EVALUATION OF THE VIBRATIONAL BEHAVIOR OF A MINING INSTALLATION USING THE FINITE ELEMENT METHOD

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Abstract: This paper investigates the vibrational behavior of a mining conveyor belt installation using the finite element method (FEM). Conveyor systems operate under varying dynamic loads generated by rotating components, material flow irregularities and structural flexibility, which can lead to excessive vibrations, reduced reliability and increased maintenance needs. A three-dimensional numerical model of the conveyor frame was developed using beam, shell and solid elements to evaluate the modal characteristics of the structure. The analysis identified the natural frequencies, mode shapes and stress distribution patterns most relevant for operational safety. Critical zones were observed in the central frame segments, where deformation and stress levels were highest under dynamic excitation. The results highlight potential structural improvements, such as local stiffening and better alignment of idler assemblies. Although no experimental measurements were available for validation, the study provides a practical methodological framework that can support future optimization and predictive maintenance strategies in mining conveyor installations.

Keywords: finite element method, vibration analysis, conveyor belt system, modal characteristics, structural dynamics

1. INTRODUCTION

Mining installations are exposed to a wide range of dynamic loads generated by operational processes, material handling, structural flexibility and the interaction between mechanical components. Over time, these dynamic effects can accumulate and negatively influence the reliability, efficiency and safety of the equipment. Among all mining systems, conveyor belts represent one of the most widely used installations for material transport, both in underground and surface operations. Their continuous

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functioning, long structural spans and rotating components make them particularly sensitive to vibration-related issues. Understanding and predicting the vibrational behavior of such systems is therefore essential for preventing mechanical failures, reducing maintenance costs and ensuring stable, predictable performance[1,2,3].

In recent years, vibration analysis has evolved significantly due to the increasing availability of numerical modelling tools and high-performance computing resources. Classical analytical methods, while useful for simple beams, shafts or single-degree-of-freedom systems, quickly become insufficient when dealing with complex assemblies such as conveyor installations. These structures combine long metallic frames, bolted joints, rotating idlers, pulleys, tensioning mechanisms, and a flexible belt whose mass distribution changes during operation. Each of these components interacts dynamically with the others, producing a multi-degree-of-freedom system that analytical solutions cannot accurately represent.

The finite element method (FEM) has therefore emerged as the most powerful and flexible tool for studying the dynamic response of conveyor systems. FEM allows the structure to be discretized into a mesh of smaller elements—typically beams, shells or solids—each governed by elasticity equations that describe how it deforms under load. By assembling these elements, the method constructs a global system of equations capable of capturing complex structural behavior. Modal analysis performed through FEM provides natural frequencies and mode shapes, offering insight into how the structure tends to vibrate when excited. Additionally, stress and strain distributions can be evaluated locally, helping to pinpoint weak points, overstressed joints or components prone to fatigue. Unlike simplified analytical approximations, FEM accounts for geometric irregularities, material heterogeneity, real support conditions and the interaction between components[4].

Conveyor systems are subjected to both deterministic and stochastic excitations. Motor imbalances, misalignments, belt–pulley interactions and roller imperfections can induce periodic loads, while material flow fluctuations, impacts and environmental disturbances generate random excitation. When these excitations coincide with the structure's natural frequencies, resonance phenomena may occur, amplifying vibration levels beyond acceptable limits. Such conditions can lead to loosening of bolted joints, cracking of welded connections, premature bearing wear and even catastrophic structural failure. An accurate finite element model is therefore essential for predicting resonance zones, evaluating structural sensitivity and informing design or maintenance strategies.

The mining industry is currently experiencing a shift toward digitalization, automated monitoring and predictive maintenance. Vibration analysis, supported by FEM simulations, plays a central role in this transition. Numerical studies allow engineers to examine the behavior of conveyor structures prior to fabrication or installation and to simulate scenarios that would be impractical, costly or unsafe to reproduce experimentally. Virtual testing can assess the influence of geometric modifications, alternative materials, reinforcement strategies, tensioning adjustments or operating speeds on the global and local dynamic response[5,6].

