration spectrum analysis. To demonstrate the effectiveness of the spectrum analysis, the signals presented in Figures 6 and 7 are transformed using FFT (Fast Fourier Transform) and are shown in Figures 10 and 11 respectively.

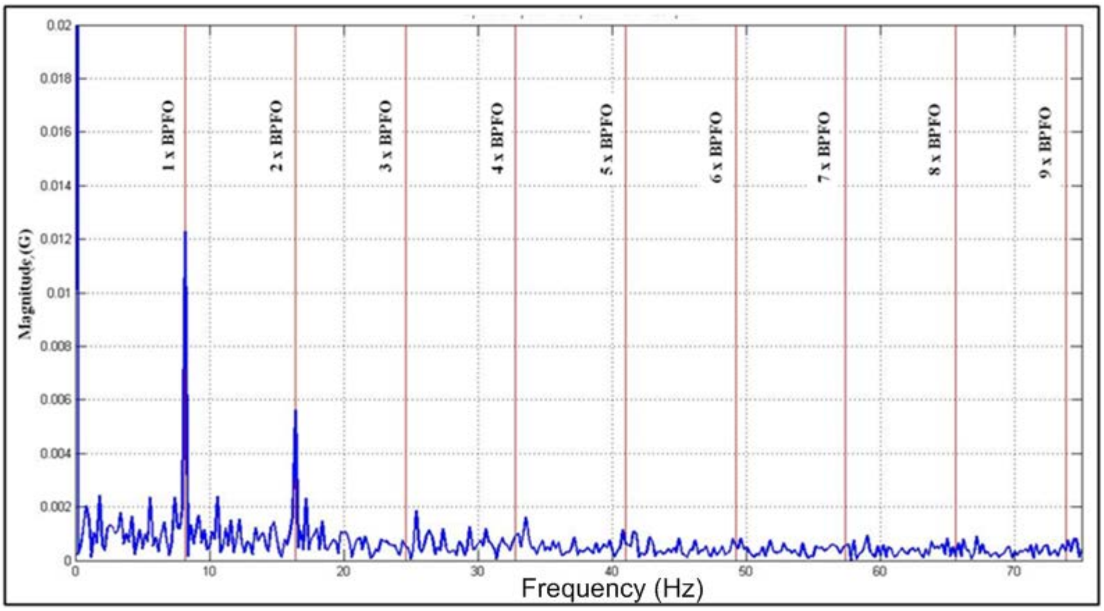

Figure 10. The spectrum of the vibration signal at a speed of 123 rpm and a 15 kgf load

As may be seen from Figure 10, the spectrum of vibration signal shows BPFO frequency component and its harmonics. The presence of BPFO signal accompanied by its harmonics is a strong indication of damage occurring at the outer race of the bearing. The remarkable thing about spectrum analysis is that although the vibration signal shown in Figure 6 does not show impact phenomenon very clearly, the spectrum of the signals clearly indicate the problem. Even more remarkable is the fact that while the vibration signal in Figure 7 does not clearly show impact phenomenon, the spectrum presented in Figure 11 still shows BPFO frequency albeit without any harmonics.

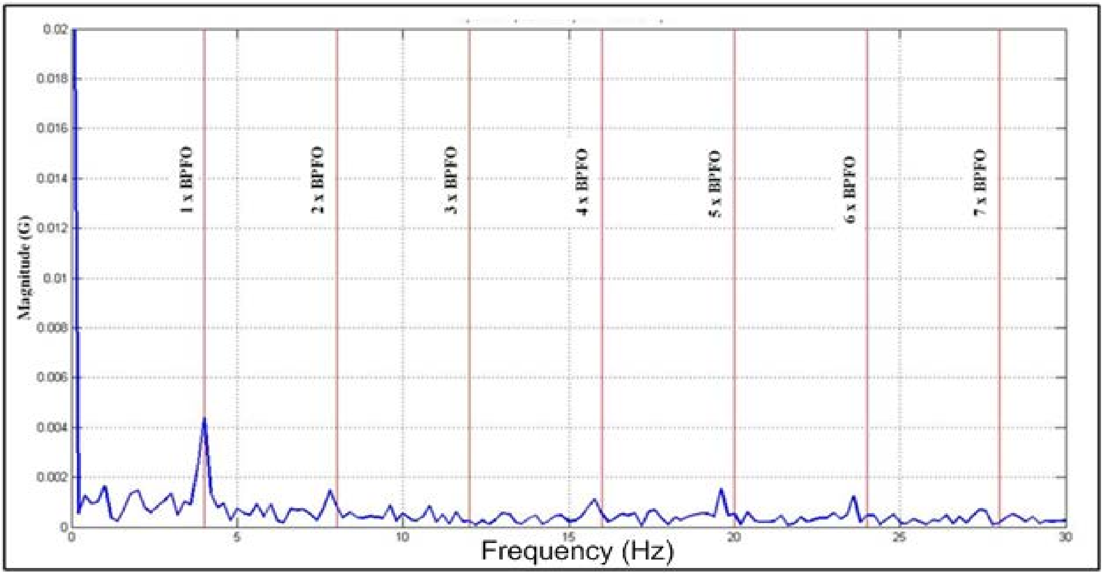

Figure 11. The spectrum of the vibration signal at a speed of 57 rpm and a 15 kgf load

If the rotational speed is reduced further as shown in Figure 4, the vibration signal becomes very weak and neither impact nor periodicity is observed in the signal. For example, if the vibration signal of the bearing rotating at 34 rpm is analyzed in frequency domain, the obtained spectrum shows neither BPFO nor its harmonics, as shown in Figure 12. Thus, at 34 rpm no damage signal appeared in time domain or in vibration spectrum.

