DIAGNOSTIC OF OPERATIONAL CONDITION OF GEAR COMPONENTS IN WINDING HEAD DRIVES USING VIBRATION ANALYSIS METHODS

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The paper addresses the diagnostic assessment of operational conditions of gear components in winding head drives of cable winding machines using vibration analysis methods. Vibration diagnostics is a key tool for monitoring the technical condition of rotating machinery, enabling early detection of gear damage without dismantling components. The research aimed to analyze correlations between vibration parameters and the reliability and durability of gear components. Results highlight the importance of precise gear backlash adjustment and the quality of manufacturing processes to minimize damage such as pitting and micro-cracks. Various diagnostic methods were applied, including low-frequency and high-frequency analyses, envelope methods, and acoustic emission methods, confirming their high sensitivity in identifying both initial and severe damages. The findings suggest regular verification of technological processes and proper setup during assembly to enhance reliability and lifespan of winding head drives.

KEYWORDS

vibration analysis, diagnostics, gear components, winding head drives, acoustic emission, gear damage, backlash, reliability, durability, condition monitoring

1 INTRODUCTION

Vibration diagnostics represents an effective tool for monitoring the technical condition of rotating machinery. Vibration measurements enable early identification of damage on contact surfaces of gear rotors in winding head drives.

The aim of this research was to evaluate correlations between dynamic variables, such as durability and reliability, in relation to measured vibration parameters. The vibration analysis of winding head drives in cable winding machines is crucial for assessing the wear of rotor gear components, ensuring reliable and safe operation in industrial cable manufacturing. Winding head drives are critical points of the monitored devices, and their malfunction can result in unexpected downtimes and significant economic losses. The diagnostic method of vibration analysis is essential from the viewpoint of operation, reliability, and maintenance of machinery in industrial environments. Accurate and timely identification of wear, damage, or technical deficiencies in rotor gear components ensures smooth production processes, minimizes the risk of unplanned equipment shutdowns, and enables more efficient maintenance scheduling.

In the case of winding head drives in cable winding devices (Fig. 1), issues most frequently encountered include wear and damage to rotor gear components, especially pinions and gears. These components are subjected to repeated cyclic loads, friction, shock loading, and occasionally inadequate lubrication during operation [Mascenik 2019]. Progressive damage to gear tooth contact surfaces leads to increased vibrations and noise, directly affecting production quality and equipment lifespan.

Figure 1. Automated cable winder with drive head diagnostics using vibration analysis methods

Vibration analysis utilizes precise measurement methods to detect initial stages of gear component damage without requiring their disassembly. These methods rely on measuring and evaluating vibrations generated during operation. Sensitive vibration sensors (accelerometers) are used for reliable results, capturing a wide frequency spectrum from low-frequency phenomena (shock impulses, eccentricity, imbalance) to high-frequency phenomena (gear tooth wear, bearing damage).

In compliance with the STN ISO 10816-3 standard, measurements were conducted using methods such as Velocity, Acceleration, and Enveloping Acceleration. These measurements assessed vibrations in both frequency spectrum and time domain, effectively identifying specific types of damage (e.g., gear pinion damage, geometry inaccuracies, incorrect assembly positioning, inappropriate gear backlash, insufficient lubrication, etc.) [Cacko 2014].

High-frequency vibration diagnostic methods, such as Enveloping Acceleration, facilitate early detection of even minimal changes on gear contact surfaces, such as initial pitting, microscopic cracks, and running-in processes. The See method (SKF), based on acoustic emission and ultrasound analysis within frequencies up to 600 kHz, offers even more refined analytical capabilities, detecting insufficient lubrication, metal contact, and initial stages of damage [Murcinkova 2015, Panda 2016, Mizera 2019].

Results from vibration signal analysis are compared against defined limits and alarm levels (warning, danger), clearly assessing the operational state of equipment. Based on the results, rapid responses can be executed, such as scheduling replacement of damaged parts, precisely adjusting gear component positions, or optimizing lubrication conditions.

