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The Importance and Prediction of Tension Distribution Around the Conveyor Belt Path

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Computerization has allowed practical design of complicated and optimized belt conveyors for bulk materials from prediction of belt tensions around the belt circuit for a wide range of belt loadings and conveyance paths. These design methods are based on a knowledge of component operating characteristics and sources of tension change. As compared to generalized 'f' methods, CEMA's historical Kx and Ky has provided nonlinear and more specific predictions of belt tension as affected by various components and operating conditions. These empirical values were developed in a different age and generalizations made in their development are now a constraint to additional conveyor improvements. This paper discusses the potential from improved and standardized 'friction' predictions and presents the results of sensitivity evaluations as affected by calculation method.

INTRODUCTION

Belt conveyors are integral to modern mine operations due to their high capacity, operating cost efficiency and reliability in the transport of mine products in bulk. Like most machines, belt conveyor dependability and cost are strongly dictated by the care and due process given to their planning and design. Over the last century, a wide range of belt conveying designs have developed to offer flexibility in the conveyance plan while component design and capacity have evolved to address most applications for transport of bulk materials in mines. The design synthesis phase from the planning to the execution has also developed significantly but remains a challenge to design and operating optimization from ill-defined and out-of-date energy use predictions.

PURPOSE

The purpose of this paper is to describe the primary role that the prediction of belt tension plays in conveyor design predictions and to illustrate the importance of accurately understanding the tensions in the nominal design and with varying operating conditions. It is hoped that this awareness will encourage improvements in tension predictions. Mine operators and suppliers both stand to gain from an atmosphere of continued improvement in standardized methodologies.

ROLE OF BELT TENSION IN CONVEYOR DESIGN

Fundamentally, a belt conveyor can be considered to cause a translating one dimensional movement. It spans distances through a combination of intermediate supports and the tension in the belt. The tension is a combination of that needed to make the flexible belt reasonably straight, that needed to overcome the resistance to movement, and other tensions necessary for various components to work consistently. All three have wide interdependencies with the conveyor path and the material handled which combine to make the accurate prediction of tension very difficult as it varies around the conveyance and return circuits. Nevertheless, belt tension is a primary influence on the cost and function of virtually all belt conveyors and is a key design parameter. Accurately predicting the tension is therefore a key objective when developing a conveyor in order to optimize investment and operating efficiencies.

Capital and Operating Cost Implications

Maximum expected belt tension has a primary influence on the most expensive component on a conveyor, the belt itself. Structural support systems and pulleys assembly costs are also directly governed by the expected belt tension. Drive motors, reducers costs vary with energy consumption or tension variation due to frictional or hysteretic loss. This same energy loss is a primary operating cost and should be incorporated with the previous items into a least total cost analysis.

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Belt speed has a major impact on the capacity and therefore width of the belt but tradeoffs are recognized with the energy loss as seen in operating tension. Similarly, belt and idler selection and idler spacing have important influences on the tension lost to cause movement. These are discussed more in the following sections. Most conveyors run satisfactorily as designed, including startup and shutdown and over many years. This is often accomplished through overdesign of the drive and other conveyance components, with varying investment cost implications, due to appropriate caution from imprecision of the prediction of operating tensions.

Conveyor Operating Reliability

One of the primary conveyor design goals is operating stability beyond the oversimplified assumption of one dimensional movement; that is, a set of installed components that work consistently well enough to cause acceptable vertical and lateral belt movement while maintaining minimum tensions to cause the belt to act rigidly. This must be done under a wide range of loading and environmental conditions as well as under acceleration and deceleration when transient tensions develop from inertia and component coupling issues. Poorly designed conveyors can cause material spillage and even loss of control of the belt path.

Straight uphill or flat conveyors are manageable since 1) the belt path does not invite wandering, 2) the systems are usually self damping, and 3) concerns for tension loss under dynamic conditions can be solved by overtensioning and overdesigning within the confidence level of the tension prediction. Other configurations are less forgiving and require a better understanding of the local tensions variation to manage the cost and path compromises.

Decline conveyor. The regenerating effect of decline conveyors counters the tension force needed to cause motion. The difference between the energy loss from movement and the potential energy gain can become more important than the maximum tension. If resistance in the decline section is overestimated, lower tension will be expected with corresponding additional increases in resistance. The result can be higher tensions and undersizing of brakes. Alternately, underestimation is more likely to cause a problem since lighter components will be used with smaller design safety factors that are quickly absorbed by the larger relative inaccuracies.