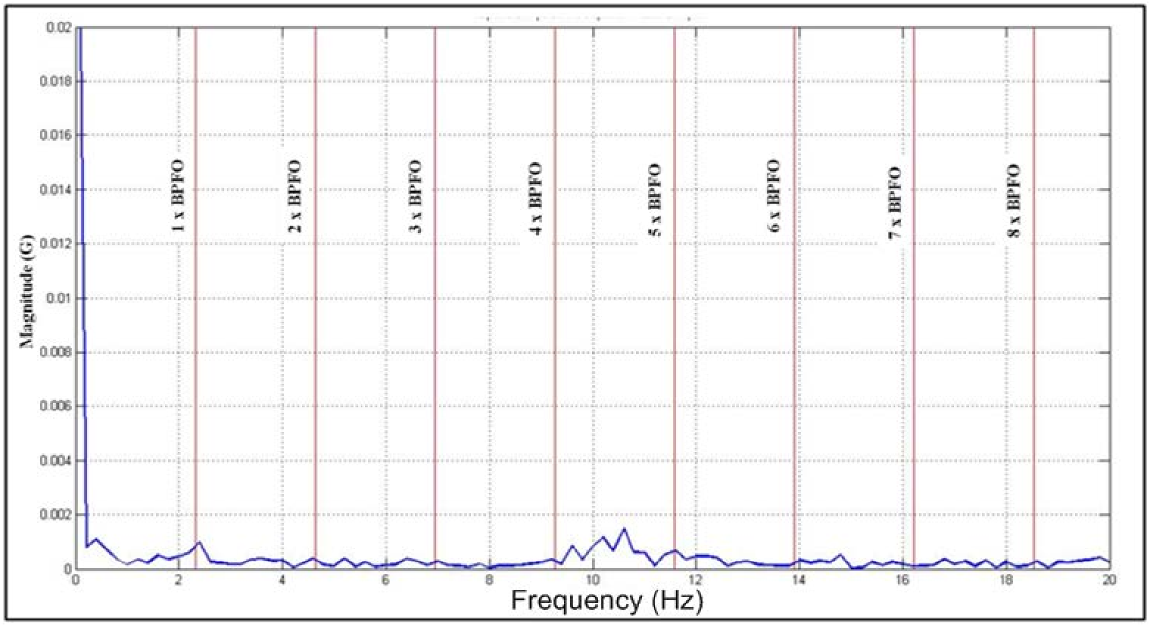

Figure 12. The spectrum of the vibration signal at a speed of 34 rpm and a 15 kgf load

Results of Shock Pulse Measurement and Analysis

Shock pulse is actually similar to vibration, thus shock pulse sensor is also very similar to accelerometer sensor. However, shock pulse sensor always has a fixed natural frequency since it measures vibration around sensor natural frequency. Hence, in contrast with vibration measurement, which is sensitive to the phenomenon occurring with frequency below 10,000 Hz, such as unbalance and misalignment, shock pulse measurement is only sensitive with phenomenon occurring at higher frequency of around 32,000 Hz, indicative of early bearing damage. One company that specializes in developing shock pulse measurement is SPM Instrument AB [6].

There are three methods of analysis that have been developed by SPM Instrument AB, which is dBm/dBc, LR/HR, and HDm/HDc. Each of these methods was developed based on the technology available at the moment. For example, the HDm/HDc was being developed only in 2010 when 24 bit ADC is available and economically feasible to be used in a portable instrument.

In dBm/dBc method of analysis, dBm or dBmax shows the maximum impact while dBc or dBcarpet shows the amount of friction occurring in a bearing. In this method, dBm is always higher than dBc. During measurement, if the dBc is high while dBm is low, it indicates poor lubrication but no mechanical damage. In other condition, if dBc is low and dBm is high, it indicates that while it has good lubrication, the bearing has already damaged. Bearing damage is identified when the different between dBm and dBc is more than 15 dB, thus dBm – dBc > 15 dB.

Figure 13 shows the variation of dBm values as the speed and load vary. As shown in this figure, the three graphs representing various loads are almost coinciding indicating that the amount of load does not change dBm values significantly. Furthermore, as the speed decreases from 1017 rpm to 24 rpm, the dBm value decreases.

