COMSOL
CONFERENCE
2024 FLORENCE

Towards Mechanical Digitalization of Mine Hoist with COMSOL

Krystof Kryniski[1], Sean Martin[2], Jacob Van Wyk[3], Mike Davis[4], Tim Gartner[5]
1. ABB, Sweden.
2,3,4. ABB, ZA.
5. ABB, Canada

Abstract

Mine hoists are significant capital investments, so their efficient, safe, and reliable operation are of vital importance to mining companies. ABB delivers numerous drum hoisting systems to underground mines in China, South Africa, as well as to Poland. ABB mine hoists are one of the largest delivered systems covering hoisting unit, motors, control systems e.g., the ACS 6000 MV drives, break control system and related technical support. Two drum systems of diameter of 5.7 m provide payload of 45 t with average payload of 1530 tph. Hoisting systems compromise several mechanical and electrical components with potential of failure and stopping production. ABB technology offers the concept of the hoist digitalization by implementing remote high-speed sensing and diagnostics combined with advanced FEM modelling using a state of art software, particularly in the design phase. However, there are increasing needs to define the dynamic behavior of individual components whose properties can be rapidly defined and improved over the running time. Mechanical digitalization of mine hoists using COMSOL is an inspiring concept that bridges theory and practice. This software is well-suited for this purpose. By developing FEA models, stress distributions and levels can be validated directly on-site, potential areas of concern can be identified, and decisions on optimizing production can be made, ensuring adequate strength and reliability. A focus is on friction hoists where multiple ropes are wound and moved by the drum. During the operation, hoisting ropes are used to lift the load while balancing ropes compensate the weight and provide stability. Frictions between the ropes and the sheaves or drums create the necessary traction for lifting or lowering the mining loads.

Keywords: Mining hoists, stress and strain, digital twin, wireless testing, energy optimization.

Introduction

Mechanical digitalization of mine hoists using COMSOL tools represents significant advancement in the mining industry. It transforms traditional engineering approaches by integrating sophisticated simulations, real-time data, and predictive analytics. The integration not only enhances the reliability and efficiency of mine hoists but also sets a new standard for safety and operational excellence in mining.

The conventional process of mechanical design is typically predictive in nature, often based on the assumption of a predetermined, limited number of mine hoist load cycles. After the initial design and commissioning of the mine hoist, the mechanical strain within the hoist components is usually no longer monitored. It is generally assumed that the safety factors incorporated into the design are sufficient to ensure the safe operation of the mine hoist throughout its lifecycle.

Well, this approach is set to undergo significant changes. By adhering to the guidelines described in the ABB patent [1], a new generation of mine hoists is going to be equipped with stress monitoring systems that continuously feed data into advanced models. These enhancements make the hoist systems safer, more reliable, and more energy efficient.

A set of wireless strain gauges is used to monitor the performance of the hoist in real time, tracking stresses within critical zones. The data is instantly analyzed and fed back to the control system, where it is cross-referenced with the models to identify potential areas of concern, optimize performance, and ensure sufficient strength and reliability to prevent unplanned downtime.

The following sections provide specific friction hoist implementations that not only demonstrate the concept but also hoping to encourage and inspire the COMSOL users to tackle field applications.

Target of the Analysis

COMSOL is an excellent tool for introducing a new generation of engineers to practical field applications. By simplifying models and integrating calculations with real-world measurements, it deepens understanding of component interactions, stress distribution, and material behavior under load. A focus is on friction hoists where multiple ropes are wound and moved by the drum. During the operation, the hoisting ropes are used to lift the load while balancing ropes compensate the weight and provide stability. Frictions between the ropes and the sheaves or drums create the necessary traction for lifting or lowering the mining loads.

Figure 1. Friction Hoist.

