

SESSION A:

EARTH MOVING AND TRANSPORTATION MACHINERY

Remarks on the influence of the dynamic behavior of belt conveyors on the response of the spreader superstructure

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ABSTRACT

This review paper emphasizes the necessity of analyzing the dynamic behavior of spreaders, as high-capacity machines for continuous transport and stacking of bulk materials. Given that spreaders are self-propelled supporting structures for belt conveyors, a dominant portion of the dynamic loads originates from the conveyors themselves. A review of the existing literature shows that transverse and longitudinal oscillations of the belt represent a significant problem, typically treated from the standpoint of bearing maintenance and variable belt tensioning. Furthermore, modernization trends focused on energy efficiency increasingly employ variable frequency drives for continuous belt speed control, directly affecting the variability of dynamic loads caused by the eccentricity of rotating components. These issues are typically addressed from the standpoint of conveyor functionality, often neglecting the potential appearance of negative dynamic effects on the supporting structure, particularly in cases like spreaders, where the conveyor is not directly resting on the ground. Given the variable configuration of the spreader superstructure, with each configuration representing a unique dynamic system, a comprehensive analysis of the system dynamic behavior is fully justified. Evaluating the structural dynamic response to periodically variable excitation loads is essential for extending the service life of existing machines and optimizing the design of future units.

KEYWORDS

Belt Conveyors, Spreaders, Dynamic Behavior, Belt Oscillations.

1. INTRODUCTION

Due to their high productivity, machines for continuous transport and spreading of bulk materials represent critical points in various industries, where operational reliability plays an essential role in ensuring a stable production process. In a large number of cases, these machines operate within serially coupled systems, e.g., bucket wheel excavator - belt conveyor - spreader, in the context of open-pit coal mining. Consequently, a downtime of a single machine results in a shutdown of the entire system, leading to significant financial losses that can exceed 9,000 €/h in the case of the mining industry [1]. Within such systems, some of the largest spreaders in terms of dimensions and transport capacities are deployed. These spreaders can feature discharge booms exceeding 100 m in length and spreading capacities of over 8,000 m³/h, Figure 1.

In the most general sense, spreaders represent self-propelled machines whose structural design enables the mobility of the belt conveyor located on the discharge boom. This arrangement maximizes the duration of continuous material spreading without requiring track displacement or relocation of the entire belt conveyor system that delivers material to the spreader. To achieve continuous spreading, the operational reliability of these machines must be maintained at a high level. Current technical regulations [2], [3] provide a solid basis for stability and strength calculations, whereas the evaluation of dynamic behavior is reduced to quasi-static calculations using dynamic coefficients, from which the limit values of acceleration at reference points can be obtained. However, unplanned downtimes and structural failures still occur in practice, indicating insufficient understanding of their dynamic behavior [4], [5], [6], [7], [8], [9], [10], [11]. Due to their complexity, reflected in their geometry and the design of supporting substructures in the form of spatial or planar truss

girders, as well as the variable configuration of the superstructure where each arbitrary position represents a unique calculation case, the analysis of each machine represents a unique case study. Given the necessity of adequate maintenance and current modernization trends for this type of machinery [12] - particularly regarding the variable frequency control of their drives - with the ultimate goal of extending their service life, a comprehensive evaluation of dynamic behavior becomes imperative. Such an evaluation would minimize the occurrence of negative dynamic effects, both for existing machines and for new units during their design phase.



Figure 1: The largest manufactured spreader, produced by TAKRAF, discharge boom length of 195 m, spreading capacity of 8,800 m³/h. [13]

Due to constant demands for increased production capacities, spreaders operate 24/7 under harsh conditions, remaining continuously exposed to dynamic loads throughout their decades-long service life [14]. To the authors' knowledge, the dynamic behavior of spreaders has not been sufficiently investigated from a theoretical standpoint, but is instead generally reduced to determining dynamic characteristics through experimental approaches [15], [16], [17]. However, through indirect analysis, it can be concluded that the cause of these loads originates from the operation of the belt conveyor located on the spreader discharge boom, as well as from the uneven distribution of the transported material.

