Diagnosing the Defects of the Gears of the Gearbox Using Vibration Analysis and Validating it by the Graphs of the CMM Machine

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Abstract

This study focuses on diagnosing gear defects in the S5-380 transmission using advanced vibration analysis and validating findings through the HÖFLER Gear Testing Machine. The research highlights key faults such as backlash, eccentricity, and shaft deflection identified via vibration measurements and confirmed using detailed gear profile and lead inspections. The vibration analysis employed V-SAM Vibrometer and V-SAM-Web Soft to detect critical parameters, including Gear Mesh Frequency (GMF) and Gear Hunting Tooth Frequency (GHTF). Results demonstrated the robustness of vibration analysis as an efficient, cost-effective alternative to Coordinate Measuring Machines (CMM) for end-of-line quality control. Furthermore, integrating vibration analysis with CMM-based validation provided precise fault identification, enabling targeted maintenance and enhanced gearbox performance. The findings underscore the potential of transitioning to AI-driven diagnostic systems in Industry 5.0 for real-time, scalable, and intelligent gearbox monitoring. This approach offers significant implications for improving durability, quality, and operational efficiency in gear manufacturing.

Keywords: Gear Fault Diagnosis, Vibration Analysis, Artificial Neural Network (ANN), Machine Learning (ML), Industry 5.0, Signal Processing

1. Introduction

In heavy-duty vehicles, the gearbox plays a critical and intricate role in the drive train system. Also referred to as the transmission, this component is responsible for transferring engine power to the wheels and managing the gear ratios to adapt to varying driving conditions. Heavy-duty vehicle gearboxes are designed with greater complexity and durability compared to those in lighter vehicles, due to the demands of handling substantial loads and maintaining optimal performance across a wide range of speeds. In the R&D division of Charkheshgar Company, a semi-heavy gearbox was engineered and manufactured to enhance and fortify gearbox performance. To address and resolve issues observed in an existing foreign model, a similar gearbox available for analysis was subjected to detailed vibration condition monitoring. This process allowed for the identification of several critical issues, including:

- **Backlash**: Excessive clearance between meshing gears, leading to loss of precision and increased wear.
- **Eccentricity**: Misalignment or out-of-round conditions in gears, affecting smooth operation and gear engagement.
- **Shaft Deflection**: Inadequate or improper shaft alignment under load, impacting the overall stability and performance of the gearbox.

The insights gained from this vibration analysis were instrumental in refining the design and functionality of the gearbox. The identified problems were addressed in the optimization process, leading to improvements in gear accuracy, load handling, and overall operational efficiency. This approach not only resolved issues present in the foreign model but also provided valuable data to enhance future gearbox designs and applications. At T.P.T. Co.'s R&D department, a proprietary software solution called V-SAM-Web Soft (under web Software) has been specifically developed for diagnosing gear and bearing faults in transmission using vibration analysis. This software is capable of identifying gear meshing frequencies (GMF), gear hunting tooth frequencies (GHTF), Gear assembly phase frequencies (GAPF) or fractional GMF, and also defects such as backlash, gear wear, excessive load on tooth, eccentric gears, misaligned gears, and cracked or broken tooth. In this study, data was collected using the V-SAM Vibrometer from the S5-380 transmission, which was subjected to load testing. Following the fault diagnosis via vibration analysis, the transmission was disassembled, and the gears were sent to the CMM unit for detailed inspection. Subsequently, the Höfler machine was employed to generate the relevant graphs, which validated and confirmed the faults identified through the vibration analysis.

2. Fault Diagnosis of Transmissions and Gears

Fault diagnosis of transmissions and gears is a critical process in the maintenance and optimization of mechanical systems, requiring specialized knowledge and advanced techniques. Below is a detailed, technical overview of the various methods used in transmissions and gear fault diagnosis:

1. Vibration analysis
2. Oil Analysis
3. Thermal Analysis
4. Ultrasonic Testing
5. Modal Analysis
6. Acoustic Emission Testing & etc.