Rope/Cable Systems

The relative motion between the ropes is also critical for operation and safety of the equipment. Tensions between the ropes are directly reflected by the stresses in the drum and respective sheaves. When the ropes exhibit similar tension and friction conditions at the contact zone, balanced tension among the ropes ensures the load is evenly distributed across. This prevents excessive stress on any individual rope and promotes uniform wear, extending the lifespan of the ropes. Unequal tension or friction can result in jerky movements, vibrations, or irregular load control. Well-maintained balance between the ropes in a multi-rope friction hoist system is not only crucial for efficient hoist operation but also serves as a reliable indicator of proper functioning hoisting system. Uneven load distribution can lead to localized stress concentrations resulting in the reduction of the ropes lifespan and increase of the risk of failure.

Koepe winder

Several rope designs are used for hoisting the loads. However, the following analysis focuses on a specific winder with a history of fatigue-related failures, particularly affecting the traction sheave, including the cheek plates, shaft, and the bolted interface between the shaft flange and the cheek plates.

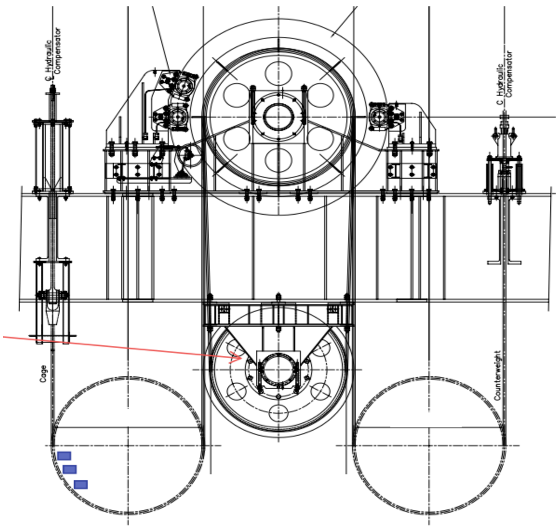

Figure 2. Koepe Winder.

To ensure a thorough understanding and mitigation of the failure mechanism, a structural review of the winder drum and shaft design was conducted.
This audit is combined in-situ strain measurements with finite element analysis (FEA). The primary objectives were to verify the input loadings and strain responses on both the drum and shaft. Following this verification, a fatigue life assessment and failure analysis were performed to evaluate the integrity and durability of the components.

Towards Digitalization

The mechanical components of hoists are usually designed using classical strength calculations. Stress and strain analyses are performed to evaluate these components under both normal operating conditions and rare, abnormal events like rope breaks or overloading. To ensure reliability, safety factors are incorporated into the design, offering an additional margin of security.
Well, conventional mechanical design processes are typically predictive, relying on the assumption of a predetermined, finite number of load cycles for the mine hoist. However, by integrating a sensing system and real-time monitoring, direct insights can be gained into the actual condition, performance, and control of the hoist. This approach enhances the ability to manage and optimize the hoist’s lifecycle, ensuring better alignment with real-world operating conditions.
In hoist applications, critical components like ropes, drums, sheaves, and brake are experiencing repeated stress during operation due to constant lifting and lowering of heavy loads. Predicting and managing fatigue life is essential to ensure safety, prevent unexpected failures, and optimize the service life of mining hoist components.

Stress sensing

Considering the preceding section, the focus remains on the Koepe winder. The design features a multi-rope system where each rope loops around the drum, passes over an idler pulley, and returns to the drum. Any imbalance in tension or friction among the ropes can significantly impact the idler pulley’s performance, leading to substantial stress redistribution, jerky movements, vibrations, and irregular load control.
Therefore, it is crucial to closely monitor the tension distribution across the drum and the principal stresses on the drum cheeks to ensure smooth operation and prevent mechanical failures.
Strain gauges were comprehensively installed on the drum, cheek plates, and shaft. Due to the presence of rotating components, stress data was transmitted wirelessly with 24-bit accuracy at a sampling rate of 1 kHz [5]. Figures 3 and 4 illustrate the placement of sensors inside the drum and the rosette strain gauge on the cheek plate, respectively. The arrangements

for torque measurements and differential sheave stress will be detailed later.

