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Vibration Analysis for Fault Diagnosis in an Overflow Ball Mill: A Case Study at Sarcheshmeh Copper Complex

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Abstract

Overflow ball mills play a crucial role in the mining industry, as any unexpected downtime in these machines can lead to production line stoppages. To prevent such interruptions, regular and planned condition monitoring is essential. In the context of the slag flotation plant at the Sarcheshmeh Copper Complex, an increase in vibration in the overflow ball mill prompted this study to diagnose the fault using vibration and thermal analysis. To conduct this analysis, we employed data measurement techniques, including a vibrometer and accelerometer probe for vibration analysis, as well as thermal imaging for assessing thermal conditions. Our examination of the collected data via frequency spectrums revealed significant vibration amplitudes in gear mesh frequencies, which are indicative of problems with the pinion and ring gear. The vibration analysis pointed towards symptoms of tooth profile errors and misalignment. Additionally, our thermal analysis uncovered an uneven temperature distribution across the pinion surface, corroborating the findings from the vibration analysis. In conclusion, we propose certain recommendations to address these issues and ensure the consistent peak performance of the ball mill.

Keywords: condition monitoring; fault diagnosis; vibration analysis; thermal analysis; overflow ball mill

1. Introduction

Ball mills are extensively employed in the mining industry for material grinding. Among the various types, the overflow ball mill is specifically designed to allow material overflow and discharge from the trunnion on the outlet side [1]. Illustrated in Figure 1, these mills comprise several key components, including the feeding end, the shell, the discharge end, main bearings, and the drive system.

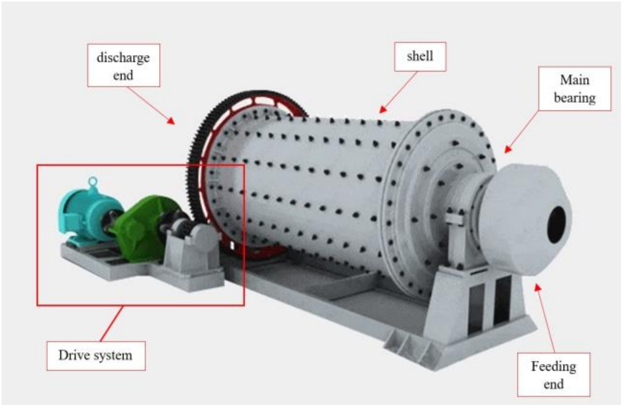


Figure 1. BallMill components.

Ball mills are critical equipment in the production line, as unexpected breakdowns can grind operations to a halt. To proactively prevent such disruptions, continuous monitoring is essential for detecting and tracking faults. Condition-based monitoring (CbM) stands out as one of the most effective maintenance approaches for assessing machinery health [2], [3], [4]. CbM involves ongoing monitoring of equipment conditions using an array of sensors. The data collected from these sensors enable real-time asset surveillance, facilitating trend identification, prediction of potential failures, estimation of asset lifespan, and overall safety enhancement within manufacturing plants [5]. Central to CbM is fault diagnosis, allowing operators not only to identify mechanical issues but also pinpoint their root causes for precise and effective repairs [6].

Vibration analysis serves as a cornerstone in condition monitoring and fault diagnosis, clarifying changes in the condition of machine components through the acquisition of vibration signals. By scrutinizing these acquired vibration signals, the underlying causes of changes and potential faults can be determined [7]. Vibration analysis has seen extensive use in diagnosing faults in ball mills [8], [9], [10], [11], [12]. Within vibration analysis, critical problems such as pinion and gear faults, bearing defects, misalignment, and motor issues are detectable at primary levels. The degradation process of ball mill gears, including changes in vibration and spectral characteristics, has been thoroughly investigated using signal processing and vibration analysis by D. Wen et al. [13]. Dobromir Dobrev and Nikolay Nikolaev conducted research that explores bearing damage detection in a ball mill using spectrum analysis and related tools [14]. Additional ball mill bearing defects have been identified with vibration analysis tools by S. Nergaard [15]. Furthermore, vibration signal spectra have been leveraged to estimate the actual grinding status of a wet ball mill, utilizing two wireless accelerometer sensors mounted at the feed and discharge ends [16].