In this study, we conducted a comprehensive analysis of the transmission using advanced vibration analysis techniques. Following the initial fault detection, we employed Coordinate Measuring Machine (CMM-HÖFLER Gear Testing Machine) technology to validate the identified anomalies. This validation was performed through precise measurement and evaluation of the gear profile and lead graphs, ensuring the accuracy and reliability of the fault diagnosis process. The integration of vibration analysis with CMM-based verification provided a robust methodology for identifying and confirming gear defects with high precision.

2.1. *Gear Vibration Theory*

When two or more gears are in mesh, the frequencies such as GMF, GHTF & GAPF, generated depend upon gear speed, number of teeth and common factors. Below we will give a detailed definition of each:

2.1.1. Gear Mesh frequency (GMF)

GMF is a crucial concept in the field of vibration analysis, particularly in the context of rotating machinery and gear systems. It refers to the frequency at which the gear teeth mesh, or engage, during operation. The Gear Mesh Frequency is calculated using the following formula:

$$\mathrm{GMF} = \mathrm{NTG} * \mathrm{RSG} \tag{1}$$

Where:

NTG : Number of Teeth on the Gear is the total number of teeth on the gear being analyzed.

RSG : **Rotational Speed of the Gear** is the rotational speed of the gear in revolutions per second (Hz).

Importance in Vibration Analysis:

- **Condition Monitoring**: GMF is a key indicator in vibration analysis for diagnosing gear-related faults. It helps in detecting issues like misalignment, wear, and tooth damage.
- **Fault Detection**: Any deviation or sideband frequencies around the GMF can indicate potential faults or defects in the gear system, such as gear tooth damage, misalignment, or lubrication problems.
- **Harmonics and Sidebands**: Typically, GMF will have harmonics, and sidebands may appear around the GMF frequency due to modulation effects, which are critical in diagnosing specific types of gear faults.

2.1.2. Gear Hunting Tooth Frequency (GHTF):

GHTF is another important concept in gear vibration analysis, particularly in systems where two or more gears mesh together. It is related to the unique periodic interaction of a specific tooth on one gear with a specific tooth on another gear. This interaction occurs over a longer cycle than the regular gear mesh frequency (GMF).

2.1.3. Understanding Hunting Tooth Frequency (HTF)

- **Hunting Tooth Cycle**: In gear systems, a hunting tooth cycle is the period it takes for a particular tooth on one gear to mesh again with the same tooth on another gear. This cycle is significant because it represents a unique combination of teeth that meet only after a certain number of revolutions.
- **Application**: GHTF is most relevant in gears with non-integral gear ratios, where the same tooth pair does not mesh repeatedly with each revolution. Over multiple cycles, different teeth interact, which can be used to diagnose specific wear patterns or faults that develop over a longer period.

The Hunting Tooth Frequency can be calculated using the following formula:

$$GHTF = \frac{GMF}{GCD} \tag{2}$$

GHTF=GMF/Greatest Common Divisor (GCD) of the number of teeth on both gears

Where:

GMF is defined as (1)

GCD : Greatest Common Divisor is the Greatest Common Divisor of the number of teeth on the driving and driven gears.

Importance of HTF in Gear Analysis:

- **Wear and Tear Detection**: GHTF can help in identifying wear patterns that develop over time, as the same pair of teeth only meet after a certain number of revolutions. This can reveal issues like pitting, spalling, or other damage that might not be evident in the regular GMF spectrum.

- **Long-Term Monitoring**: GHTF provides insight into the long-term interaction between gear teeth, which is crucial for predictive maintenance and avoiding unexpected gear failures.

GHTF is particularly useful for monitoring complex gear systems were identifying unique, long-cycle interactions can help prevent significant damage and extend the life of the machinery.

2.1.4. Gear assembles phase frequencies (GAPF) or Fractional GMF

GAPF or Fractional gear mesh frequency refers to a frequency that occurs in gear systems and is a fraction of the standard gear mesh frequency. When the number of teeth on each meshing gear has a common factor greater than 1, and one of the gears is eccentric, every Nth tooth (where N is the common factor) on the well-aligned gear can be imprinted or worn by the eccentric gear. This imprinting or wearing causes the Nth cycle of the gear mesh frequency to have a higher amplitude than the other cycles.