Figure 3. Installation of Strain Gauges Inside the Drum.

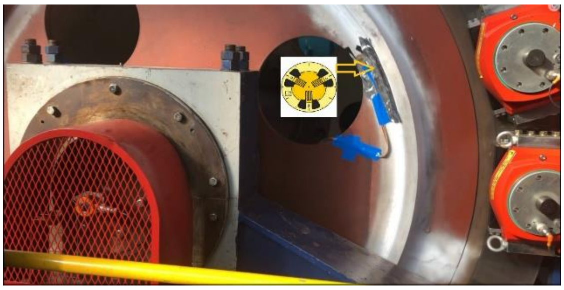

Figure 4. Strain Gauges Rosette on Drum Cheek

Figure 5 presents the ropes' compressions obtained from the drum during the operational cycle.

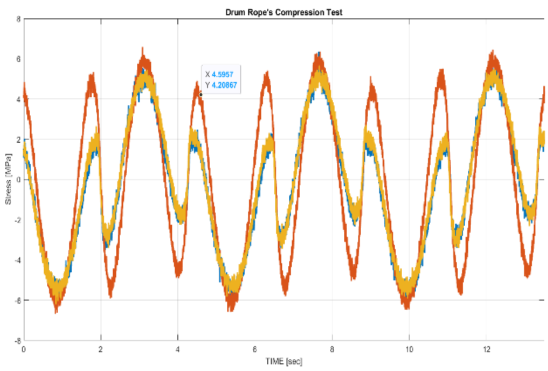

Figure 5. Strain Gauges Rosette on Drum Cheek

The measurements were taken for an empty cage, a cage loaded with a group of miners, and a cage with a mining vehicle weighing 17 tons. The data displayed on the graph corresponds to the empty cage. The readings from the channels near the opposite cheeks are nearly identical, indicating a well-balanced load across the drum.

Over time, cyclic stresses can cause microcracks to form in the material, which may eventually lead to fatigue failure if not detected early. To ensure safety and reliability, it is crucial to monitor the stresses at critical locations, particularly where stress concentrations could accelerate fatigue failure. In the context of fatigue analysis, principal stresses help identify the most critical stress points where failure is most likely to occur. The principal stresses are derived from the stress components acting on an element by transforming the stress tensor to a coordinate system where shear stress is zero, leaving only normal stresses.

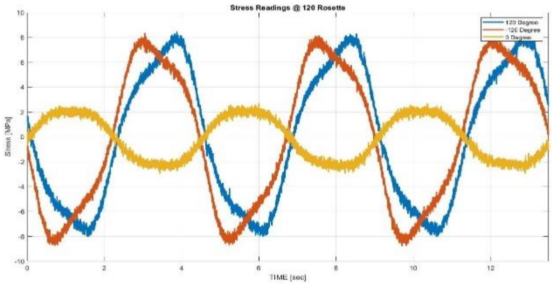

Figure 6. 120-Rosette Stress Reading on the Drum Cheek

FEA component model

ABB hoists are designed using advanced FEA packages such as ANSYS, Abaqus, and Nastran. COMSOL Multiphysics provides also robust tools for evaluating principal stresses and fatigue life through its Structural Mechanics and Fatigue modules with sufficient accuracy. However, a key advantage of this approach is the ability to develop reliable models and produce virtual sensors just on standard PCs, which can then be deployed in the cloud at a low cost, enabling efficient and scalable monitoring solutions.