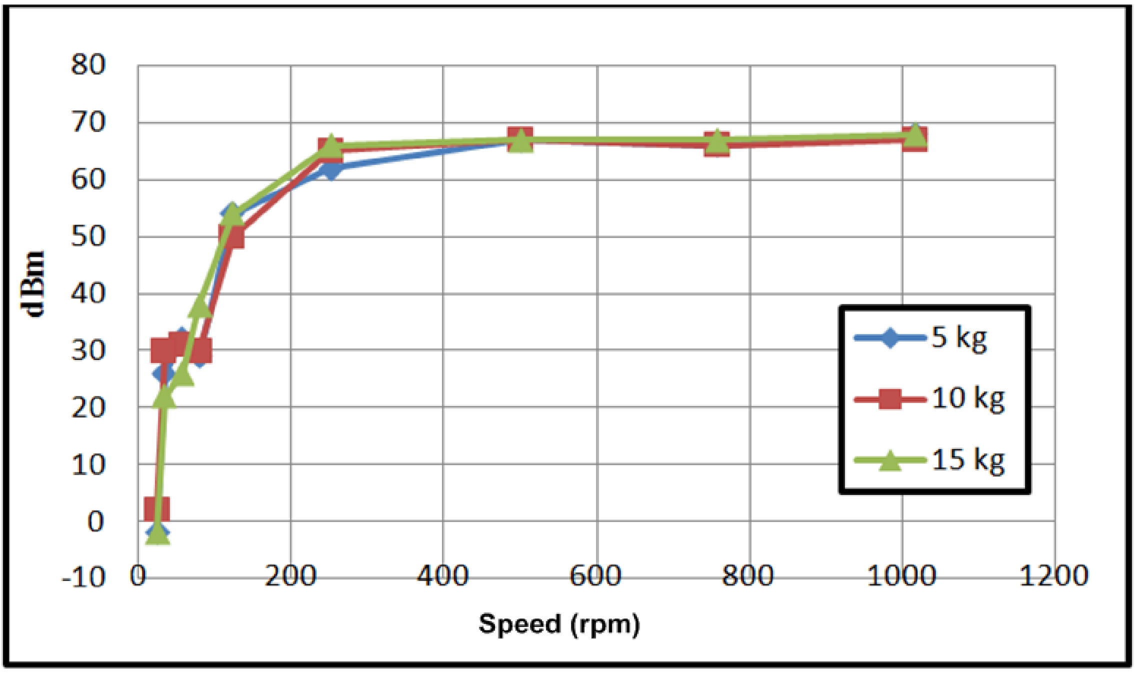

Figure 13. dBm as a function of rotational speed and load

Similar to Figure 13, Figure 14 shows the variation of dBc as the speed and load vary. It may be seen that the amount of load does not change dBc values significantly and as the speed decreases from 1017 rpm to 24 rpm, the dBc value also decreases. Thus neither dBm nor dBc could be used as an indication of bearing damage. The relative value between dBm – dBc, however, gives a good indication of the existence of bearing damage.

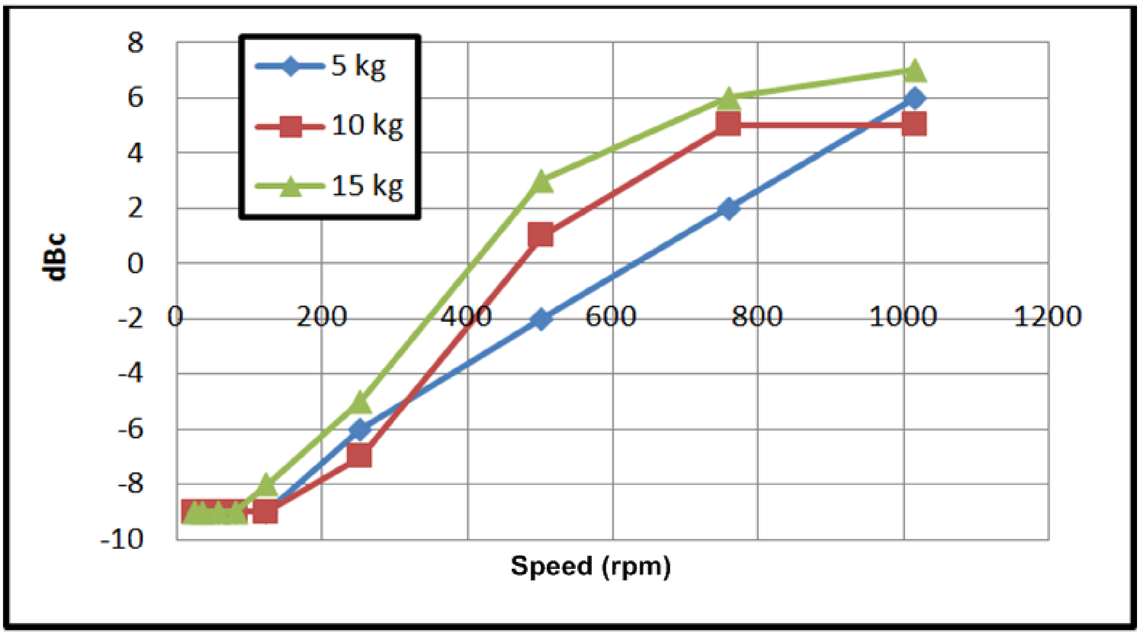

Figure 14. dBc as a function of rotational speed and load

Figure 15 shows the relative value between dBm and dBc, that is dBm – dBc. It may be seen that dBm – dBc decreases as the speed decreases but much more constant than dBm itself. For example, Figure 13 shows that dBm starts to decrease at speed of around 200 rpm. However, as shown in Figure 15, the dBm – dBc value decreases only after the speed decreased to less than 123 rpm. Furthermore, the value of dBm – dBc less than 15, which is an indication of bearing damage, only happen at 24 rpm.

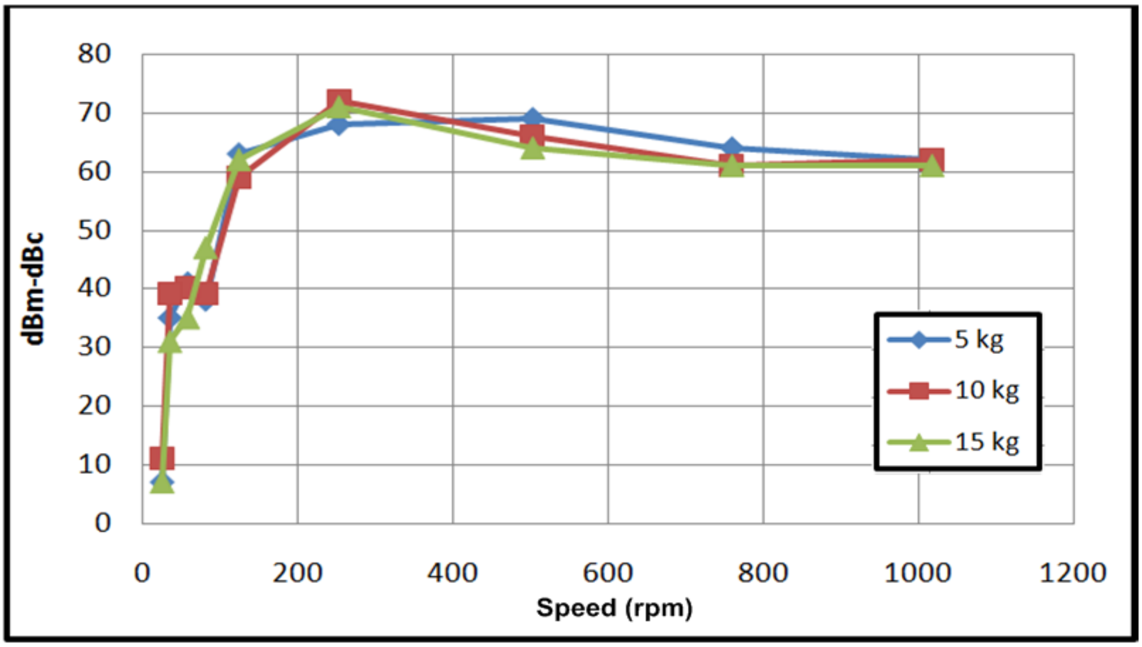

Figure 15. dBm - dBc as a function of rotational speed and load

The dBm/dBc method of analysis has been adopted by other instrument manufacturers but they use vibration sensor and not special shock pulse sensor. The signal generated by vibration sensor is then processed mathematically to produce shock pulse signals. The advantage of this method is its low cost and no need to separate vibration and shock pulse measurements. However, the dBm/dBc values obtained from such measurement are not as good as those obtained using special shock pulse sensor, especially at low speed.