The objective of this study is to uncover the root cause of the substantial vibration amplitudes observed in an overflow ball mill situated within the slag flotation plant of the Sarcheshmeh copper complex. Vibration analysis is employed to diagnose the fault, with vibration measurements taken using the OLIP VIBPRO V4, 2CH Vibration Analyzer. To enhance the accuracy of the results, thermographic analysis is also conducted using the FLIR TG500 thermal imaging camera.

2. Setup and methodology

Condition monitoring through vibration analysis is a technique employed to oversee the health of various industrial equipment. Typically, vibration-based condition monitoring of equipment is conducted according to a predetermined schedule. In the slag flotation plant at the Sarcheshmeh copper complex, the overflow ball mill, denoted as 37-2103-01 (Figure 2), undergoes regular monitoring in accordance with this schedule. Recent data collected from these monitoring efforts have revealed both an increase and fluctuations in vibration amplitudes.

Figure 2. Overflow ballmill.

The condition of the ball mill is assessed by measuring vibrations on non-rotating components in accordance with the principles outlined in "ISO 10816". As per the standard, measurements are conducted on the four bearing pedestals, as illustrated in Figure 3. Vibration data is recorded in three distinct axes—vertical, horizontal, and axial—for all four bearing pedestals.

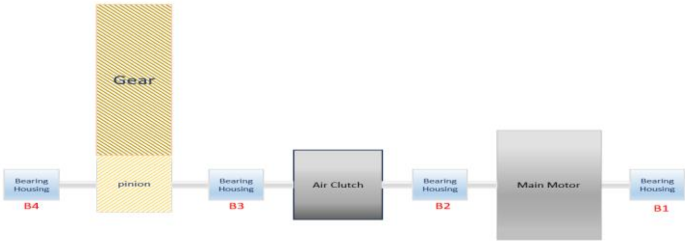


Figure 1. Data measuring points.

To define vibration limits and boundaries in alignment with equipment specifications, the ISO 10816-1 criteria are utilized to assess vibrations in the ball mill, whereas the ISO 10816-3 criteria are applied to evaluate motor vibrations. A summary of the ball mill specifications can be found in Table 1.

Table 1. Ball mill specifications.

equipment	Parameter	Value
Motor	Type	synchronous
	Power	3600 kW
	Voltage	6.6 kV
	No. of poles	30
	Speed	200 rpm (3.3Hz)
	Foundation condition	Rigid
Pinion & Gear	Type	Helical Gear
	Pinion speed	200 rpm (3.3Hz)
	Gear speed	14.4rpm (0.24 Hz)
	No of pinion teeth	19
	No of gear teeth	264

To identify faults using vibration spectra, the fault frequencies of power transmission components are initially calculated (Table 2).

Table 2. Fault Frequencies.

		Frequencies (Hz)			
		FTF	2xBSF	BPFI	BPFO
Bearings	B1	Journal bearing			
	B2	Journal bearing			
	B3(fix)	1.43	23.33	34.1	25.9
	B4(float)	1.43	23.33	34.1	25.9
Pinion & Gear	GMF	63.3			
Motor	Pole Pass Frequency	1.6			

Data acquisition was carried out using a VIBPRO V4-2 Channels vibrometer (with a maximum frequency of fmax = 40 kHz) and an accelerometer vibration probe. To ensure the accuracy of the results, thermography analysis was also conducted using the FLIR TG500 thermal imaging camera.

3. Results and discussion

In this section, we delve into the performance of condition monitoring through a comprehensive examination, utilizing both vibration and temperature analysis.

3.1 Vibration condition monitoring

The initial step in this section involves data acquisition for vibration analysis. The obtained results have been compiled in Table 3, which presents the RMS values of vibrations for both velocity and acceleration in three distinct directions. The table also includes the vibration evaluation zones according to ISO 10816-1 (for gear and pinion vibrations) and ISO 10816-3 (for motor vibrations), distinguished by various colors.