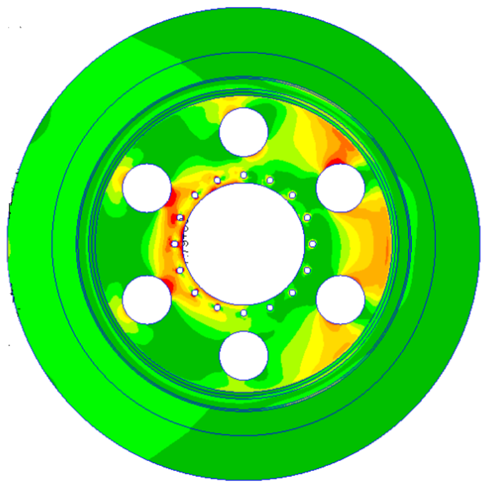

Figure 7. Maximum Principal Stress on the Drum Cheek

The COMSOL software produces similar results that can be validated against the stress data collected on-site. The model can be continuously refined with real-time data, enabling dynamic adjustments to the hoist's operation. This approach helps optimize both production efficiency and the fatigue life of critical component.

Torque Sensing

Electrical digitalization is central to hoist automation. The voltage and current of the driving motor are monitored and reflect the hoist's loading conditions. However, these relationships are not straightforward. Accurate torque measurements are necessary to optimize hoist performance, reduce energy losses, and preserve the integrity of mechanical components.

The hoist's driving shafts experience not only pure torque but also bending moments due to heavy lifting loads. Figure 8 shows a full-bridge strain-gauge arrangement designed to minimize the impact of bending effects [3], [6].

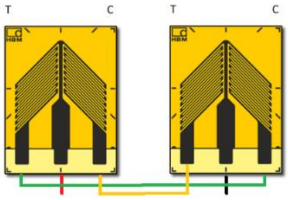

Figure 8. Full-Bridge Torque Sensing

In practice, it is feasible to differentiate between these loads, gaining additional bending information. COMSOL simulations can be employed to validate this idea.

Field torque testing was initially conducted with the brakes engaged, first on the non-drive end (NDE) and then on the drive end (DE). Full torque was applied in both directions during these tests. Strain was measured using an HBK [3],[4] 45-degree rosette gauge positioned on the drive shaft, as depicted in Figure 9.

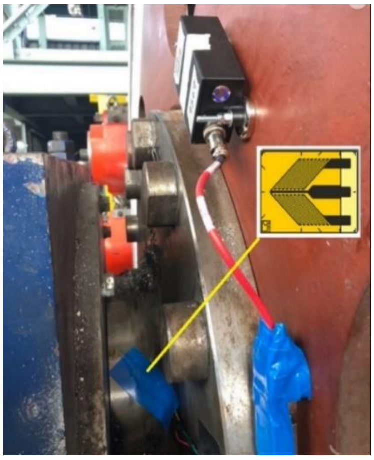

Figure 9. Half-Bridge Torque Sensing

The strain gauges were wired as a half-bridge to account for the fact that the shaft's movement was restricted by the front or rear brakes, thereby keeping the bending moment constant. Figure 10 shows the captured time record.

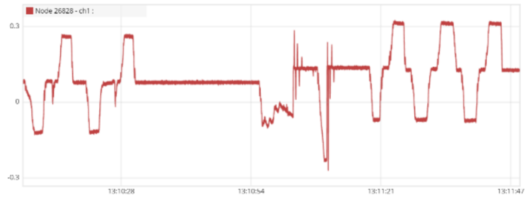

Figure 10. Torque Time Record

Torque measurements taken on a locked shaft enabled comparison with torque values derived from the motor's electrical characteristics. The results, based on stress measurements, closely aligned with the electrical estimates. Any discrepancies between the non-drive end (NDE) and drive end (DE) were attributed to minor variations in moment caused by the rope system.

During the hoisting operation, the brakes are released, and torque is applied to lift the load. Figure 11 shows the recorded data.

