Analysis of Contact Stress and Vibration of Rolling Element Bearing

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Abstract. The initial surface and operating condition of rolling element bearing are very important as this may reduce or extend the lifetime of the bearings. Bearing condition monitoring is one of the most used method to evaluate the bearing performance. In this study, the vibration level and surface deformation produced by different contact stress condition is investigated. The experiment is carried out using rolling contact rig and the roller samples are fabricated to produce line contact similar to the roller bearing. The rollers are made from four different materials to produce different contact characteristics. The finding shows that the contact stresses affect the vibration level and the surface deformation of the rolling contact.

1. Introduction

In various rotating mechanical or work machines, rolling bearings plays important role as parts of the machine. Rolling bearings is used to reduce friction produced by energy and power which enables the force acting between the moving and the fixed parts inside the mechanical process. Analysis of vibration is important in failure diagnosis and monitoring the rotating machines. During rolling operations, it is affected by friction, lubrication, material properties, and contact mechanics. Surface failure in rolling contact occur due to the critical mechanisms which are the wear and plastic deformation.

Halme and Andersson[1] diagnosed rolling contact wear and rolling contact fatigue by combining measured and interpreted data with theory. Plastic deformation, wear and fatigue cause surface degradation. Vibration level increase due to surface degradation which the wear particles formation and rolling surface roughening occur in bearing kinematic. Vrček et al.[2] described a methodology to investigate micro-pitting damage on bearing steels using a twin-disc machine to better represent mechanical components. Smooth-rough combination of specimens fasten the micro-pitting wear. Wear always occurred on the smooth surface due to stress by the rougher surface.

Yusof and Ripin[3] evaluated the surface degradation by surface roughness and waviness parameter. The results show that the surface degradation change most with the areal surface roughness parameter (Sₐ) and surface waviness parameter (Wₐ). Wang et al.[4] studied about the influence of friction and wear of the bearing on vibration under different rubber materials of the bearing lining and contact conditions. The results show that bearing vibration is affected by both friction and wear which are cause by the speed, load and temperature. The higher speed produces low friction coefficient hence results in low vibration level.

Sulka et al.[5] studied the vibration on a rotary shaft with a ball bearing roller and compared the results of damaged and undamaged rolling ball bearing by means Short-Time Fourier Transformation (STFT) and Fast Fourier Transformation (FFT). The results show that the deformation degree
increases lead to increase of vibration level. Khadersab and Shivakumar[6] proposed a technique to identify the bearing faults by vibration analysis for the rotating machinery. FFT, Inverse Fast Fourier Transformation (IFFT), and spectrogram is used for analyzed bearing faults to determine the failure of machine. Kulkarni and Wadkar[7] investigated the distributed defects of the ball bearing on the vibration response. The level of vibration varies with the increase of surface deformation. When the speed increase, the vibration level reduced. As the load increases, the surface deformation and the vibration level increase. Machado et al.[8] investigated the wear of journal bearing on rotating system in time domain.

2. Methodology

2.1. Experimental setup

In this study, a test rig for measuring rolling contact surface deformation is used as shown in Figure 1. The rig is consisting of roller specimens, stepper motor, linear guide, and four ball bearings. The test rig is put directly under Alicona Infinite Focus Microscope (IFM) therefore the surface scanning can be carried out directly. Load is applied to top roller. During surface characterization, the load is removed and there is an access hole to allow the microscope to scan the surface of the specimen. Both roller specimen is supported by two ball-bearings, but the top roller is free to move in the vertical direction, and the movement in the horizontal direction is limited by linear guides and the holders. The rolling stepper motor drives the lower roller which subsequently drives the upper roller via the line contact.

The rolling stepper motor is controlled by using Arduino which is Adafruit Motor Shield v2. The speed for the stepper motor is set at 200 rpm. The delay time after a complete cycle is set at 2 second. The programming is uploaded using Arduino Software. The slow speed is necessary in order to avoid slip and dynamic loading. Higher speed will cause higher deformation rate and as most materials are strain rate dependent, this may affect the deformation of the asperities. The high speed and dynamic loading condition may affect the ball bearings. During the experiment, the contact is dry, and the nominal contact length is 5 mm. The applied load is 50 N.

![Figure 1. Experiment setup](image)

2.2. Fabrication of roller specimens

The rollers are made from four different materials to produce different contact characteristics. Aluminium rod, brass rod, mild steel rod and stainless-steel rod were used to fabricate top roller and stainless-steel rod were used to fabricate four bottom rollers. Stainless steel was used as bottom roller to produce different contact condition with different upper roller materials. The diameter of both upper and bottom roller is 20 mm. For the fabrication of specimen, few steps have been taken in order to fit the specimens into the experimental rig. The specimen’s dimension must be considered to make sure it fit into the experimental rig.

First, the metal rod of aluminium, brass, mild steel and stainless steel were cut into smaller rod using metal cutting hacksaw machine to reduce material waste. The specimen was tightly gripped into a chuck of the CNC lathe machine and the coolant was supply to the tip of the tool to avoid
damage to the surface of the specimen and also the tool. Then, the dimension of the specimen needs to be set up into the programming of the machine and then the machine was run. The machine door was closed for safety precaution which is avoid the chip from specimen leaps out.

After the bottom roller and top roller have been fabricated, the surface finish is produced. The specimen is gripped into a chuck of Conventional Lathe Machine. Then, the machine is run at 180 rev/min. The surface is being polished using 600 grit sandpaper. 600 grit sandpaper are used for all material rollers to produce the same surface roughness. The specimen is furthered cleaned with acetone solution to remove dirt.