2.2. GEAR PROBLEMS AND CAUSES

Vibration analysis is a powerful diagnostic tool used to detect and analyze various types of gear failures in mechanical systems. By monitoring and interpreting vibration signals, maintenance professionals can identify potential issues early and prevent catastrophic failures. Below is a detailed examination of common gear failures and how vibration analysis can be used to detect them:

- Eccentric gears
  Eccentric gears can take many forms. For explanation purposes, eccentric gears are divided into four broad categories:
  1. Meshing gears that have a common factor and one gear is eccentric
  2. Gears that do not have a common factor and one or both gears is eccentric
  3. Gears that are out-of-round or have several high places
  4. Gears installed on a bent shaft
- Loose and worn gears
- Misaligned gears
- Backlash Issues and Oscillating Gears
  Backlash issues or oscillating gears can induce a significant second harmonic at the gear mesh frequency. An elevated amplitude at twice the gear mesh frequency is a strong indicator of backlash or oscillating gears. To accurately diagnose this condition, further analysis in the time domain is essential. It is important to note that the second harmonic appears at the peak of the signal, which implies it is 180° out of phase with the fundamental frequency. This phase discrepancy is characteristic of a backlash-related issue. Conversely, if the second harmonic were due to misalignment, both signals would be in phase, and the second harmonic would manifest at the trough of the signal. The observed out-of-phase condition in this instance

suggests that the gears are experiencing back-and-forth motion. Consequently, inspections for gear looseness or associated bearing issues may not reveal any obvious abnormalities. The underlying causes of backlash and gear oscillation are multifaceted. Some potential sources include:

- **Lightly Loaded Gears:** Gears operating under light loads are prone to oscillation.
- **Inconsistent Loading:** Irregular loads in equipment such as agitators or digesters can lead to gear oscillation.
- **Draw Issues in Paper Machines:** Tension problems in paper machines can exacerbate both of the aforementioned conditions.
- **Electric Drive Power Source Issues:** Malfunctions in the power source for certain electric drives may contribute to these problems.
- **Excessive Backlash:** Excessive gear backlash may also be a contributing factor.
- **Broken, cracked, or chipped teeth**

2.3. All needed Information for frequencies calculation and vibrometer setup

According to the documents received from the Charkheshgar Co., all frequencies related to: Gear Mesh Frequency, Fractional Gear Mesh Frequency, Hunting Tooth Frequency and Gear Life Expectancy are calculated in V-SAM-GearboxFcal software according to the table 2. It is worth noting that software inputs are displayed in yellow according to the table 1