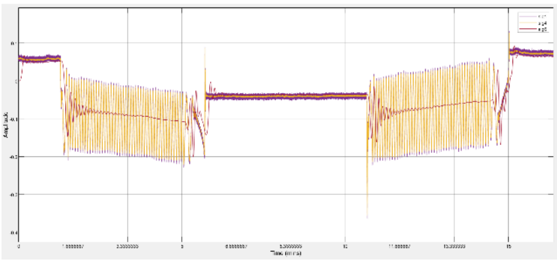

Figure 11. Combined Torque and Bending Record

The 45-degree rosette sensor rotates with the shaft, detecting both torsional and bending strains. The bending strain varies with the shaft rotation, producing a semi-sinusoidal pattern, while the torsional strain remains nearly constant. A quick estimate of the applied torque can be obtained by isolating the strain signal using a low-pass filter. which separates the torque from the bending components. Figure 12 shows the amplitude characteristics.

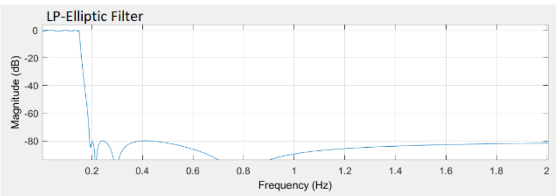

Figure 12. Elliptic Filter Characteristics

The original strain signal was decimated before the filtering process.

Further, the components can be separated more accurately with a sufficient accuracy using e.g. a tracking notch Kalman filter [2]. A technique works perfect even for variable speeds.

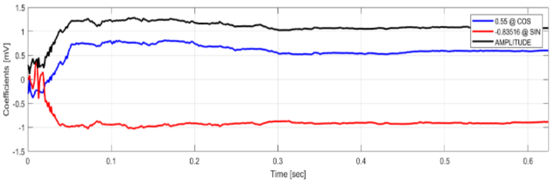

Figure 13. Tracking Kalman filter

Differential sheave stresses

Multi-cable hoists are commonly used for moving heavy efficiently and safely, enabling the load weight to be distributed more evenly with greater stability during lifting operations.

Figure 14. Differential Sheaves

The differential sheaves, as shown above, are designed to manage multiple ropes, enabling differential movement between them. This system precisely controls the lifting, lowering, and positioning of loads. The sheaves are directly driven by the ropes, accurately reflecting their tensions and movements. By continuously monitoring the rotation of the sheave wheels, any disruptions in the ropes' motion are promptly detected and corrected. A diagnostic technique, along with field testing, is comprehensively detailed in [2].

Figure 15 illustrates an example of instrumenting the differential sheaves. A set of wireless strain transducers was mounted on the spokes of each sheave, allowing for simultaneous measurements at a high sampling rate.

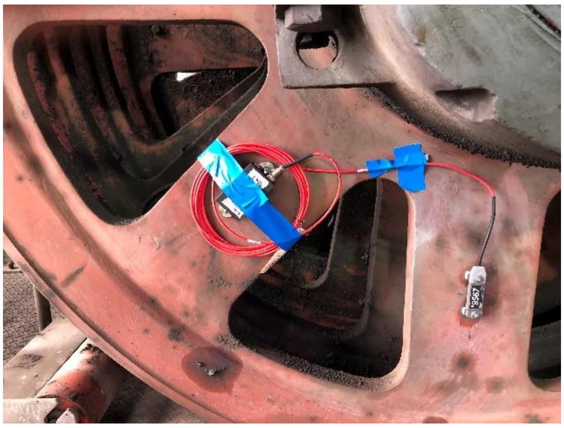

Figure 15. Instrumented Differential Sheaves

The results on the pre-selected spokes of the sheaves are presented in Figure 16.