2.3. Contact stress calculation
The contact stress that occur during the contact between two rollers made of different material is determined using Hertzian contact pressure equation [9] as shown below:

\[
\frac{1}{E^*} = \left( \frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \right)
\]

(1)

Effective Radius Of Curvature,

\[
\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}
\]

(2)

Hertzian contact stress, \(P_H = \left( \frac{PE^*}{\pi R} \right)^{0.5} \)

(3)

where \(E\) is Young’s Modulus, \(\nu\) is Poison’s ratio, \(R\) is radius of curvature and \(P\) is load.

From the equation, it is shown that the contact pressure is contributed by material properties: - there are Young’s modulus and Poisson’s ratio, load and also specimen geometry which is the radius of the rolling elements that were in contact. In this work, the roller geometry and the load are similar for all specimens and only different materials were used. Therefore, the different contact pressure obtained in all 4 tests are contributed by the material properties.

2.4. Vibration measurement
The vibration measurement is carried out using acceleration parameter where the accelerometer is used. The accelerometer is placed on the 3 different locations on the jig as shown in Figure 2. The first accelerometer C4, is placed on the upper roller mounting. The second accelerometer C2, is placed on the lower roller mounting. The third accelerometer C3, is placed on the base of the experimental rig. The acceleration level is recorded after the motor is running stably which is after a few minutes switched on the motor.

![Figure 2. Location of accelerometer on the experimental jig](image-url)
2.5. Surface roughness measurement
Surface scanning is carried out using Infinite Focus Microscope (IFM). The IFM is able to scan surface topography and also measure surface roughness of the surface. The roller surface roughness is evaluated using average roughness \( R_a \) parameter. It is described as the arithmetic average of the absolute values of the profile height deviations from the mean line, recorded within the evaluation length. The surface roughness of the upper roller surfaces is measured every 20 cycles up to few hundred cycles.

3. Results and discussion
3.1. Contact stress analysis
The maximum contact pressure and shear stress acting on the two cylindrical surfaces in contact is calculated using Hertzian equation. From Table 1 the configuration of surface contact between stainless steel and aluminium has the lowest contact stress compared to other materials followed by brass, mild steel and stainless steel. This shows that the Hertzian contact stress is dependent on the modulus of the elasticity of the material in contact. From calculation, it is found that as the value of modulus of the elasticity increases, the maximum contact pressure increases. Even though the stainless has the highest contact stress, it is still relatively low if compared to the yield stress. From Table 1, it is shown that aluminium has the highest contact stress/ yield stress ratio.

| Material |
|----------|
| Lower roller |
| Upper roller |
| Stainless steel |
| 200 |
| 265 |
| 250 |
| 1.05 |
| Mild steel |
| 200 |
| 265 |
| 250 |
| 1.05 |
| Brass |
| 97 |
| 215 |
| 135 |
| 1.50 |
| Aluminum |
| 69 |
| 191 |
| 20 |
| 9.55 |

3.2. Vibration level
Figure 3 shows the average value of vibration level at 3 different locations. The highest vibration level occur on the base of experimental rig. This is expected due to the vibration of stepper motor that is attached on the base. The vibration level at the upper roller mounting is the lowest due to the high speed of the stepper motor which result in low vibration level from the mating surfaces. The vibration level at the upper roller mounting for all materials are the same due to the vibration is produced by the contact and not by the rig. Aluminium produced highest vibration level followed by brass, mild steel and stainless steel. At high \( P_H / P_Y \), plastic deformation occur, thus resulted in high vibration level.
3.3. Surface roughness analysis

The average surface roughness, $R_a$, after experiment is compared with the initial $R_a$ value as shown in Figure 4. It shows aluminium has the highest percentage of reduction followed by brass, mild steel and stainless steel. For aluminium, the high ratio between contact stress and yield stress ($P_H/P_Y$) cause plastic deformation drastically occur on the surface therefore reduce the $R_a$ value for 22.8% after a few cycles. In comparison with stainless steel, the contact stress and yield stress ratio is low ($P_H/P_Y = 1.055$) therefore the contact is partly elastic and very less plastic deformation occur. This is the reason why the $R_a$ reduction is very small at 2.1%. It is found that as $P_H/P_Y$ increases, the surface deformation occurred on the surfaces increases. By comparing Figure 3 and Figure 4, it is found that as the percentage of average roughness reduction higher, the vibration level also higher.

![Figure 3. Average value of acceleration level at 3 different location against type of materials](image)

![Figure 4. Average surface roughness ($R_a$) before and after rolling contact](image)

4. Conclusion

The conclusions from this study are:

1. In rolling contact, the Hertzian contact stress between two mating surfaces may influence the vibration level and rate of surface deformation. Aluminium roller with high $P_H/P_Y$ cause high vibration level due to the contact occur at the plastic condition ($P_H/P_Y = 9.55$). Surface deformation also happen abruptly at this contact condition where the $R_a$ reduce for 22.8%
after few cycles. In comparison with stainless steel roller with $\frac{p_u}{p_v} = 1.05$, the vibration is relatively low and surface roughness reduction is small with 2.1%. This is due to less plastic deformation and the contact is partly elastic.

2. The finding shows that, the selection of materials and load is very important in machine operation. The contact condition has high influence on vibration and surface deformation.

5. References

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