The LR/HR analysis is proposed as an improvement to dBm/dBc method. In this method HR or High Rate is the magnitude of shock pulse signals that occurs 1000 pulses per second. High value of HR indicates that the bearing lubrication is not good. In contrast, LR or Low Rate is the shock pulse signals that occurs 40 pulses per second. High value of LR indicates that there is a lot of mechanical impact which is a good indication of bad bearing condition. Delta value is the difference between LR and HR, in other words LR-HR. Based on delta value; it is possible to evaluate bearing condition (COND).

Figures 16 to 18 show the variation of LR, HR, and LR – HR values as the speed and load vary. The results of LR/HR measurements are almost the same with those obtained from dBm/dBc measurements. However, further analysis could be done using LR/HR method.

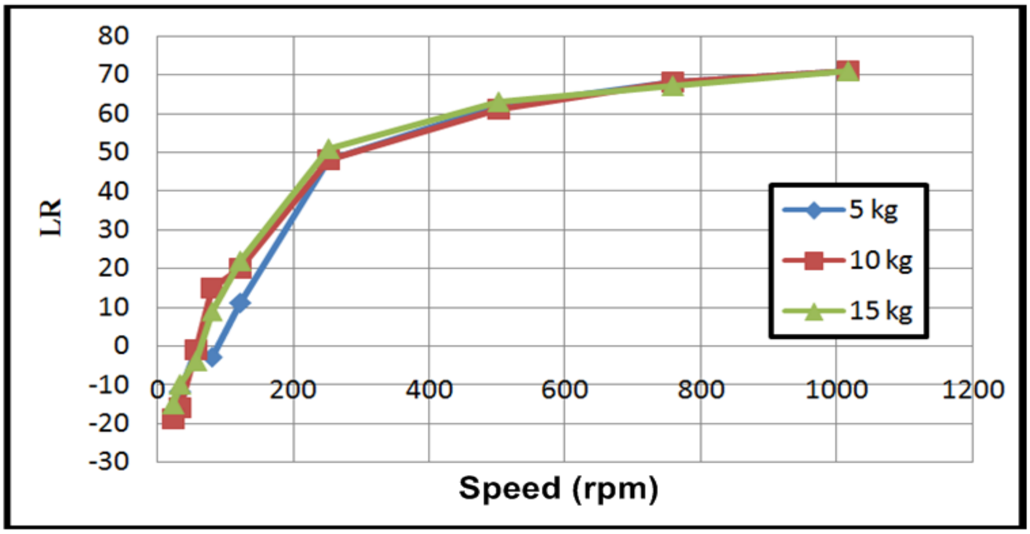

Figure 16. LR value as a function of rotational speed and load

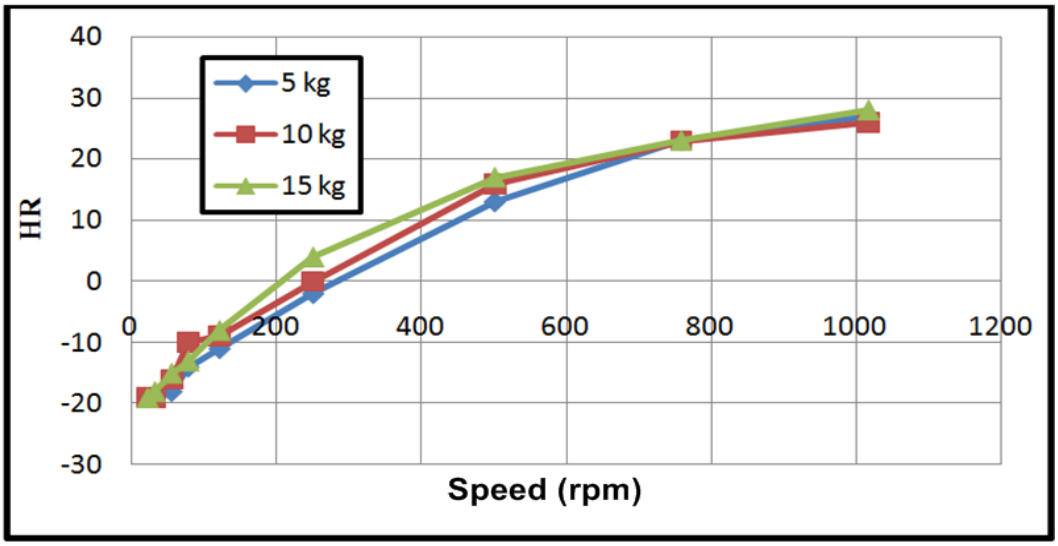

Figure 17. HR value as a function of rotational speed and load

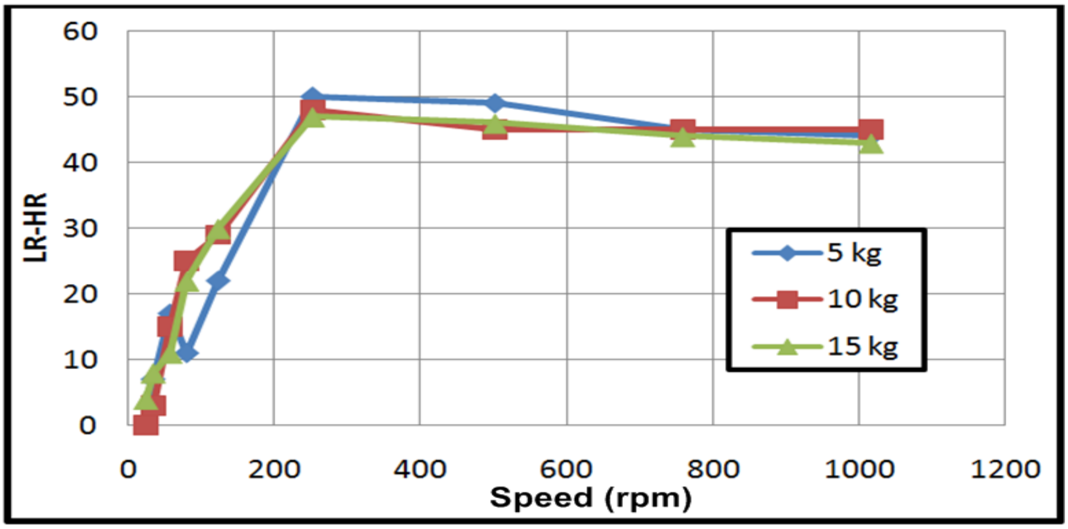

Figure 18. LR-HR values as a function of rotational speed and load

Based on LR/HR measurement, SPM Instrument AB provides user with LubMaster software which could be used to evaluate bearing condition. The summary of the bearing evaluation produced by the LubMaster software is presented in Table 1. In this table, CODE D means bearing in damage condition, CODE C means that dry lubrication and possible bearing damage, CODE A means bearing in good condition, and CODE E3 indicates that the shock pulse signal is too small so that bearing condition could not be evaluated.

Table 1. Results of Bearing Damage Evaluation Using LubMaster

Test	Speed (rpm)	Load 5 kgf		Load 10 kgf		Load 15 kgf	
		COND	CODE	COND	CODE	COND	CODE
1	1,017	65	D	65	D	65	D
2	759	65	D	65	D	65	D
3	502	65	D	65	D	65	D
4	252	65	D	65	D	65	D
5	123	35	C	62	D	65	D
6	80	-	A	47	D	29	C
7	57	-	E3	-	A	-	A
8	34	-	E3	-	E3	-	E3
9	24	-	E3	-	E3	-	E3