As depicted in the table, it's evident that the vibration amplitudes are notably high for bearings No.1, 3, and 4 in the axial direction. Bearing No.1, for instance, exhibits an RMS vibration value of 8.23 mm/s in the axial direction, placing it in zone D—a classification indicating significant severity that could lead to machine damage. Bearing No.3 presents a similar situation with an RMS value of 12.78 mm/s, which is the highest amplitude among all. Similarly, the vibration amplitude in the axial direction for bearing No.4 is noteworthy at 10.87 mm/s, categorizing it in zone C. According to the standard, this condition is not suitable for prolonged operation.

Analyzing the trend over a one-month period reveals variable amplitude vibrations observed in the axial direction of the first, third, and fourth bearings. Examining the axial direction of the frequency spectrum for bearing No.3 (see Fig. 4) and bearing No.4 (see Fig. 5) reveals that the dominant peaks are associated with gear mesh frequencies. Specifically, the 2xGMF frequency predominates in the axial direction of bearing No.4, whereas the 1xGMF frequency is the dominant peak in the axial direction of bearing No.3. Additionally, there are discernible 1xRPM and 2xRPM sidebands surrounding the 1xGMF and 2xGMF frequencies in the frequency spectrum of both bearing No.3 and No.4.

Table 3. Overall RMS values.

	Velocity - mm/s (2-2000 Hz)						Acceleration - g (10-10000 Hz)		
	Vertical (mm/s)		Horizontal (mm/s)		Axial (mm/s)		Vertical (g)	Horizontal (g)	Axial (g)
	Am.	*V.S	Am.	V.S	Am.	V.S	Am.	Am.	Am.
B1	**1.53**	**A**	**1.24**	**A**	**8.23**	**D**	**0.09**	**0.07**	**0.33**
B2	**3.73**	**A**	**1.23**	**A**	**4.72**	**C**	**0.18**	**0.08**	**0.22**
B3	**2.37**	**B**	**1.56**	**A**	**12.78**	**D**	**0.21**	**0.14**	**0.78**

B4	1.85	A	1.61	A	10.87	C	0.25	0.18	0.76

Equipment conditions:	* **Vibration Severity (ISO 10816-3) (For Motor Bearings):**				
CLASS: Group 1 ☒ Group 2 ☐	**Zone**	**A**	**B**	**C**	**D**
A: Good B: Satisfactory C:Unsatisfactory D: Unacceptable	**Vibration (mm/s –RMS)**	**≤ 2.3**	**2.3 – 4.5**	**4.5– 7.1**	**≥ 7.1**
		Good	Satisfactory	Unsatisfactory	Unacceptable
Equipment conditions:	**Vibration Severity (ISO 10816-1) (Pinion Bearings):**				
Class: I ☐ II ☐ III ☒ IV ☐	**Zone**	**A**	**B**	**C**	**D**
A: Good B: Satisfactory C:Unsatisfactory D: Unacceptable	**Vibration (mm/s –RMS)**	**≤ 1.8**	**1.8 – 4.5**	**4.5– 11.2**	**≥ 11.2**
		Good	Satisfactory	Unsatisfactory	Unacceptable