Table 1. V-SAM-GearboxFcal software

Basic Input & Output											
Input RPM (S1: Input Shaft)											
2325.6	RPM	38.76	Hz	Z-Input	26	Z-Mate-lay shaft	34	Z-G1	43	Z-Mate-lay shaft-G1	14
.				GMF: Z-Input with Z-Mate-lay shft (Gear Mesh Frequency)				GMF: Z-G1 with Z-Mate-lay shft-G1 (Gear Mesh Frequency)			
579.0139535	RPM	9.650232558	Hz	60465.6	CPM	1007.76	Hz	24897.6	CPM	414.96	Hz
Output RPM (Gear 2: Output Shaft)											
1003.2	RPM	16.72	Hz	Ratio G-1							
Output RPM (Gear 3: Output Shaft)				Ratio G-2							
1659.84	RPM	27.664	Hz	Ratio G-3							
Output RPM (Gear 4: Output Shaft)				Ratio G-4							
2325.6	RPM	38.76	Hz	Ratio G-5							
Output RPM (Gear 5: Output Shaft)				Ratio G-Re							
3218.057143	RPM	53.63428571	Hz	Na:(Z-Input with Z-Mate-lay shft)-(common factor)				Na:(Z-G1 with Z-Mate-lay shft-G1)-(common factor)			
Output RPM (Reverse Gear : Output Shaft)				2				1			
655.2	RPM	10.92	Hz	Z-Input with Z-Mate-lay shft:Gear Assembly phase frequency (GAPF)				Z-G1 with Z-Mate-lay shft-G1:Gear Assembly phase frequency (GAPF)			
Lay shaft RPM				1-GAPF	503.88	Hz		1-GAPF	414.96	Hz	
1778.4	RPM	29.64	Hz	2-GAPF	1007.76	Hz		2-GAPF	829.92	Hz	
Set Fmax-Input shaft				3-GAPF	1511.64	Hz		3-GAPF		Hz	
3275.22				4-GAPF	2015.52	Hz		4-GAPF		Hz	
Set Fmax-G1				5-GAPF	2519.4	Hz		5-GAPF		Hz	
1348.62				Hunting Tooth Frequency (HTF)-Z-Input with Z-Mate-lay shft				Hunting Tooth Frequency (HTF)-Z-G1 with Z-Mate-lay shft-G1			
Set Fmax-G2				2.28	Hz			0.689302	Hz		
2119.26				2 HTF-Z-Input with Z-Mate-lay shft				2 HTF-Z-G1 with Z-Mate-lay shft-G1			
Set Fmax-G3				4.56	Hz			1.378605	Hz		
2697.24				1X Gear (HTF SIDEBANDS)Hz-Z-Input with Z-Mate-lay shft				1X Gear (HTF SIDEBANDS)Hz-Z-G1 with Z-Mate-lay shft-G1			
Set Fmax-G4				27.36		31.92		8.960930233		10.33953488	
3275.22				1X Pinion (HTF SIDEBANDS)Hz-Z-Input with Z-Mate-lay shft				1X Pinion (HTF SIDEBANDS)Hz-Z-G1 with Z-Mate-lay shft-G1			
Set Fmax-G5				36.48		41.04		28.95069767		30.32930233	
3660.54				GMF (HTF SIDEBANDS)Hz-Z-Input with Z-Mate-lay shft				GMF (HTF SIDEBANDS)Hz-Z-G1 with Z-Mate-lay shft-G1			
Set Fmax-Reverse Gear				1005.48		1010.04		414.2706977		415.6493023	
1348.62				GMF_Input (Sidebands)-Input				GMF_Z-G1 with Z-Mate-lay shft-G1 (Sidebands)-Mate-lay shaft-G1			
T.P.T.CO				930.24	969	1046.52	1085.28	355.68	385.32	444.6	474.24
				GMF_lay shaft (Sidebands)-Mate-lay shft				GMF_Z-G1 with Z-Mate-lay shft-G1 (Sidebands)-G1			
				948.48	978.12	1037.4	1067.04	395.6595	405.3098	424.6102326	434.2604651
www.vibro-sam.com											

Based on drawing, the gearbox in question has 5 gears, and all mentioned frequencies have been calculated for all gear engagement conditions. However, this case study focuses only on Gear 1. Considering the gear mesh frequency for Gear 1 is 414.96 Hz, and taking into account a multiplier of 3.25 times the gear mesh frequency, which is 1348.62 Hz, the vibration analyzer device, V-SAM, has been setup as follow:

Instrument: V-SAM 2 Channel, F_{max}: 2500 Hz, No. of line: 6400, Ave. No: 4, Unit: Acceleration (m/s^2), Sensor type: CTC AC-102-1A, Window Type: Hanning, Ave. Type: FFT Linear, FFT Type: Liner.