In addition to bearing evaluation CODE, LR/HR measurement also produces LubMaster evaluation graph which describe operating condition of the bearing. Figure 19 shows the LubMaster evaluation graphs at three operating speed for a 10 kgf load. These graphs show three colors of bearing operating region. The green region is the safe operating region, the yellow region is the warning region, and the red region is the dangerous operating region. The bearing operating condition is shown as a black dot in this graph. As clearly indicated in these graphs, at a speed of 123 rpm, LR/HR measurement indicates that the bearing is in dangerous region due to the damage. However, as the rotational speed reduces to 80 rpm the operating point (the black dot) moves downward. At speed of 57 rpm, the LR/HR measurement indicates that the bearing is in good condition which is not a correct conclusion.

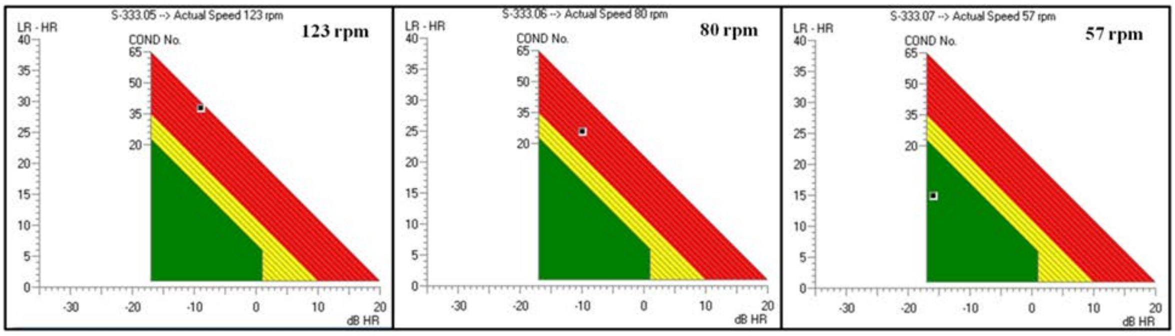

Figure 19. LubMaster graphs at speed of 123 rpm, 80 rpm, and 57 rpm. Load 10 kgf

Thus although LR/HR method does not improve the early damage detection capability at low speed over the dBm/dBc, it gives more detail analysis and it is easier to use, especially for ordinary users. The red, yellow, and green symbols used in LR/HR method enables the users to easily identify bearing condition, especially when dealing with hundreds or thousands of machines in their industry.

The HDm/HDc is the most advance method for detecting bearing damage. This method is developed by SPM Instrument AB around 2010 and implemented in Leonova Diamond. As mentioned before, this method was only developed when the 24 ADC is technologically available and economically feasible to be implemented in a portable instrument.

The results of HDm, HDc, and HDm-HDC measurements for the bearing with artificial damage under various speed and load levels are shown in Figures 20 – 22. The results of HDm (Figure 20) and HDc (Figure 21) seemed similar to those obtained from dBm/dBc and LR/HR measurements. However the results of HDm – HDc, as shown in Figure 22, are completely different than those dBm-dBc and LR-HR. As depicted in this figure, the values of HDm – HDc are almost constant even below 100 rpm. This condition means that HDm – HDc values indicate bearing damage better even at low speed.