The present paper aims to evaluate the vibrational behavior of a mining conveyor belt installation using the finite element method. The study focuses on the modal characteristics of the supporting metallic structure and its sensitivity to dynamic excitation. While no experimental measurements are available at this stage, the numerical model is constructed using realistic engineering assumptions, widely accepted material properties and representative boundary conditions. The objective is to illustrate a methodological framework that can later be validated through in-situ measurements and expanded to include operational vibration monitoring, ultimately contributing to improved reliability, safety and performance of mining conveyor systems.

2. METHODOLOGY AND RESULTS

The mining conveyor belt considered in this study is a typical installation used for transporting bulk material along inclined or horizontal galleries. Its main purpose is to ensure continuous, stable and energy-efficient movement of material between operational points within a mine. The installation consists of several interconnected mechanical subsystems: the driving station, the tensioning station, the conveyor frame, the idler assemblies and the rubber belt itself.

The driving station includes an electric motor, a gearbox, a coupling and the head pulley, which transmits motion to the belt. The motor operates at a constant rotational speed and delivers the torque required to overcome both frictional resistance and the weight of transported material. Vibrations can arise from motor imbalance, misalignment or variable loads transmitted through the gearbox.

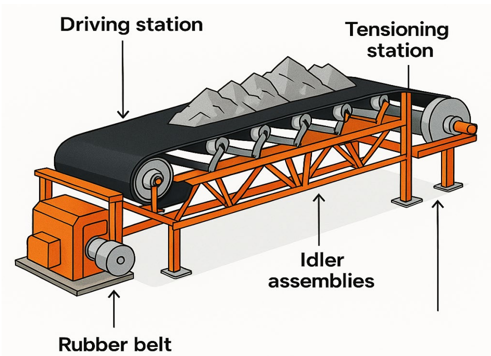

Fig.1. The mining conveyor belt

The tensioning station ensures adequate belt tension to prevent slippage on the head pulley. Depending on the design, tension may be achieved through gravity counterweights or mechanical tensioners. Fluctuations in belt tension can modify the stiffness distribution along the structure, thus influencing natural frequencies.

The frame structure typically consists of welded or bolted steel beams arranged in standard modular segments. These support the idler sets and provide overall stability to the conveyor. Due to its length, the frame behaves as a flexible beam-like structure that can experience bending, torsional vibrations and local oscillations in the joints.

The idler assemblies consist of sets of rollers that support the belt and allow low-friction movement. Imperfect roundness, bearing wear or uneven loading during operation can introduce periodic excitation into the system.

In addition, misalignment between consecutive idler sets may create lateral oscillations that propagate along the belt. Variations in roller stiffness can also generate localized dynamic effects that influence the global modal response. The cumulative behaviour of multiple idler assemblies often leads to complex vibration patterns that are difficult to detect without numerical modelling[7]. Furthermore, operational dust ingress can affect bearing performance, increasing noise and mechanical resistance. These factors collectively highlight the importance of including representative mass and stiffness distributions for the idlers within the FEM model.

Finally, the belt is a composite rubber structure reinforced with textile or steel cords. Although deformable, its mass distribution contributes to the dynamic response of the system.

In this study, the conveyor is modelled with a typical length of 25–30 metres, supported by steel frames placed at regular intervals of 1–1.5 metres. The components most relevant to the modal behaviour are the metallic frames, head and tail pulleys, and the distributed mass of the idlers and belt. Operational conditions assume nominal belt loading and steady-state motion.

The numerical analysis was performed using a finite element approach suitable for complex mechanical assemblies. The conveyor structure was modelled as a three-dimensional system composed of beam, shell and solid elements, depending on the geometry of each component. Beam elements were used for the longitudinal and transversal frame members, providing an efficient representation of the global stiffness. Shell elements were applied to pulley surfaces and support plates, allowing accurate modelling of bending behaviour. Solid elements were used for regions where stress distribution is important, such as shaft–hub connections.