Based on Figure 2, data acquisition was conducted horizontally under load, with the corresponding acceleration spectrum graphs shown in Figure 3 and the time signal presented in Figure 4. (According to V-SAM-Web Soft)

Based on the spectrum analysis and the strong presence of the second harmonic of the first gear pair's meshing frequency, along with prominent left and right sidebands at the lay-shaft speed frequency, and considering the details provided in Section **Backlash Issues and Oscillating Gears**, a potential backlash issue in the gear is anticipated. For a more detailed examination, the spectrum presented in Figure 1 was magnified, and all meshing frequencies and sidebands are precisely identified in Figure 3. Upon magnification, a sideband with a frequency of 2.03 Hz (the hunting tooth frequency of the gearbox input gear pair) was also observed.

For a more detailed examination, the time signal in velocity units was analyzed as shown in Figure 4, and it matched exactly with the information presented.

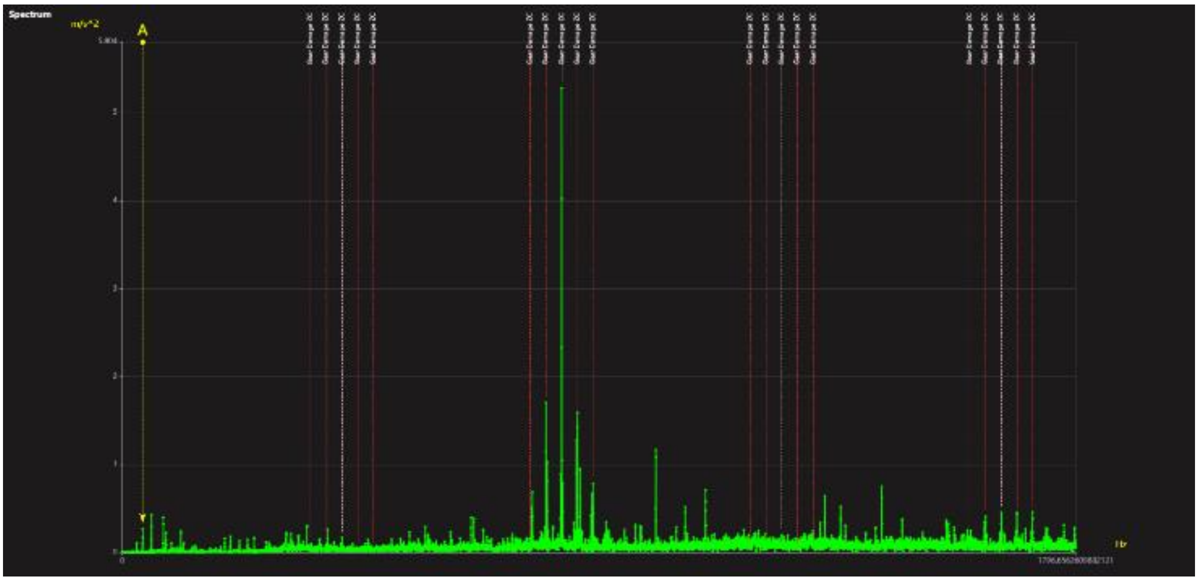

Fig.1. Horizontal -Acceleration Spectrum (1st Gear Mesh Frequency & harmonics)