Identifying the causes of vibrations constitutes another crucial aspect. Besides operational factors like load, rotational speed, and temperature, key causes of damage include manufacturing inaccuracies of gear components and deficiencies in gear backlash adjustments during assembly. Therefore, regular verification of technological production processes and inspections of geometrical parameters of produced components are recommended.

It can be concluded that vibration analysis represents a comprehensive multidisciplinary approach, ensuring timely, precise, and non-invasive assessment of equipment technical condition, significantly extending operational lifespan, enhancing reliability of manufacturing processes, and reducing economic costs associated with failures and maintenance.

Based on analysis of scientific publications indexed in research databases, studies addressing vibration analysis for gear rotor condition assessment were identified. These studies explore various aspects of diagnostics and gear set condition monitoring through vibration methods. The article titled "Vibrodiagnostic Classification of Failures to Enhance Industrial Machinery Safety" compares the effectiveness of various classification models using MATLAB Classification Learner to analyze data from time and frequency domains. These data are derived from real measurements on CNC vertical machining centers, aiming to recognize three fundamental tool damage states and enhance industrial equipment safety [Zuth 2021]. Contributions by [Xingkai 2023, Jorani 2023, Hassan 2024, Baron 2022] describe effective diagnostic system applications, enabling early detection of faults to prevent downtime and enhance process reliability and safety. Authors focus on detailed evaluation of vibration signals to identify different types of failures (e.g., tool damage, bearing wear), utilizing real experimental measurements from industrial machinery. Publications by [Vishwakarma 2017, Baron 2016, Zuth 2018, Hee 2013, Tiboni 2022, Urbanek 2012] concentrate on identifying and diagnosing faults such as imbalance, misalignment, bearing damage, or friction between rotor and stator, aiming to improve reliability and efficiency. Many of these studies apply advanced signal processing methods and machine learning for accurate detection and fault prediction.

The article "Vibration Analysis of Rotating Elements of A Motor" addresses vibration analysis of rotating motor elements to reduce shaft vibrations. Authors designed a system composed of shaft, bearings, and gear, selecting bearings from the SKF catalogue and designing the shaft according to A.S.M.E. standards. Shaft vibrations were measured by sensors with the goal of reducing system vibrations. This study emphasizes the importance of vibration analysis for enhancing rotating machinery effectiveness and lifespan [Urbanek 2023].

These studies provide valuable insights into the application of vibration analysis in diagnosing and monitoring gear rotor component conditions, closely relating to the issues addressed in our presented study.

2 METHODOLOGY AND RESULTS

The measurement methodology applied in this research was based on a systematic approach to identifying damage in gear components of cable winding machine rotors, with the primary goal of assessing the current operational state of rotor pinion gears without requiring their disassembly from the equipment. Diagnostics were carried out in accordance with the recommendations of the technical standard STN ISO 10816-3, which establishes procedures and threshold values for evaluating measured dynamic vibration quantities.

Advanced instrumentation and equipment were employed to conduct diagnostic measurements, specifically a frequency analyzer and MicrologGX data collector with AptitudeAnalyst analytical software. Vibration recording was performed using Wilcoxon Research accelerometers, specifically model SKF786M, with a sensitivity of 100 mV/g and a frequency range from 1 Hz to 20,000 Hz, enabling detailed analysis across a wide frequency spectrum of vibrations.

Several diagnostic methods across various frequency ranges were utilized during measurements, including:

- **Low-frequency range** (10–800 Hz): Vibration velocity measurement (Velocity) expressed in mm/s with RMS detection.
- **High-frequency range** (up to 16 kHz): Vibration acceleration measurement (Acceleration) expressed in g units with peak-to-peak (PtP) detection.
- **Envelope methods** (Enveloping Acceleration): Damage detection in frequency bands up to 1 kHz, up to 10 kHz, and up to 20 kHz, expressed in gE units with peak-to-peak (PtP) detection.
- **Ultrasound diagnostics and acoustic emission methods**: See method and HFD (High-Frequency Detection), capable of identifying even minor changes caused by damage, seizing, insufficient lubrication, or metal surface contacts within frequency ranges up to 600 kHz.