Over time, from their initial design to the modern configurations established at the end of the 19th century - upon which the current operating principles are still based [18] - belt conveyors have become some of the most efficient machines for the continuous transport of bulk materials. Through the analysis of relevant literature, it can be observed that with the advancement of mathematical and computational tools, modernization trends in belt conveyors are predominantly focused on developing analytical and numerical models to avoid negative dynamic effects during transient operating regimes, establishing optimal control strategies to increase energy efficiency, and consequently, initiating new research into behavioral analysis under non-uniform material distribution on the belt. However, it can also be noted that these studies are based on the assumption that the conveyor is an isolated system, without further consideration of the impact of the resulting operating loads on the supporting structure where the conveyor is situated, as is precisely the case with spreaders. A common feature of these studies is that operational optimization is reduced to the appropriate variation of speed, which frequently requires the implementation of variable frequency drives that enable continuous variation of the rotational speed of the drive units, and thus, the belt speed. A fact that is also neglected in modern research is the potential existence of eccentricity in the rotating components of belt conveyors. Namely, the physical nature of this problem lies in the fact that a large number of rotating elements comprising a belt conveyor may possess a certain eccentricity within specified tolerance ranges even during their manufacturing phase [19], while operational eccentricities can also occur during spreader operation due to material buildup. From the perspective of the spreader, the existence of these eccentricities results in additional periodically variable loads in the form of centrifugal forces. With the introduction of variable frequency control, these forces acquire a variable character and are transmitted to the spreader supporting structure through idler frame and drum supports. Furthermore, certain studies have demonstrated that conveyors frequently operate with a non-uniform distribution of material on the belt. Given that the dynamic behavior of a system depends on mass distribution, these studies can also be significant when analyzing the response of the spreader. Considering all the aforementioned factors, some of the relevant problems that, either independently or through their solutions, can influence the dynamic behavior of spreaders are presented below.

2. RELEVANT PROBLEMS OF BELT CONVEYORS

2.1. Belt Oscillations

Belt oscillations represent a phenomenon that can have an indirect negative impact on the service life of the belt, and consequently, on the functionality of the belt conveyor as a system. As demonstrated below, belt oscillations can lead to fluctuations in belt tension over time, non-uniform distribution of tension along the belt itself, and unfavorable dynamic effects during inadequate drive startup, among other issues. To quantify this impact, and considering that belts generally consist of upper and lower rubber covers and a wire rope core or textile carcass [20], [21], conveyor belts for bulk material transport cannot be considered rigid bodies. Instead, their mathematical formulation requires models that account for both elasticity and damping due to the viscoelasticity of the constituent material. In the literature, this problem is most frequently addressed by applying the Kelvin-Voigt mathematical model (a spring and a damper connected in parallel), Figure 2 [22], [23], [24].

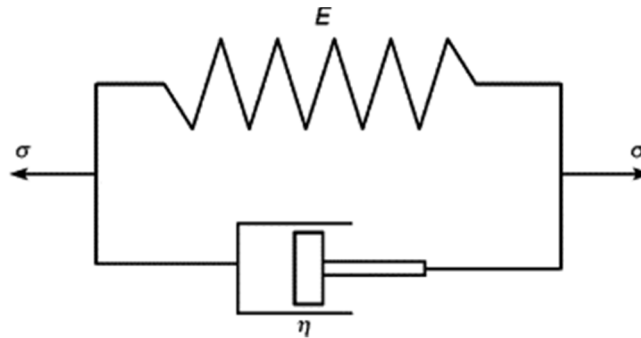


Figure 2: Kelvin-Voigt model

A procedure for establishing a constitutive model of the conveyor belt itself, along with an analysis of its dynamic parameters, is presented in [25]. This study does not consider the conveyor as a whole; instead, it focuses on the mechanical characteristics of steel-cord rubber belts and the influence of excitation parameters on the damping and elastic moduli of the rubber cover and steel cords. In this approach, the periodically variable excitation is developed into a Fourier series, while the belt is modeled using the Kelvin-Voigt model. The verification of the mathematical model was performed through experimental testing conducted on a tensile testing machine using an ST1600 belt specimen (1,100 mm in length, with 6 steel cords), where a 96% correlation between the experimental measurements and the analytical curve was achieved. Furthermore, it was demonstrated that with an increase in excitation frequency, the damping coefficient and elastic moduli of the rubber cover decrease. Conversely, with an increase in amplitude, the belt stiffness increases, while the damping initially decreases and subsequently increases. Such an approach provides a basis for selecting operating frequencies and amplitudes to prevent the degumming of the rubber cover from the steel cords, which negatively affects the service life of the belt.