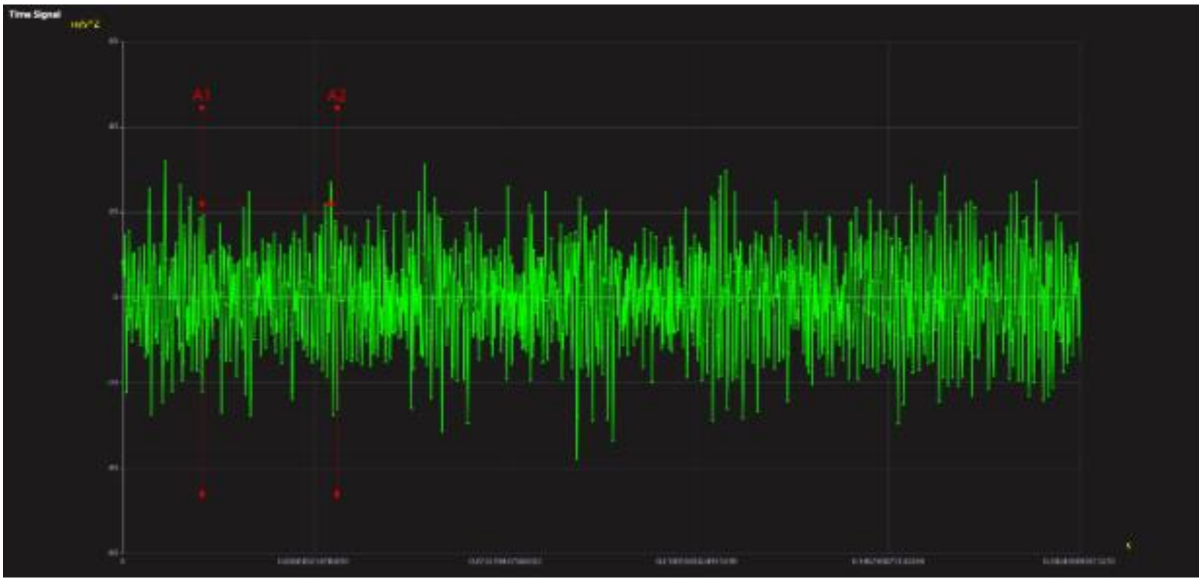

Fig. 2. Horizontal -Acceleration time signal

Fig.3. Magnified Horizontal -Acceleration Spectrum including lay-shaft speed and hunting tooth frequencies sidebands around 2nd harmonic of Gear Mesh Frequency

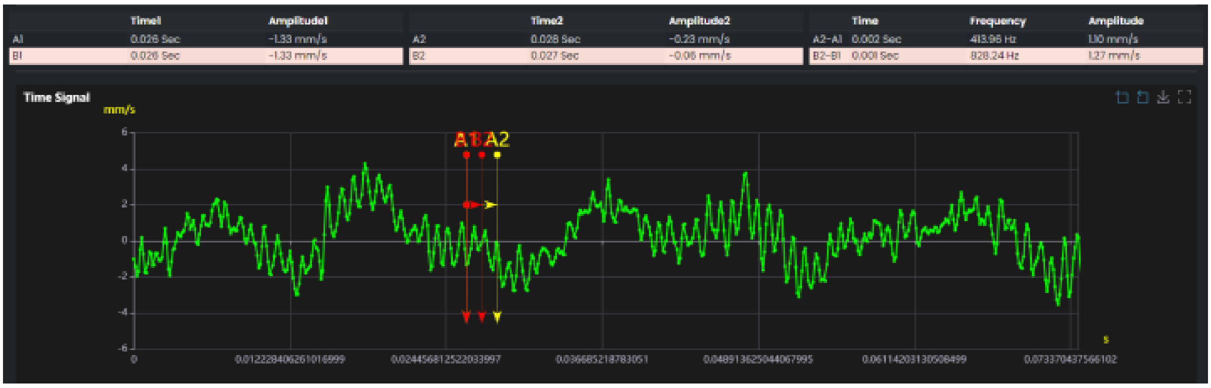

Fig.4. Time Domain Signal of One- and Two-Times Gear mesh.

2.4. Gear lead and profile inspection

There are many tools for increasing durability, quality and decreasing noise and vibration of gears at the step of designing, production and control. One of them is the gear Lead and Profile control chart according to design and production parameters. There are different procedures of gear control chart drawing in the standard documents such as ISO, AGMA and DIN. According to the standard, the control parameters for the lead and profile of the gear are as shown in figure 5 and 6:

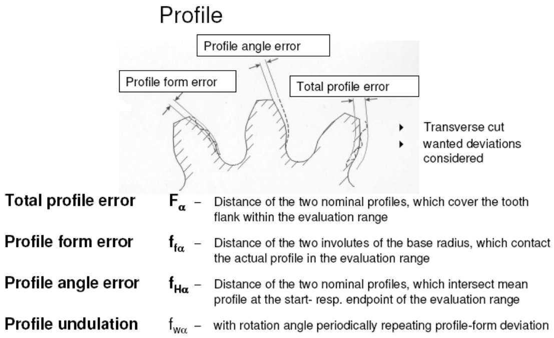

Fig.5. Gear profile inspection parameters

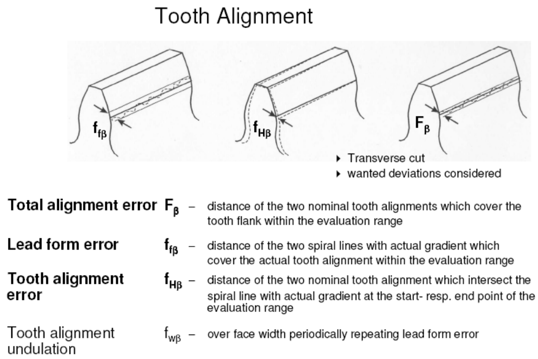

Fig.6. Gear Lead inspection parameters.

To evaluate the data obtained from the vibrations and according to gear inspection parameters that mentioned we decided to disassemble the gearbox and to conduct a more detailed examination of the first gear pair, it was sent to the CMM unit using the Höfler machine. Based on the graphs obtained from the Höfler machine, as shown in Figures 7, 8, 9, and 10, the issue related to backlash was confirmed and validated.