Collected data were subsequently analyzed using FFT (Fast Fourier Transform) spectra, allowing for identification of characteristic signal amplitudes corresponding to specific types of gear component damage, especially damage to the gear pinion tooth surface. Analyses were also supported by vibration time recordings, facilitating observation of damage progression dynamics over time.

Measured values were compared to defined alarm limits according to standard recommendations, where alarm A1 (warning) was set at a value of 2.8 (mm/s or gE), and alarm A2 (danger) was established at a value of 4.5 (mm/s or gE). Elevated vibration values (exceeding alarm level A2) clearly indicated more serious gear damage, such as significant wear, pinion tooth damage (e.g., pitting, microcracks, or severe abrasive wear). The analysis confirmed the presence of high vibration amplitudes at the gear meshing frequency (approximately 2.6 kHz), clearly indicating damage to gear components.

Table 1 summarizes the vibration measurement results of winding head drives. Data from the table indicate that rotor No. 1 exhibited increased measured vibration values exceeding alarm limit A2, signaling symptoms of rotor (gear) damage.

Table 1. Summary of Vibration Measurement Results for Monitored Winding Head Drives

	Vel [mm/s]	Acc [g]	EnvAcc up to 1 kHz	EnvAcc up to 10 kHz	EnvAcc up to 20 kHz	Assessment
Rotor 1	0.6	4.3	2.6	12.4	4.1	*Critical condition – Alarm A2*
Rotor 2	0.5	0.5	0.9	1.4	1.4	*No damage detected*

The FFT spectrum recording (Fig. 3) indicates a high amplitude at the gear meshing frequency. This is a sign of rotor component damage. The condition is unsatisfactory, and repair or replacement of the rotor is necessary.

An identical measurement was conducted after replacing the damaged component – the gear pinion of the winding head drive rotor (Fig. 3). In this case, the FFT spectrum shows no dominant amplitude, i.e., no indication of damage.

The time record identifies an increase in the signal from the damaged tooth surfaces of the rotor gear pinion. Such a condition must be evaluated as unsatisfactory - indicating that pinion replacement is necessary (Fig. 4).

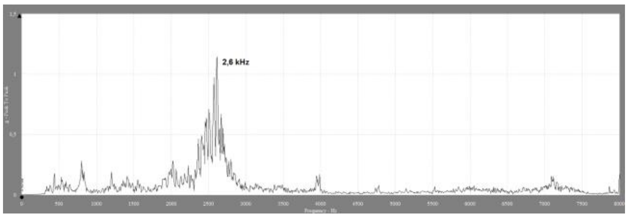

Figure 2. FFT Acceleration spectrum – indication of gear pinion damage on the rotor

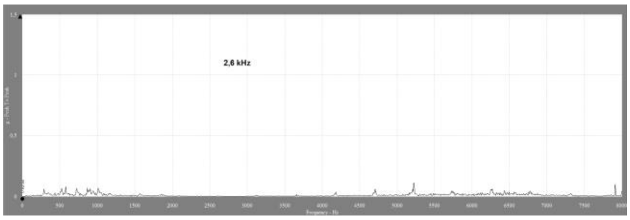

Figure 3. FFT Acceleration spectrum after replacement of the damaged rotor pinion

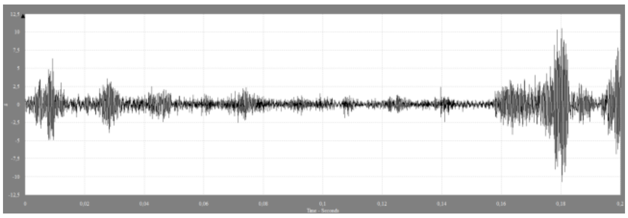

Figure 4. Time record of Acceleration (g PtP) before component replacement

After replacing the damaged component, the time record indicates trouble-free operational condition of the rotor (Fig. 5). The measured signals are within the recommended limits.