In [22], an analytical procedure for solving partial differential equations was presented, where the system was modeled using the Kelvin-Voigt model, taking into account the mass of the belt, the mass of the transported material, and the masses of the idlers and drums, with the aim of obtaining a general solution for the system. During the solution process, assumptions were introduced that transverse oscillations of the belt, shear and bending stresses, as well as length changes due to vertical oscillations, could be neglected. With this approach, the conveyor was not observed as a static element, but rather as a continuous body whose dynamic behavior was described by partial differential equations. This enabled the authors to analyze the influence of various control parameters and conveyor design solutions - such as the design of the take-up device, belt speed, and drive control during transient operating regimes (startup) - on the longitudinal oscillations of the belt. It was demonstrated that with an increase in the damping coefficient, the maximum acceleration values during startup decrease, leading to more stable operation, while the total belt tension increases. Furthermore, it was determined that an increase in the take-up force effectively reduces the tension caused by dynamic belt tensioning. An increase in the material mass on the conveyor leads to an increase in tension due to dynamic belt tensioning, but this relationship is non-linear in nature. Additionally, an increase in belt speed results in higher tension values due to dynamic belt tensioning.

From the perspective of control regimes, through the conducted simulations, it was shown that a parabolic acceleration profile during startup - with a duration 15 to 20 times longer than the fundamental vibration period - has the most favorable effect on startup uniformity, maximum acceleration and tension values, as well as on longitudinal vibration impacts throughout the entire system.

In [26], an investigation into the dynamic characteristics of long-distance belt conveyors was presented, conducted on a conveyor equipped with a gravity take-up device. As in previous studies, the mechanical model of the conveyor in this work was formulated using the Kelvin-Voigt model, while also accounting for the force due to gravity tensioning of the belt. To numerically solve the system of differential equations, the authors applied the fourth-order Runge-Kutta method. Within the scope of investigating the system's dynamic response (dynamic tension distribution), the authors' focus was placed on three points: the head, mid-span, and tail of the conveyor. By analyzing the influence of various system parameters, it was observed that increasing the speed from 2 m/s to 4 m/s, at a fixed acceleration time during startup, leads to

an increase in the maximum tension value - by 32.6% in the case of the head point, which simultaneously exhibits the highest sensitivity to this parameter. Furthermore, the conducted analysis demonstrated that extending the acceleration time during startup yields favorable results for the dynamic behavior of the system. In addition, to further improve the conveyor startup regime, the authors proposed an original drive startup method which, according to the authors, reduces the maximum tension value by approximately 9–13%.

It should be mentioned that in addition to the Kelvin-Voigt model, other methods can be found in the literature for formulating mechanical belt models that can account for the viscoelastic properties of the material. For instance, Guo and Wang in [27] proposed a method for optimizing the conveyor startup regime by modeling the belt using rigid finite elements interconnected by a spring and a damper. The verification of the method was performed through experimental field measurements, yielding satisfactory agreement between the results of the analytical method and the experiment. The authors analyzed several different startup regimes and established that extending the startup time drastically reduces the dynamic belt tension.

In addition to the analysis of longitudinal oscillations using the Kelvin-Voigt model, in studies such as [28], [29], [30], the authors addressed the problem of creating new mathematical models that also account for transverse oscillations and their impact on the functionality of belt conveyors, exploring non-linear models that encompass the mechanical, geometric, and electromechanical aspects of the conveyor. Thus, through the aforementioned studies, the influences of the belt trough geometry, the effects of belt sag between idlers on belt tension, the variability of motion resistance, and the influence of the eccentricity of rotating components were analyzed. It is interesting to mention that in [30] a drive controlled by variable frequency regulation is also considered with the aim of achieving a soft-start, as well as reaching the nominal belt load, regardless of the mass of material present on the conveyor. Such a multidisciplinary approach provides a comprehensive analysis of the conveyor as a whole, aiming to describe the dynamic response to variations in different parameters as precisely as possible.

2.2. Energy-Efficient Speed Control

When discussing conveyors, in addition to the requirement for reliable operation - which, as previously demonstrated, is significantly influenced by the startup regime - the efficiency of their drive units plays an essential role. As energy efficiency demands continue to rise, and given that electricity costs for conveyors can account for up to 40% of the total operating costs of a mine [31], a considerable number of papers on this topic can be found in the literature.