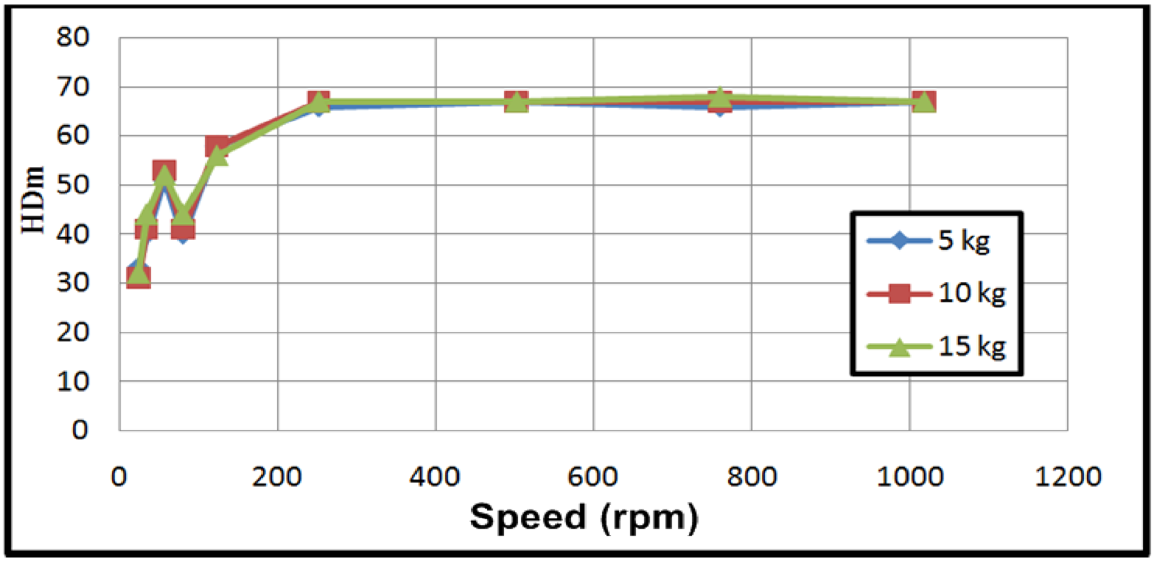

Figure 20. HDm value as a function of rotational speed and load

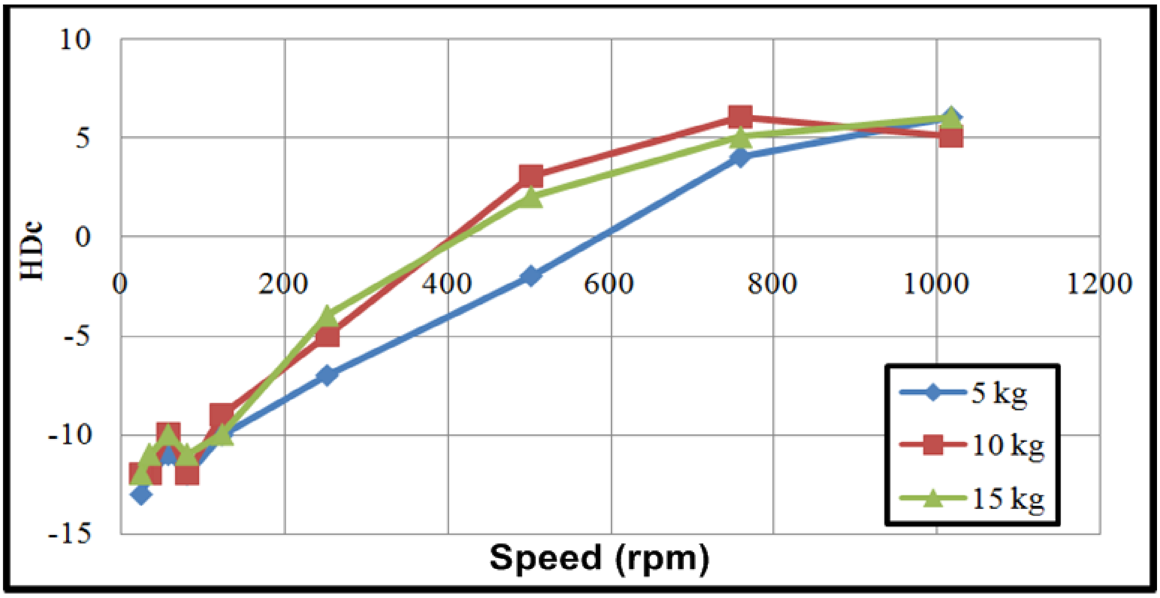

Figure 21. HDc value as a function of rotational speed and load

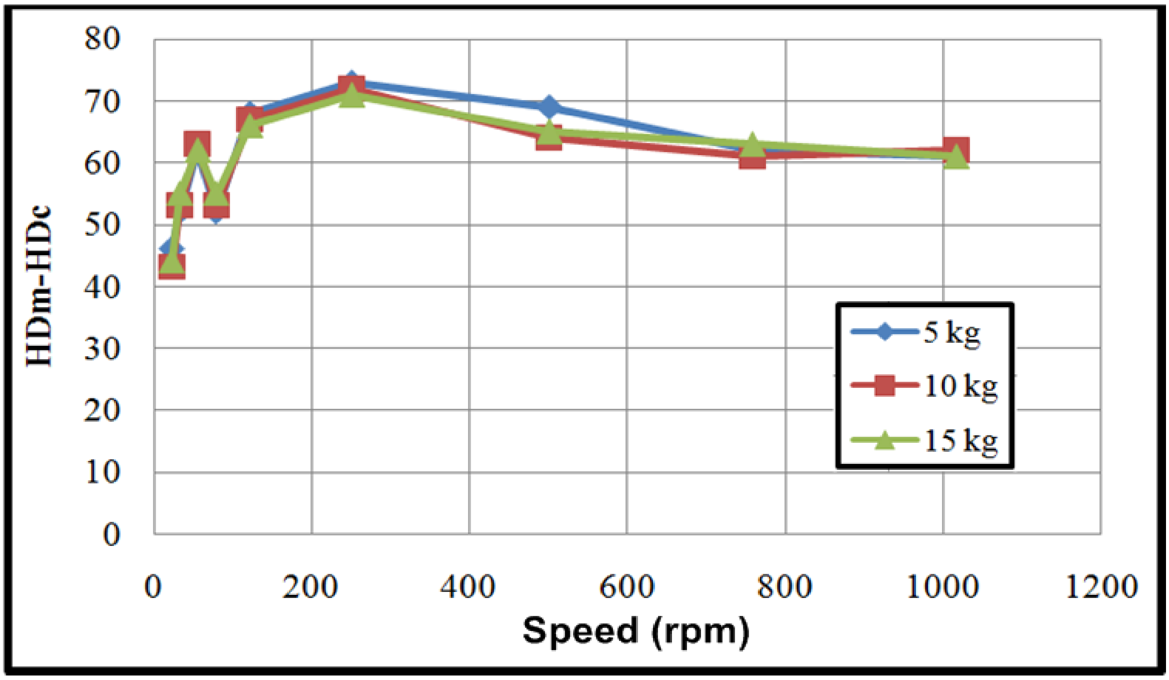

Figure 22. HDm – HDc value as a function of rotational speed and load

As shown in Figure 22, even at the lowest speed (24 rpm), the HDm – HDc value is still high (>15 dB) compared to those values at higher speed. Thus, it may be concluded that HDm/HDc measurement yields better results than both dBm/dBc and LR/HR measurements. This conclusion could be verified by investigating the HD spectrums.

Figures 23, 24, and 25 show the HD spectra of the damage bearing with a load of 15 kgf, and at speed of 57 rpm, 34 rpm, and 24 rpm, respectively. As clearly shown in Figure 23, the HD spectrum shows signal with BPFO and its harmonics. This result indicates that there is outer-ring damage in the tested bearing. Furthermore, Figure 24 also shows that HD spectrum at 34 rpm still shows the BPFO and its harmonics. As shown in Figure 25, even when the speed is reduced to 24 rpm, the BPFO signal is still visible although the harmonics are no longer clearly visible.