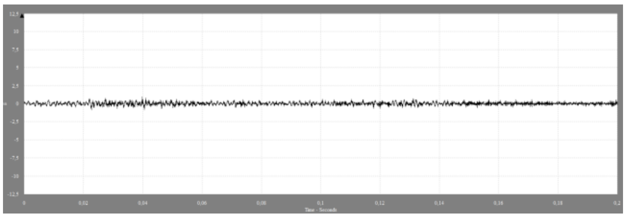

Figure 5. Time record of Acceleration (g PtP) after maintenance intervention

The time record of EnvAcc (gE PtP) allows real-time analysis of machine component conditions, identification of recurring impulses (e.g., damaged gear teeth or faulty bearings), and provides an indication of the equipment's condition based on defined alarm thresholds. The EnvAcc time record clearly indicated a periodic increase in signal amplitude, which was a sign of damage to the rotor gear pinion (Fig. 6). After replacing the damaged component, vibration amplitudes were significantly reduced, confirming the restoration of the equipment's proper operational state (Fig. 7). This method is therefore suitable for monitoring the operational condition without the need for equipment disassembly.

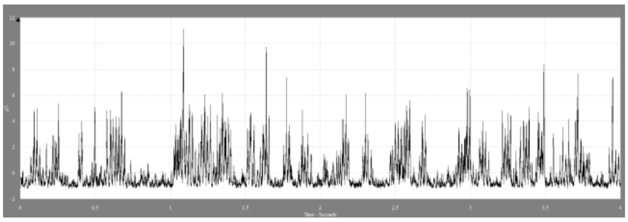

Figure 6. Time record of EnvAcc (gE PtP) – before maintenance intervention

After replacing the damaged component, the time record indicates a good operational state of the rotor. The measured signals are within the acceptable range, but small, periodically recurring signal deviations can be observed. This condition may also be caused by geometric inaccuracies of the rotor gear pinion teeth.

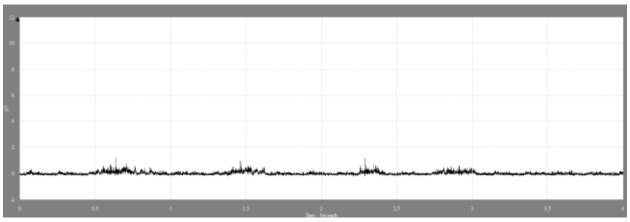

Figure 7. Time record of EnvAcc (gE PtP) – after component replacement

From the perspective of applied high-frequency vibration measurements, the following conclusions can be drawn:
The condition of the gear pinion tooth contact surfaces in the initial hours of operation showed mild to moderate running-in processes, accompanied by increased vibration signal levels. After the running-in period and subsequent smoothing of the contact surfaces, the dynamic parameters improved significantly, with observed vibration values dropping below the defined alarm limits. The increased vibration levels in the early phase of operation were primarily caused by the adaptation processes of the gear pinion tooth surfaces.

Figure 8. Types of damage to the rotor gear pinion

For some pinions, increased vibration signal values were recorded after component replacement or repair, attributed to manufacturing inaccuracies of the gear teeth or improper alignment of the pinion and gear, specifically excessive or insufficient gear backlash. These inaccuracies and misalignments can be sources of high-frequency vibration signals and may negatively affect the operational reliability and service life of the gearing.
The assessment of component condition using acoustic emission (AE) measurement was conducted simultaneously with vibration measurement. The See (SKF) acoustic emission method was used, with the See unit, along with High-Frequency Detection (HFD) analysis to identify lubrication conditions, contacts, and wear.
The results of the AE measurement showed a significant increase in signal amplitude on damaged rotor No. 1, particularly in the frequency range up to 600 kHz, which correlated with the high vibration values up to 20 kHz recorded using the Enveloping Acceleration method. The measured AE signal values exceeded the recommended A2 (danger) alarm threshold, indicating severe damage to the gear pinion tooth surfaces. Rotor No. 2, which did not show damage in the vibration analysis, was assessed as in good condition according

to the AE measurement, with significantly lower signal amplitudes remaining below the A1 (warning) alarm threshold.
After replacing the damaged component (gear pinion) on rotor No. 1, the AE signal amplitude significantly decreased below the alarm thresholds, confirming the success of the repair and the restoration of the equipment's operational condition. Acoustic emission measurement thus represents a reliable, non-invasive method for detecting the early stages of damage and monitoring the operational condition of mechanical components.