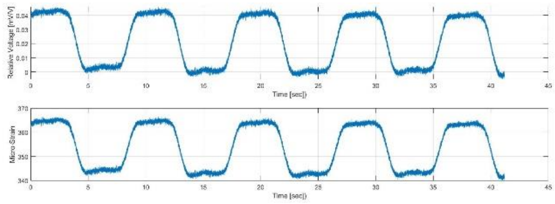

Figure 16. Differential Sheaves Stress Records

Digital Twin Prototyping with COMSOL

From the perspective of structural mechanics, a wide range of software is available, including advanced professional packages such as ANSYS, Abaqus, Nastran, and others. However, COMSOL offers unique features and has gained a significant interest in hoist applications by possibility of seamlessly integrating sensing technology with FEA models. COMSOL Multiphysics® version 6.2 introduces powerful functionality for developing and using surrogate models, which are simpler, usually computationally less expensive. A rapid development of automation solutions requires flexible platform for dynamic component modelling, integrating sensing systems, processing data, and reporting results. This is where COMSOL excels in meeting a prototype requirement. The software itself offers a robust, well-proven track record in structural mechanics capable of running efficiently on standard PCs. It is particularly effective at predicting critical stress concentration points, a feature essential for calculating stresses across different parts of a structure and cross correlating the results. Additionally, COMSOL aids in optimizing sensor placement, eliminating redundant sensors, and even developing virtual sensors for hard-to-reach areas.
In addition, the software optimizes the system by integrating advanced simulation capabilities such as energy analysis and optimization algorithms. This enables more precise adjustments to the hoist's operation, resulting in enhanced performance, reduced component wear, and extended system

lifespan. Furthermore, built-in optimization tools can automatically identify the optimal operational parameters to maximize efficiency and minimize stresses, improving both production, safety and component durability.
The digitalization of sensors for mechanical measurements represents the future of modern automation and control. Decentralized intelligence, data economy, cost-effective setups, as well as efficient operations go hand in hand with increased accuracy and improved reliability. Newly released features in COMSOL, including LiveLink™ for MATLAB®, offer new functionality for plotting, parameter setting, and other key tasks [7].
To prototype a mechanical digital twin of the hoist, it is crucial to perform many stress simulations under various loading scenarios. Field measurements conducted on-site will offer valuable insights into the dynamic behavior of the hoist, both through direct measurements and virtual sensing techniques. Reliable experimental validation is essential for developing an accurate model that reflects the hoist's performance, enabling more efficient operation, energy savings, and enhanced safety.
Then, the use of COMSOL tools introduces new research opportunities, particularly in Surrogate Model Training to develop a deep neural network (DNN) and deployed on multi-core processors e.g., GPU. The faster model evaluation enabled by the surrogate model allows for a more interactive user experience, simplifying the process of updating the hoist's dynamic behavior based on data from sensors positioned at key locations.

Conclusions

At this stage, the prototyping concept is already well-established, with several key functions successfully tested. However, there is still work to be done, particularly with the introduction of new functionalities. ABB strongly encourages the next generation of engineers to take on this challenge, recognizing the vast opportunities for innovation and advancement it presents.
The upcoming conference offers an excellent opportunity to showcase further progress and engage in discussions with software developers about the approach. Moreover, COMSOL introduced a groundbreaking concept with significant potential rapidly develop digital twin to optimize the ABB hoists control and transform the mining industry.

References

[1] ABB patent WO2022223095, "Mine Hoist Monitoring System", 2022.
[2] ABB patent pending PCT/EP2024/058351, P230650WO01, “Mining Rope Diagnostics”, 2024.
[3] HBK resources, The Wheatstone Bridge Circuit Explained - HBK (hbkworld.com).
[4] HBK resources, Strain-Gauge catalogue, S01265.pdf (hbm.com).
[5] HBK resources, LORD, Microstrain sensors, https://www.microstrain.com/sites/default/files/sg-link-200-oem_user_manual_8500-0093.pdf.
[6] DEWESOFT resources, Krypton technical manual | Dewesoft Forum.
[7] COMSOL resources, Resources on Training Surrogate Models for Faster Simulation Apps (comsol.com).

Acknowledge

I want to sincerely thank Thoralf Schulz, ABB, DE for creating the research project opportunity and providing the necessary financial support.