An overview of current engineering solutions aimed at improving energy savings is provided in [32]. Among other aspects, the mentioned study describes the application of variable frequency drives (VFDs) to enable belt speed control within a specific range, with the objective of achieving better real-time belt filling. According to research conducted in [33], this management approach can reduce energy consumption by up to 20%. To optimize conveyor operation from the perspective of energy consumption, Kawalec et al. [34] introduced the Specific Energy Consumption (SEC) index as a criterion for evaluating the energy efficiency analysis of belt conveyor systems at a Polish open-pit coal mine. In addition to the number of conveyors in the system, belt width, trough angle, and material flow rate, the authors varied the belt speed. Through a combination of these parameters, a reduction in electricity consumption of 27.78% was achieved in the best-case scenario.

Vasic et al. in [35] address these issues in the context of conveyors deployed in open-pit mines. Since the amount of material on the conveyor in such cases depends on the operating conditions of bucket wheel excavators, which frequently do not operate at full capacity, there is a well-founded need to control the conveyor belt speed to adapt to the current real-time material volume. This avoids operating the conveyor at maximum speed when small quantities of material are being transported, thereby providing opportunities for energy savings and a subsequent reduction in financial costs. In their research, the authors presented a mathematical model for determining the required belt speed and the times necessary for acceleration/deceleration, under the assumption that speed adjustment should only be performed if the desired speed is at least 15% higher than the current speed [36]. Through a simulation conducted on a conveyor deployed at the Drmno open-pit mine in Serbia, based on annual operating data of the bucket wheel excavator that is serially coupled with this conveyor, the authors demonstrated that within the considered time period of 360 s, the conveyor would operate below its nominal speed the entire time, inevitably leading to a more energy-efficient operation of the system.

He et al. in [37] propose a new method, Estimation-Calculation-Optimization (ECO), which determines the minimum time required to adjust the belt speed based on the amount of material present on it, aiming to reduce energy consumption and CO₂ emissions while accounting for the dynamic behavior of the conveyor. Within the scope of this method, the acceleration regime (avoiding excessive belt tension), the deceleration regime (avoiding motor operation in regenerative braking mode), and the speed adjustment time (avoiding mechanical jerks) were taken into consideration. Following the analytical formulation of the method, a case study was conducted on a conveyor in the Port of Rotterdam, where the belt moves at a constant speed while the mass of material on the conveyor varies depending on the available cranes. The authors formulated a simulation model and, based on single-day operating data of the conveyor, compared specific operating parameters under constant and variable speed conditions. Through the conducted analysis, it was demonstrated that when controlling the drive using the ECO method under the same operating conditions, the belt filling would be higher by approximately 25%, energy consumption would be reduced by 12%, annual energy savings would amount to 160 MWh along with 86.9 t of CO₂, while the annual financial savings would reach €13,260.

Through the research conducted in [38], He et al. extended the application of the ECO method from individual conveyors to conveyor systems by integrating an active speed control strategy using the Delft Systems Approach method [39]. Within the investigation, the operation of a two-conveyor system was simulated, where the first conveyor moves at a constant speed, while the speed of the second conveyor is constant in the first case and controlled based on the amount of material arriving from the first conveyor in the second case, ranging from 2 to 4 m/s with a step of 0.5 m/s. The results of the conducted simulation showed that the applied method yields benefits in terms of reducing electricity consumption and CO₂ emissions, as well as providing financial savings, while achieving system operation under favorable dynamic conditions.

2.3. Non-Uniform Material Distribution on the Belt

According to the DIN 22101 standard [40], the material cross-section is considered a constant value along the entire conveyor path; the same assumption applies to the DIN 22261-2 standard [2]. In practice, a uniform distribution of material along the entire conveyor is rare, particularly for conveyors deployed in open-pit mines, where belt loading directly depends on the periodic discharge of the bucket wheel excavator buckets or operational conditions during excavation. For instance, Semenchenko et al. [41] conducted a 17-hour field measurement of the energy performance of a conveyor deployed at the Dovzhanska-Capital mine (Ukraine), demonstrating that non-uniformity of the material on the belt inevitably exists, which is also reflected in the uneven loading of the two conveyor drive motors. Based on the conducted analysis, the authors concluded that to save energy and extend the system's service life, it is necessary to implement belt speed regulation based on the current material flow rate.

In [42], the problem of non-uniform material distribution was analyzed from the perspective of conveyor energy efficiency. In their research, the authors modeled the conveyor belt using the Kelvin-Voigt model, where the belt was discretized into a finite number of elements whose dimension depends on the belt speed. Each of these finite elements is assigned a material mass obtained through laser scanning of the cross-section. By varying the loading levels (empty conveyor, light-load regime, and overload) and the startup duration in the conducted simulations, the authors established that a longer startup time has a favorable effect on the dynamic behavior of the system. Furthermore, the proposed method provides a basis for a drive control strategy that accounts for the actual material distribution on the belt.