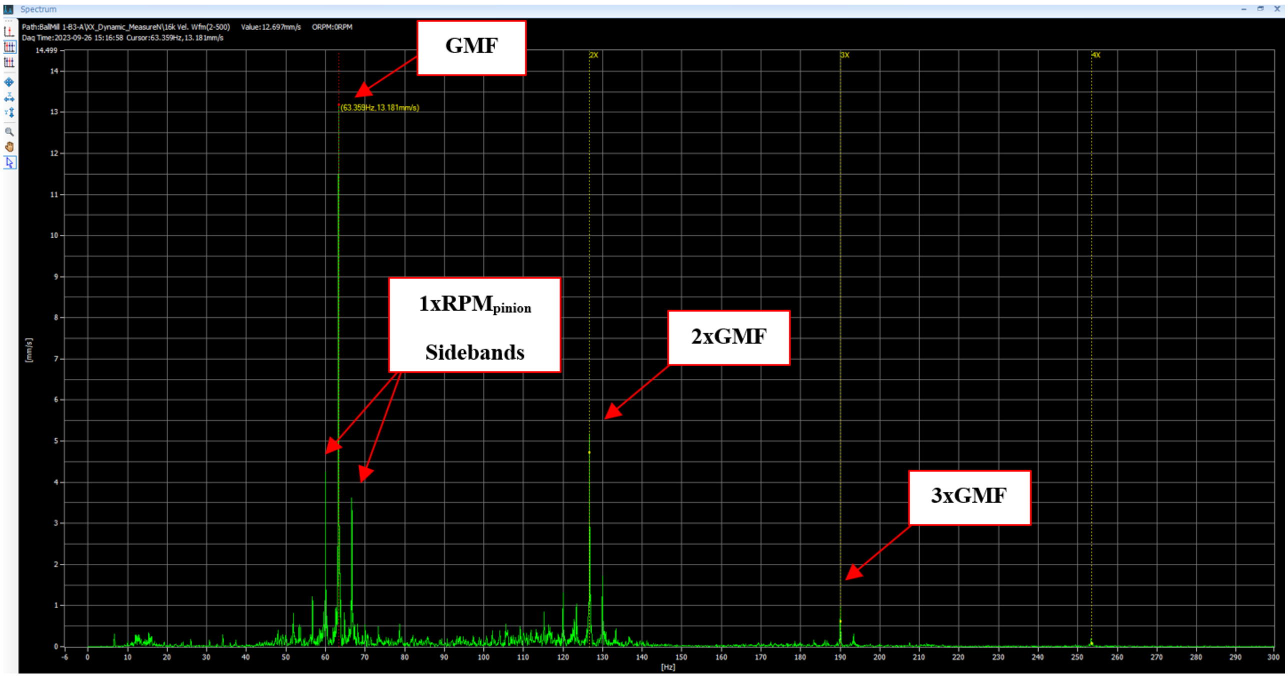


Figure 4. Bearing No.3 Frequency spectrum axial direction.

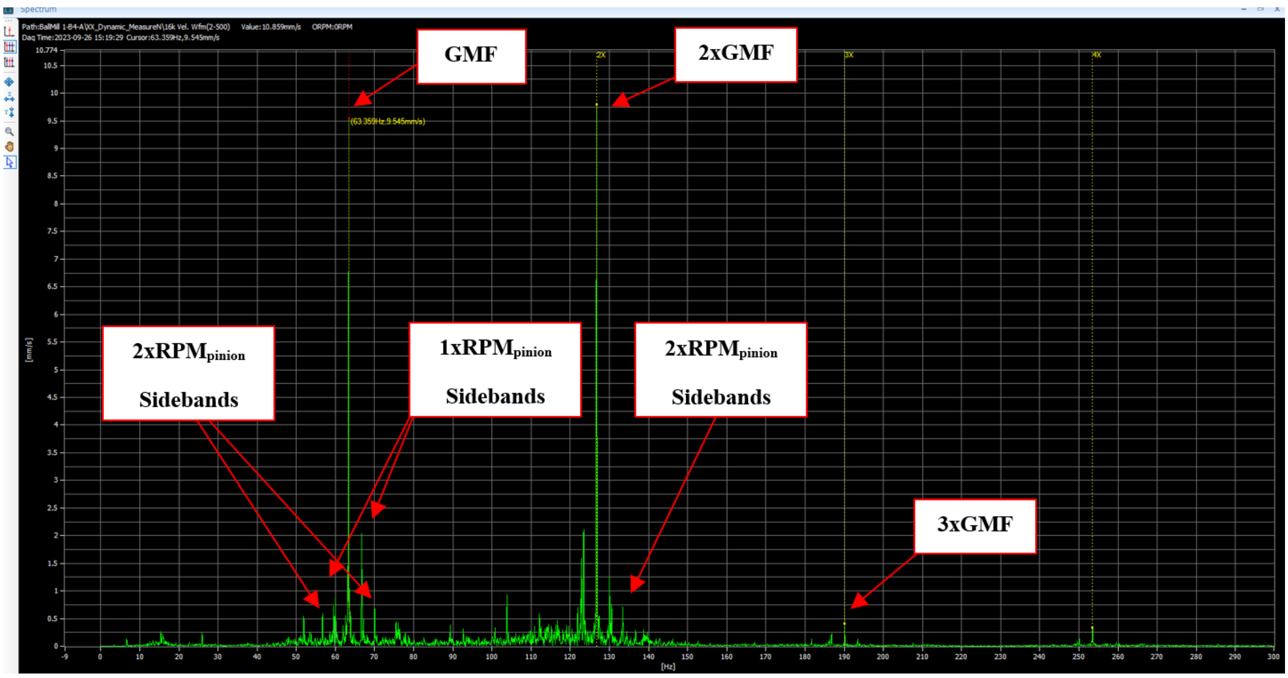
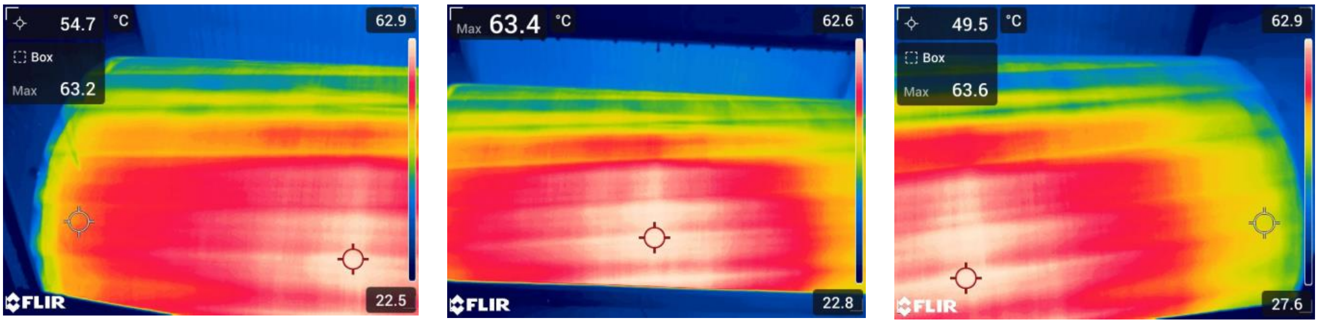