Vertical curves. When conveyors change slopes a gradual transition, or "vertical curve," is needed to prevent over- or understressing of the belt due to trough depth effects and to manage the vertical loads on components. A concave curve can cause liftoff of the belt from the idlers when the belt travels to a steeper angle from the belt tension vector normal to the movement direction. This tendency is overcome by the distributed gravity effect over the length of the curve. Loaded and unloaded sections have dramatic effects and force large radii when only the belt weight is available to keep the belt in the trough. This is compounded with tension inaccuracy though overestimation of tension loss will likely develop curves on the safe side. Similar belt forces in convex curves are transferred to the idlers so liftoff is not a concern though required idler capacity and conveying friction can be affected.

Horizontal curve. Stable belt tracking is a concern when the belt direction changes laterally. Again, gradual curves are used to manage the tension distribution across the belt and to provide a gradual mistracking effect from similar tension vectors as described above. These lateral belt forces are managed by gravity forces acting on idler "wing" or vertically angled rolls as well as steering correction from laterally angled rolls. They have similar sensitivities as described above but analysis is compounded by added force directions so a stable design becomes even more sensitive to correctly understanding the operating tension, including additional resistances that develop from radial loading of the curve.

In addition, longer conveyors accumulate the effect of inaccuracy on stability since the upcoming tension is affected by the prior tension contributions. The combinations of loaded and unloaded sections further increase the tension variations with consequences discussed above. Modern design programs allow the accumulation of these varying tension influences but can't compensate for poor accuracy in the tension prediction.

TENSION DISTRIBUTION ALONG THE CONVEYOR PATH

Automatic takeups, used on most long conveyors, serve as a point of known tension. Intermediate drives equipped with closed loop tension control also are used to reestablish a point of predictable tension, important to erase accumulated errors in complex circuits. The tension in the belt is constantly changing from these controlled tension locations as it moves along the conveyance path due to the collection of incremental changes along its length. The tension distribution is consistent until altered when the flow rate changes or is interrupted. Since the incremental change or rate of tension change varies with several operating conditions, including the local belt tension itself, changes in the tension will be seen throughout the conveyor circuit from accumulating effects of local changes.

The same behavior applies to conveyor tension models but prediction inaccuracies are compounded. Conveyor design requires analyzing or predicting and accumulating of these local tension changes around the full circuit of belt travel and ensuring a stable belt path for a particular set of design parameters over the range of conditions that may develop over the life of the conveyor. Optimization involving capital and operating costs for various sets of these design parameters, components, paths, etc., leads directly from iterating these tension summation exercises.

Tension Influences

The influences on belt tension can be broken into categories for simplification in their use in design. We will be looking only at the sources of long continuous tension change and acknowledge that "point" or short sources such as various pulley contributions and conveyor accessories have important load effects as well. The following descriptions are oriented to the need for a quantitative understanding of the "local" tension that exists at a point in time at any particular point on the conveyor path.

Application parameters are those that describe the design requirements. They include 1) material including its variability; 2) tonnage, range and duty cycle; 3) environment, especially temperature; and 4) the belt path. Though expected variations need to be evaluated, these cannot be modified, except in cases that the conveyor layout, flight length, etc., are within the scope of the project.

Design parameters are those that the designer selects such as 1) conveyor speed, width and trough profile; 2) belt properties including carcass stiffness and cover thickness and material; 3) idler spacing, alignment and design, involving roll diameter and bearing and seal design.

Operating influences are those that develop as a consequence of the above parameters but have an inconsistent contribution due to variations in the material loading along the belt. These belt loads, both gravity and tension, affect the local contribution to the total belt tension.

The above have various interactions and effects, both in strong and weak ways, on several primary mechanisms of energy change. Energy or "work" is seen as tension change through a distance or correspondingly as a rate of tension change per unit length. This is often considered as a friction though strictly speaking viscous or plastic movements cause many of the energy losses rather than classic Coulomb friction which is, by definition, loss proportional to load. Rate of work clearly leads to power consumption.

Tension Variation

With the exception of decline conveyor sections, tension must increase in the direction of belt movement. Various authors have described a range of the energy loss mechanisms that require makeup energy from the drive to maintain motion. It is useful to review these with their primary operating influences.

Constant resistances are those that develop simply from conveyor movement. These are primarily internal losses in the idler from seal drag and grease viscosity. These are due to viscous and sliding movements inherent to the idler design. Though they don't change with load, temperature and age have strong effects on them.

Gravity load dependencies can be seen in many of the loss sources. The simplest and most accurate to predict is the linear change in potential energy from lifting or lowering the belt and bulk material. Another is loss in the idler bearings and from nonelastic internal belt deformations including that in the belt covers. Transverse sliding losses on the idler from misalignment are also a function of the local load.