3 DISCUSSION

The measurements demonstrated significant differences between damaged and undamaged components. Rotor No. 1, with damaged gearing, exhibited vibration values exceeding the A2 (danger) alarm level, with the highest amplitudes detected at the gear meshing frequency (2.6 kHz). After replacing the damaged gear pinion, the measured vibration values significantly decreased and remained below the alarm thresholds.
The analysis of vibration time records before the replacement confirmed the presence of recurring high signals, indicating damage to the tooth contact surfaces. After replacing the gear pinion, the records showed a stabilization of the condition, although small periodic deviations persisted due to geometric inaccuracies of the gear teeth.
The aim of the research was not only to identify existing damage but also to determine its root causes. The primary causes were identified as manufacturing inaccuracies of the gearing, incorrect alignment of the gear components (gear backlash), and insufficient lubrication. Based on the results, recommendations were formulated to improve the quality of the gear manufacturing process and ensure proper assembly conditions, leading to a significant reduction in damage risks and increased reliability of winding head drives:

- Verification of the gear manufacturing process should be carried out for both the gear pinion and the gear wheel. The verification should include an inspection of fundamental technological operations, including finishing machining processes. Special attention should be paid to the quality of the material used, the stability and dynamics of the manufacturing process, as well as the precision of the shape and positioning of the manufactured components. During verification, it is crucial to monitor the accuracy class of the gears, including geometric deviations in shape, positioning, and microgeometric surface parameters.
- Proper alignment of the gear pinion and the gear wheel, particularly gear backlash adjustment, is a key factor in ensuring optimal rolling and sliding conditions within the gearing. Inadequate gear backlash can lead to dynamic shocks, resulting in increased dynamic stress on components and the generation of high-frequency vibration and acoustic signals, indicating an improper operational state. Poor meshing conditions, often associated with insufficient lubrication and inadequate oil film formation, can cause premature fatigue damage to contact surfaces. These damages initially manifest as microgeometric changes on surfaces (increased roughness, abrasive wear) and may later develop into more severe damage, such as surface cracks, pitting, or fatigue fractures of gear teeth. Proper gear backlash adjustment, considering specific operating conditions such as rotational speed, load, and operating temperature, has a decisive impact on the dynamics of gear meshing, durability, and reliability of the entire mechanical system.

4 CONCLUSIONS

The measurements confirmed the high effectiveness of vibration diagnostics and acoustic emission analysis for non-invasive assessment of the technical condition of gear components in winding head drives. The results demonstrated the high sensitivity of the applied diagnostic methods in identifying damage to gear contact surfaces, such as surface cracks, pitting, and running-in wear. The measured vibration and acoustic emission values allow for the clear definition of alarm levels (A1 warning, A2 danger), which are crucial for the early detection of critical damage.
Diagnostic measurements confirmed that the primary causes of gear damage are manufacturing inaccuracies and improper gear backlash adjustment during component assembly. To minimize the risk of such damage, it is recommended to regularly verify and optimize the technological process of gear manufacturing, with a focus on the precision of geometrical and microgeometrical parameters of the components.
Furthermore, the importance of proper alignment between the gear pinion and the gear wheel has been confirmed, particularly regarding gear backlash adjustment. Proper adjustment significantly reduces the occurrence of dynamic shocks, which can lead to premature damage and, subsequently, a significant reduction in the operational lifespan of components.
The application of vibration analysis methods in accordance with the STN ISO 10816-3 standard has proven to be a reliable tool for non-invasive diagnostics and monitoring of the technical condition of winding head drives. Vibration analysis enables early problem detection, helping to prevent unexpected failures and unplanned production downtimes, thereby increasing the reliability of manufacturing processes and reducing maintenance and repair costs.
To further enhance the accuracy of diagnostics and gear condition assessment, it is recommended to implement a comprehensive monitoring system that combines various diagnostic methods (low-frequency and high-frequency vibration methods, acoustic emission). Such a multi-method diagnostic system ensures precise and reliable assessment of gear operational conditions, making it suitable for long-term monitoring and trend analysis during operation.

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