Material properties were selected based on commonly used engineering steels: Young's modulus $E = 210$ GPa, Poisson's ratio $\nu = 0.3$, and density $\rho = 7850$ kg/m³. For simplification, the belt was included as a distributed mass without modelling its deformation behaviour, which is acceptable for modal analysis focused primarily on structural components. The damping effects of joints and bolted connections were not explicitly modelled, but their influence is expected to slightly red uce the resonance amplitudes. Additionally, all components were assumed to behave linearly, allowing the analysis to clearly capture the natural frequencies and mode shapes relevant to early-stage design evaluation.

Boundary conditions were applied at the base of the supporting legs, assuming fixed constraints representing anchorage to the ground. Connections between frames were modelled as rigid joints, while idler assemblies were included as lumped masses positioned along the belt path. The model includes approximately 20,000 elements, providing a balance between accuracy and computational efficiency.

The analysis consists of two main stages. First, a modal analysis is carried out to determine natural frequencies and corresponding mode shapes. This step is essential for identifying resonance risks and understanding how the structure behaves under dynamic excitation. The first several modes typically represent global bending and torsion of the entire frame, while higher modes correspond to local vibrations in individual segments.

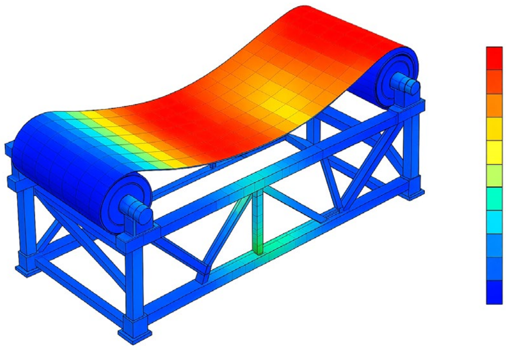

Fig.2. FEM model of a conveyor belt

This image shows a FEM model of a conveyor belt, with stresses and deformations displayed using a color scale ranging from blue (stable areas) to red (critical zones). The highest deformation occurs in the central section of the belt, where the material is most flexible, while the metal frame generally remains in low-stress regions. The color distribution highlights the areas sensitive to vibration and the zones where structural reinforcement would be beneficial.

Secondly, a simplified harmonic response analysis is performed to estimate vibration amplitudes when the structure is subjected to periodic loads, such as roller imperfections or motor-induced excitation. The excitation frequency range was selected between 10 and 60 Hz, reflecting typical operational conditions. This analysis helps identify the natural frequencies of the system and potential resonance conditions that could amplify vibrations.

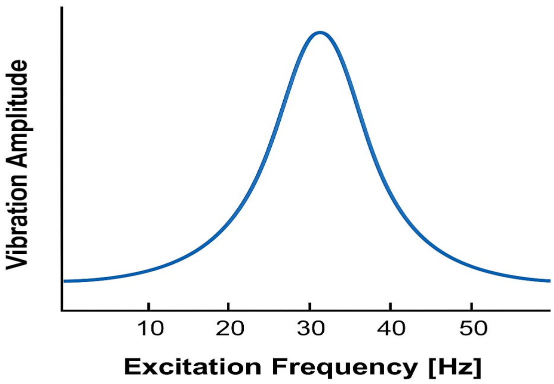

Fig.3. Hramonic respounse

This graph illustrates the result of a simplified harmonic analysis, showing the vibration amplitude as a function of the excitation frequency applied to the structure. The curve highlights a progressive increase in amplitude up to the resonance region, where a significant peak is reached at around 30 Hz. Beyond this point, the amplitude gradually decreases, indicating that the structure responds less intensely to higher frequencies. The graph supports the idea that structural improvements should focus on the frequency range near the system's natural frequency.

CONCLUSIONS

The modal analysis revealed that the first natural frequency of the conveyor structure lies around 14–16 Hz, corresponding to a global vertical bending mode. The second mode, occurring at approximately 22–24 Hz, represents torsional deformation along the longitudinal axis. Higher-order modes above 30 Hz are associated with localized deformations in frame sections, idler supports or pulley assemblies.