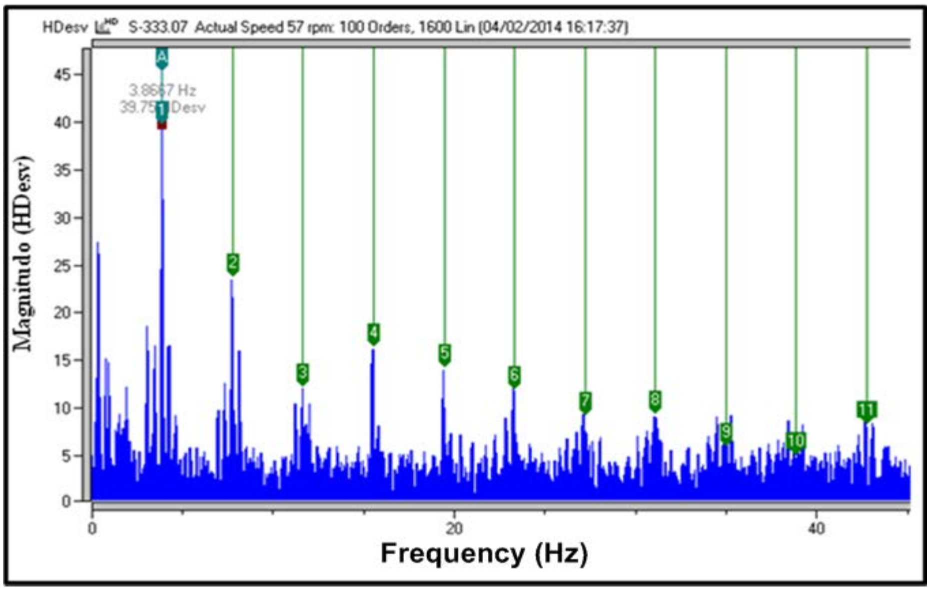

Figure 23. The spectrum of HD signal at speed of 57 rpm and 15 kgf load

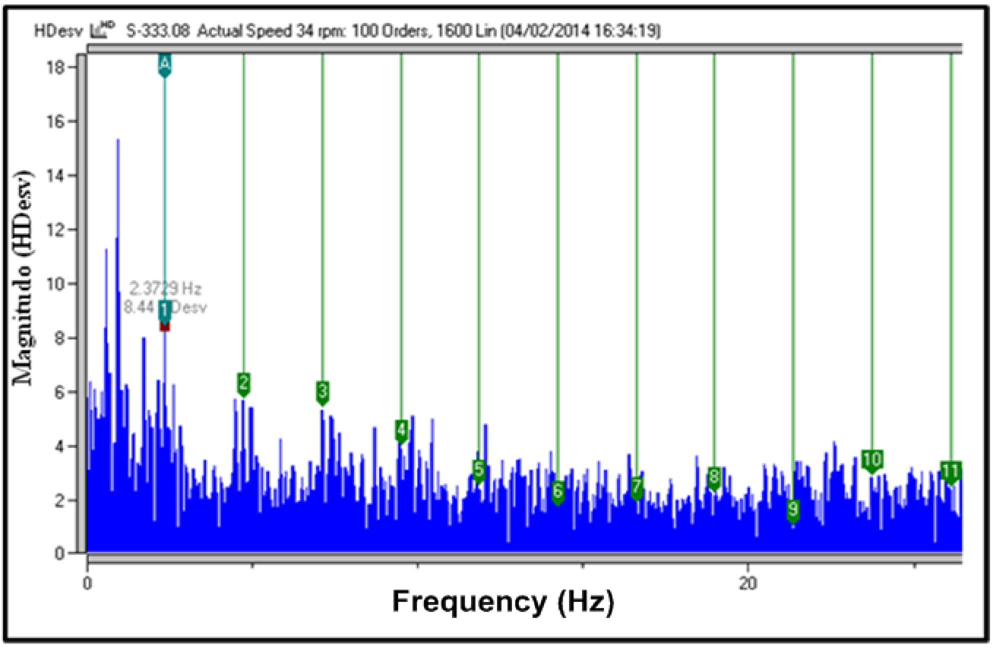

Figure 24. The spectrum of HD signal at speed of 34 rpm and 15 kgf load

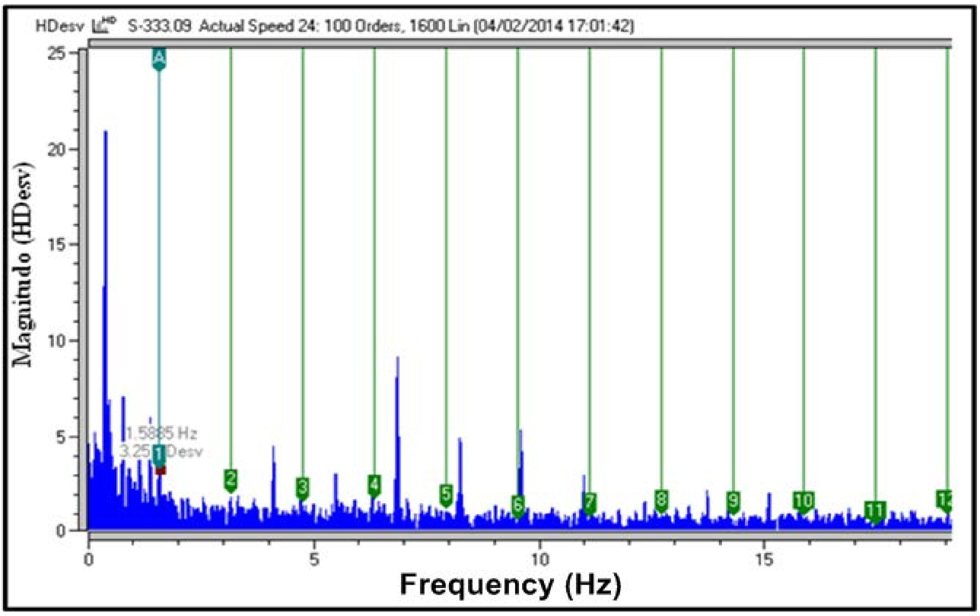

Figure 25. The spectrum of HD signal at speed of 24 rpm and 15 kgf load

It should be pointed out that the magnitude of signal with BPFO frequency is 39.75 HDesv at 57 rpm (Figure 23), 8.44 HDesv at 34 rpm (Figure 24), and 3.25 HDesv at 24 rpm (Figure 25). Although the HD signal consistently shows spectrum with peak signals at BPFO and its harmonics even at low speed, their magnitude is getting smaller at slower speed. However, the decrease of HD signal is much slower than vibration signal. Thus shock pulse measurement has a better chance of detecting bearing damage especially at low speed compare to vibration measurement.

Conclusions

In this paper, the effectiveness of vibration as well as shock pulse measurements to detect bearing damage has been demonstrated, especially in low speed. In vibration measurement, the RMS value is not a good indicator for bearing damage in low speed. On the contrary, CF (Crest Factor) value is a better indicator of the early bearing damage. In shock pulse measurement, HDm/HDc method of analysis is the better method to be used in bearing damage detection compare to either dBm/dBc or LR/HR method. Compare to vibration measurement, shock pulse measurement could detect bearing damage at lower speed.

Discussions

The results presented in this paper indicate that the HDm/HDc method of analysis used in shock pulse measurement could detect local bearing damage at speed as low as 24 rpm. However, this value is not the absolute limitation of the instrument (able to measure from a very low rpm; 1 – 20,000 rpm). As already discussed, higher load produces better impact signals thus easier to identify bearing damage. The maximum load used in this work is just 15 kgf out of 25.7 kN dynamic basic load bearing rating (or 150 N/25,700 N = 0.58 %). This level of load is too small to be considered applicable in practice. In future study, heavier loads must be used in order to assess the limit capability of the instrument.