3. DISCUSSION

Based on the presented literature review, it becomes evident that the majority of studies a priori consider conveyors whose supporting structures rest directly on the ground. Through this approach, the conveyor can be observed as an isolated system that does not interact with its environment. However, if the focus is shifted to spreaders, whose primary purpose is the spreading of bulk materials precisely via the conveyor located on them, the dynamic effects generated during conveyor operation are transmitted to the spreader supporting structure through their own framework.

On the other hand, the solution to the presented problems largely lies within the conveyor speed control methodology. If the issue is excessive belt tensioning, which is addressed in Section 2.1, the objective is to prevent undesirable dynamic effects during transient operating regimes of the conveyor, namely during startup and shutdown. The solutions to the problems described in Sections 2.2 and 2.3 lie in controlling the belt speed relative to the quantity and distribution of the material currently present on the conveyor. The presented control strategies aimed at energy efficiency and financial savings primarily account for transient dynamic effects within the conveyor as an isolated system, while the resulting dynamic transmission onto the wider supporting structure remains unaddressed.

When observed from the perspective of the dynamic behavior of continuous bulk material spreading machinery, a portion of the excitation load originates precisely from the operation of the conveyor [16]. The cause of this lies not only in the dynamic effects resulting from belt oscillations and inertial loads occurring during transient operating regimes, but can also be significantly induced by the eccentricities of rotating masses (idlers and drums) [43]. To the authors' knowledge, the influence of eccentricity on the dynamic behavior of the spreader supporting structure has not been sufficiently investigated. Given that spreaders are machines with a variable configuration, where each configuration represents a unique dynamic system, when combined with specific parameters such as the inclination angle of the spreader discharge boom, the amount of material on the belt, and the belt speed, even the eccentricity values defined by technical regulations [19] can lead to the occurrence of resonance, and consequently, to undesirable dynamic effects [44]. On the other hand, the conveyor belt speed has a direct impact on the periodically variable load caused by the eccentricity of rotating masses. In [45], under the assumption that no drive control strategy exists relative to the configuration of the spreader superstructure, it was demonstrated that for inertial forces occurring due to the manufacturing eccentricity of the take-up drum, which remains within prescribed tolerance limits, the response analysis of the superstructure eliminates as much as 46.6% of the belt speed spectrum ranging from 2.5 m/s to 6.5 m/s, from the standpoint of the reference point acceleration limits. If a 5% belt slip is additionally taken into account, only 29.3% of the speed spectrum would be usable. Such an analysis clearly indicates that even control strategies yielding optimal operational results for a conveyor as a closed system cannot be directly applied to conveyors on specialized machines like spreaders; instead, the dynamic response analysis must be extended to the entire system.

4. CONCLUSION

The flexibility and simplicity of belt conveyors enable their easy adaptation to various operating conditions, as well as the achievement of high material transport capacities. Through the literature review conducted in this study, some of the most common problems have been highlighted, along with modern trends aimed at improving the energy efficiency of these machines. Whether addressing the problems of belt oscillations or developing optimal control strategies regarding the amount of material on the belt, researchers predominantly focus on finding solutions through variations in belt speed, i.e., the rotational speed of the driving electric motor. However, in the case of conveyors installed on specialized machinery for continuous bulk material spreading, namely spreaders, where the mobility of the conveyor itself is enabled through a supporting structure that can weigh several thousand tons to ensure continuous material spreading at stockyards, strategic speed variations may yield favorable results for the conveyor itself, but unfavorable outcomes for the entire supporting structure of these machines. Speed parameter variation can have a particularly significant impact in the presence of eccentricity in the rotating components of the conveyor, as additional excitation loads are generated and transmitted to the supporting structure of this type of machinery. Given the large number of rotating elements (idlers and drums), the question arises as to the impact of these excitation loads if they exist only on a certain number of rotating components or across all rotating elements, and whether the eccentricity remains within manufacturing tolerance limits or occurred during operation. Furthermore, speed variation is coupled with the material volume on the belt, which can also influence the system response to such excitation. All the aforementioned aspects simultaneously represent potential directions for future research aimed at describing the impact of conveyor dynamic behavior on the dynamic behavior of the spreader supporting structure, with the ultimate goal of preventive maintenance for existing units and the elimination of potential engineering errors during the design phase of new spreaders.

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