Figure 5. Bearing No.4 Frequency spectrum axial direction.

3.2 Temperature condition monitoring

To gain a more precise understanding of the issue, temperature analysis was performed using the FLIR TG500 thermal imaging camera, and the results are illustrated in Fig 6. As evident from the illustration, the temperature distribution across the pinion's surface is uneven. The region with the highest temperature, signifying the contact surface, tilts towards the left (the drive-end side). Specifically, the temperature on the left side measures 54.7 °C, whereas on the right side, it registers at 49.5 °C.



a. Pinion left side (DE)　　b. Pinion center　　c. Pinion right side (NDE)

Figure 6. Thermal analysis of pinion surface.

4. Fault diagnosis

Upon analyzing the frequency spectrum of the third and fourth bearings, it becomes evident that the high amplitude of vibrations can be attributed to the gear mesh frequencies. These gear mesh frequencies (3xGMF, 2xGMF, GMF) consistently appear in the standard frequency spectrum with minimal amplitudes. However, any increase in the amplitude of these peaks or sidebands suggests the potential presence of an issue within the gear assembly, necessitating further investigation. The spectrum analysis of the third and fourth bearings has unveiled the existence of certain defects, listed below in order of priority.

Tooth Profile Error: The presence of fluctuating vibrations in the gear and pinion system indicates the existence of a force with variable amplitude. One contributing factor to this variable amplitude force is errors in the tooth profile. A tooth profile error becomes problematic when the manufactured tooth profile deviates significantly from the ideal design state. As illustrated in Figure 7, the black profile represents the ideal and design state, while the purple profile depicts the actual manufactured profile. A tooth profile error can lead to issues such as incorrect backlash or gear meshing problems.

Misalignment: An increase in vibration amplitude at the 2xGMF frequency, along with the presence of 1xRPM and 2xRPM sidebands, suggests the existence of a misalignment problem within the gears. This misalignment issue is further confirmed by examining the thermography images (Figure 6). The temperature distribution across the pinion surface is non-uniform, indicating that the contact area may not be symmetrical, which is a problem resulting from misalignment. Misalignment can manifest in various forms, as illustrated in Figure 8.

Radial Misalignment (Mode b): In this mode, the center distance between the two gear axes is excessive, leading to an increase in backlash, with the contact area primarily in the addendum.

Axial Misalignment (Mode c): Here, the center distance corresponds to the correct size, but the two gears have different axial distances. This results in a lack of contact on a portion of the tooth's surface, even though the backlash remains constant.