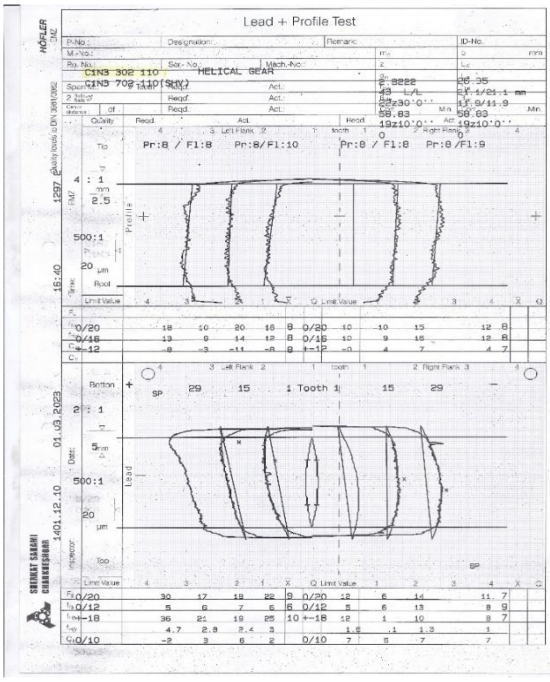

Fig.7. Lead and Profile of Gear 1 according to DIN 3961

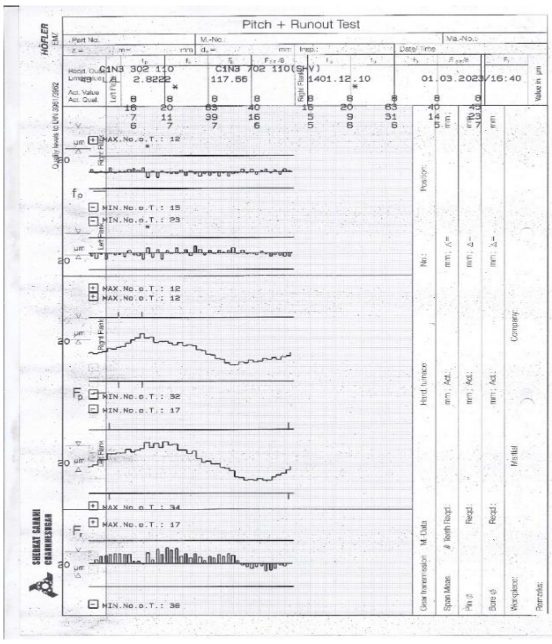

Fig.8. Pitch and Run out of Gear 1 according to DIN 3961

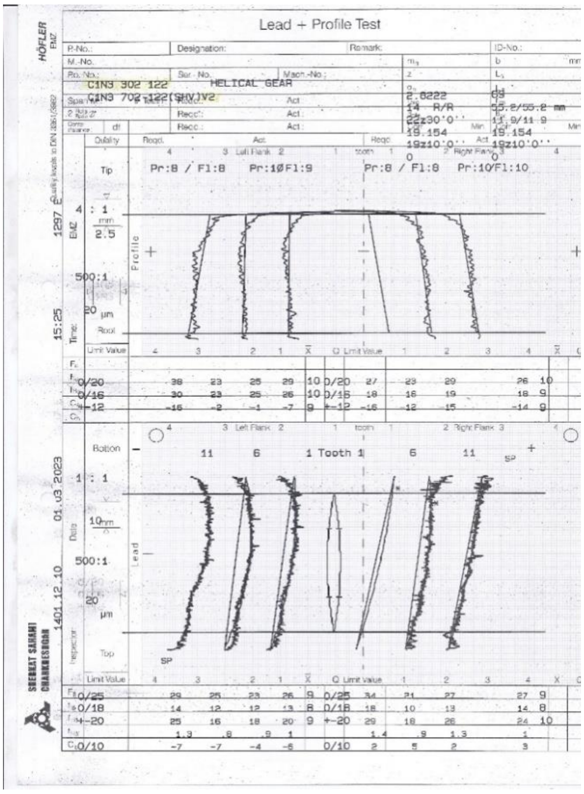

Fig.9. Lead and Profile of Mate Gear 1 according to DIN 3961

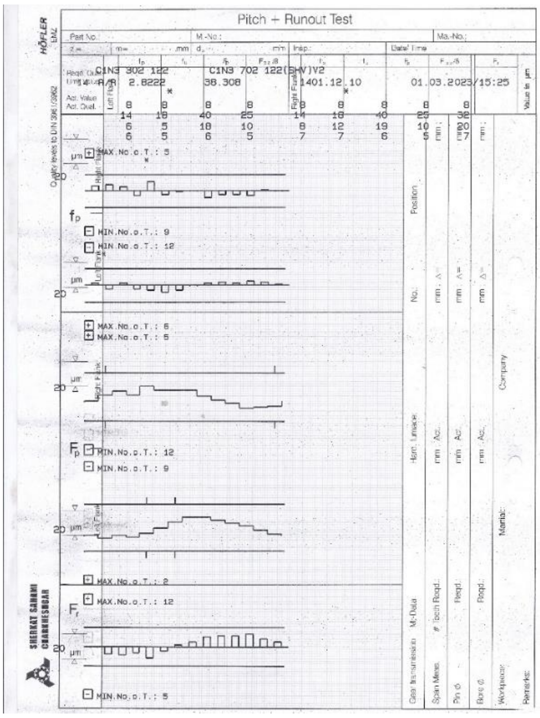

Fig.10. Pitch and Run out of Mate Gear 1 according to DIN 3961

Based on the graphs obtained from the Höfler machine, all parameters related to the surface quality of the gear (lead and profile) were found to be outside the standard range. This issue leads to improper meshing of the gear pair on the pitch circle, confirming and validating the backlash problem that was identified through vibration analysis.

3. Discussion and Conclusion

Given that both vibration measurement and measurement using CMM (Coordinate Measuring Machine) are methods for diagnosing gearbox issues, this paper validated the results of vibration analysis with the graphs obtained from the CMM, and both methods clearly indicated the presence of backlash. Considering that it is not feasible to measure all the gears produced in gearbox production lines using CMM, vibration analysis can be a suitable alternative for end-of-line (quality control and testing) diagnostics. Vibration measurement can test all gears under load with less time and cost.

Currently, gearbox quality is typically assessed at the end of the production line by operators using auditory methods. By using vibration analysis, not only can faults be identified, but the exact source of the fault can also be determined. This allows for precise repairs in the maintenance unit without additional disassembly time.

Given the advancements and the transition to Industry 5.0, there is also the potential to implement AI-based monitoring and diagnostics programs at the end of gearbox production lines.

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