Acknowledgement

The authors would like to thank PT. Dwihasta Pirusa and SPM Instrument (Asia) Pte Ltd for donating a Leonova Diamond instrument and Condmaster Ruby software to FTMD Institut Teknologi Bandung, Indonesia. The instrument and software have enabled us and our students to understand and to explore the potential capability of shock pulse measurement.

References

[1] T. Doguer, and J. Strackeljan, “New time domain methods for the detection of roller bearing defects,” In: *Proceedings of International Conference on Conditioning Monitoring & Machinery Failure Prevention Technologies CM 2008*, Edinburg, 2008.

[2] P. Shakya, M.S. Kulkarni, and A.K. Darpe, “A novel methodology for online detection of bearing health status for naturally progressing defect,” *Journal of Sound and Vibration*, Vol. 333, No. 21, pp. 5614-5629, 2014.

[3] W. Kruger, “*Tracking Rolling Elements Bearing Failure Using Mechanical and Electrical Vibration Testing Methods*,” ALL-TEST Pro, 2009, [Online]. Available: www.alltestpro.com/documents/RollingElementBearingFailureswithESAandMVA20 [Accessed: July, 2014]

[4] R.C. Eisenmann Sr., and R.C. Eisenmann Jr., *Machinery Malfunction Diagnosis and Correction*, Prentice Hall PTR, New Jersey, 1998.

[5] W. Kurniawan. *Damage Detection of a Rolling Bearing NTN Type N204 at Low Speed Using Vibration and Shock Pulse Measurements*, Thesis(BSc), Mechanical Engineering Department, Institut Teknologi Bandung, 2014 (in Indonesian).

[6] SPM Instrument Inc. *What’s New in Nova 2010 What’s New in Condmaster ® Nova 2010 Spm Instrument Ab I Box 504 I Se-645 25 Strängnäs I Sweden*, [Online]. Available: http://www.spminstrument.nl/data/pdf/instructions/71904B.pdf [Accessed: April, 2014]