Yaw Misalignment (Mode d): This form of misalignment involves non-parallel orientation of gear shafts, tilted at an angle on the horizontal plane. Yaw misalignment can alter the clearance and backlash, depending on the angle, impacting the contact area and gear noise.

Pitch Misalignment: When the pinion and gear shafts are misaligned by introducing an angle in the vertical plane, pitch misalignment occurs. This type of misalignment leads to increased wear on the

flank edges, reducing the cushioning effect and causing the gears to impact and separate along the flank edges during meshing.
Addressing these potential defects is crucial to ensuring the continued and reliable performance of the ball mill.

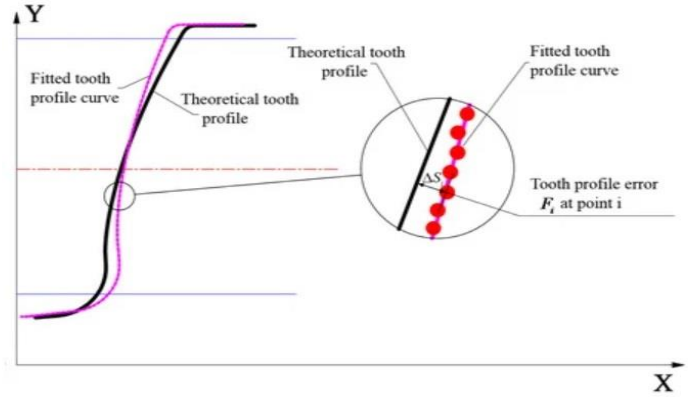


Figure 7. Tooth profile error.

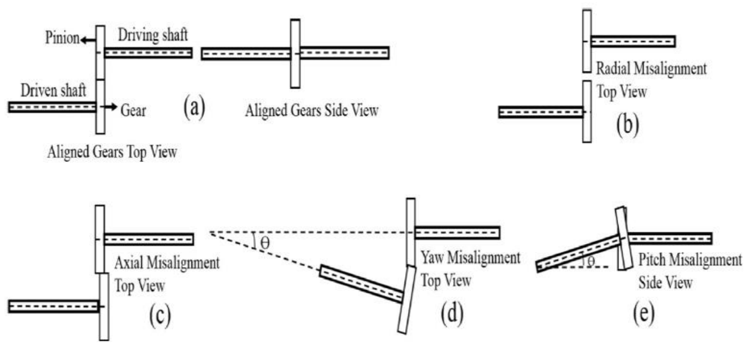


Figure 8. Five types of misalignment.

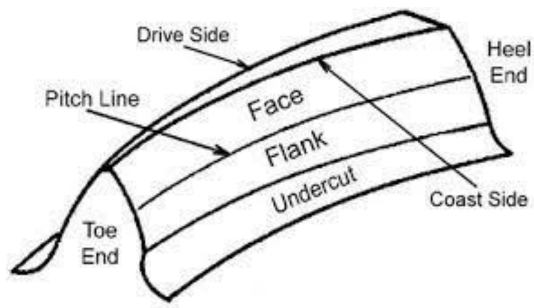


Figure 9. Flank zone in the tooth surface.

5. Conclusion

This study involved the comprehensive process of vibration condition monitoring and fault diagnosis on a ball mill situated within the slag flotation plant of the Sarcheshmeh copper complex. To accomplish this, a vibrometer and accelerometer vibration probe, along with a thermal imaging camera, were deployed for data acquisition. A thorough analysis of the collected data revealed abnormally high vibrations in the axial direction of three bearings. Further scrutiny of the frequency spectra unveiled that the dominant peaks within this heightened vibration were attributed to gear mesh frequencies.
The utilization of vibration and thermal analysis led to the identification of two potential faults that could impact these gear mesh frequencies: tooth profile errors and misalignment. Misalignment was

indicated by an uneven wear pattern on the tooth surfaces. As a recommended course of action, it is advisable to initiate a thorough cleaning of the tooth surfaces and subject them to visual inspection. Investigating the manner and location of wear on the tooth surface can be particularly effective in detecting misalignment and identifying its specific type, as elaborated in the analysis section.

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