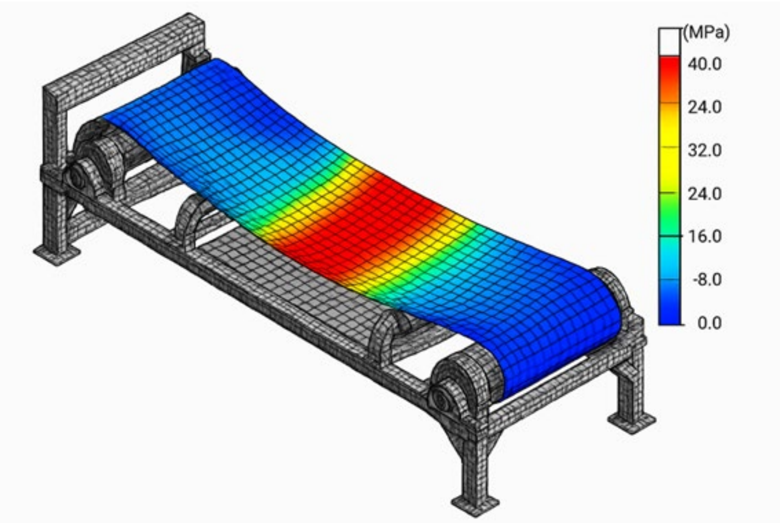

Fig. 4. Mesh + Stress Distribution

This image shows an FEM model of a conveyor belt, where the structure is displayed with a detailed element discretization (mesh) to highlight the mechanical behavior. The stress distribution is represented using a color scale, indicating maximum values in the central area of the belt and lower stresses in the metallic frame. The visualization emphasizes the most highly loaded regions of the system, suggesting where structural improvements may be necessary.

These results indicate that the conveyor is most sensitive to excitation within the 12–25 Hz range, which may coincide with frequencies generated by rotating elements or belt interactions. The harmonic response analysis confirms this: when excited near 20 Hz, displacement amplitudes significantly increase, especially in mid-span frame sections. Although the structure remains within admissible stress limits, repeated cyclic loading in this range may accelerate fatigue.

The analysis highlights several potential improvements. Reinforcing or stiffening the central frame segments would increase the natural frequencies, reducing the likelihood of resonance. Optimizing idler alignment and ensuring regular maintenance can also limit vibration sources. Furthermore, adding damping elements in critical regions may reduce response amplitudes.

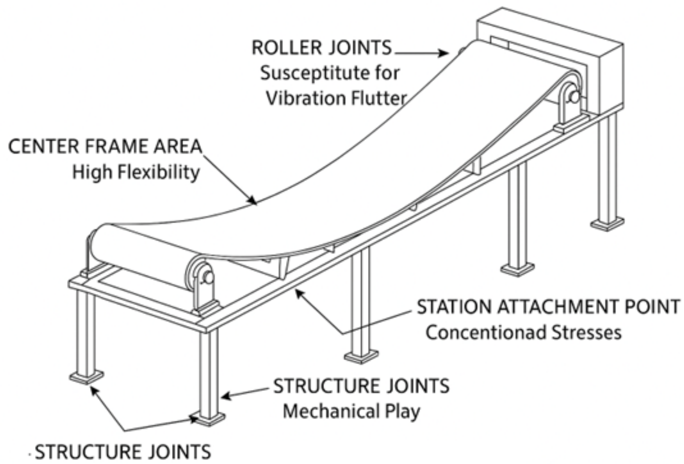

Fig. 5. Weak Points Highlighted

The image shows a technical sketch of a conveyor belt, in which the structural points considered vulnerable from a vibrational and mechanical standpoint are highlighted. The central area of the frame is indicated as being highly flexible, making it sensitive to deformations and resonance. The roller joints are marked as regions prone to vibrational flutter, while the mounting point of the station induces local stress concentrations. In addition, the structural nodes of the frame are identified as potential areas with mechanical play that may amplify vibrations during operation.

Overall, the study demonstrates that finite element modelling provides valuable insight into the dynamic behavior of mining conveyor systems. Even in the absence of experimental measurements, the methodology allows identification of critical frequencies and structural weaknesses[8,9]. The results can support future design optimization, predictive maintenance strategies and experimental validation campaigns.

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