Tension-dependent tension losses come primarily from energy losses due to internal movement, or repeated plastic yielding, in the bulk material and the belt due to sag and profile deformations. These deformations develop from the gravity load but their magnitude is also strongly affected by the local tension itself, which is a combination of the takeup tension and the accumulations between the takeup and the point in question. Belt stiffness and material properties also interact with this deformation. Importantly, these losses diminish significantly near high-horsepower drives or other locations where the tension is very high.

It should be noted that tension "losses" are stated relative to the high tensions at the drive location though calculations proceed from the point of known constant tension, usually an automatic takeup, in the direction of belt travel. Fixed takeup systems require analysis of belt length and accumulated stretch.

TENSION PREDICTION CALCULATIONS

Various authors dating from the 1950s have provided a wide range of insights into the calculation of conveyor power requirements. Suffice it to say that most have an empirical basis with various causal variables as described above. Inherently, these methods are most accurate for applications that match the test conditions used for their development. Spaans (1991) provided a notable exception to the empirical methods and provided functional equations based on local loads and conditions. His published work falls short of providing a full design-ready model due to difficulty in defining the inter idler belt deformations.

Historically, many belt and conveyor manufacturers provided calculation methods to promote the safe use of their products. The simple methodologies were useful for their time but are lacking where understanding local tension variations is important.

DIN and ISO 'f'

A commonly used concept around the world is the use of a fictitious friction factor as a multiplier to the local gravity load. Various evolutions of DIN 22101 standard requires the selection of a single f in a range of 0.010–0.04 based on several qualitative variables, making it unsuitable for local loss variations (DIN 2002).

CEMA Ky and Kx

Like 22101, CEMA's pseudo friction loss factors, Ky and Kx (CEMA 1997), were developed to be assigned as an average over the full length of the conveyor and conservancy overrides the need for understanding of actual local tensions. Nonetheless, it does provide charts and values of Ky and Kx friction factors versus a limited range of gravity loading, belt tension, idler spacing, and CEMA member idler sets. Many designers have successfully extrapolated past the range of data provided with varying accuracy. As such, it has proven quite useful, with "tuning," for use on the expanded range of conveyor layout described above. Unfortunately, the inherent oversafety and outdated and limited range of data make the current version of the CEMA method fall short of the needed universal design method.

Custom Properties and Prediction

The accurate calculation or prediction of the belt tensions is of increasing importance due to more complex conveyor layouts allowed by current computerized design programs. This has justified many studies and subsequent papers which have provided insight on various loss mechanisms. Though typically driven by the desire to reduce power rather than understand tensions variation, this has lead to some conveyor designs with increased precision in the tension prediction, especially where extremely high tensions reduce the "sag" loss and special testing is justified. Specific issues include the following.

Belt cover materials and construction. Researchers, including Schwarz (1967) and Jonkers (1980), have shown by test and calculation the important contribution that viscoelastic indentation of the cover between the belt and idler roll contributes to the total energy loss in long conveyors. The cube root interaction between load, cover thickness and inversely to roll diameter squared is commonly accepted as a good basic indicator of this loss but rubber properties incorporating belt speed and temperature effects needed to utilize this calculation are less straightforward. Standard rubber tests have not shown to have direct and consistent effects but methods have been developed to provide a reasonable prediction of internal rubber losses (Lodewijks 1995). Applied testing such as that by Hager and Hintz (1993) has added to the understanding of this source of loss but a truly useful tool requires a standard parameter consistently describing the belt material and a model incorporating its effects.

Idlers. CEMA's (1997) Kx provides useful rolling resistance values for several idler designs especially when individual roll contributions are extrapolated from the data provided. These have proven to frequently overstate the actual torque required to rotate the rolls on an idler again from a oversimplified understanding of "conservative." This and the need for improved speed and temperature effects has been justification for some to do independent testing directed at a particular application (Granig 2000). Aging has proven to complicate the stability of the above predictions and adds another source of variability to the rate of tension change along the belt.

In many large-scale conveyors, the benefits of a better understanding of specific sources has been incorporated as a relative improvement to DIN or CEMA for the estimated importance of a particular category (Behrens 1968) of loss so that actual precision of the tension prediction is not always significantly improved, though the benefit of component improvements can be estimated. A better understanding and breakout of the other sources of loss is needed to fully incorporate the benefits of understanding indentation and idler "friction."

CONVEYOR OPERATING RELIABILITY AND OPTIMIZATION

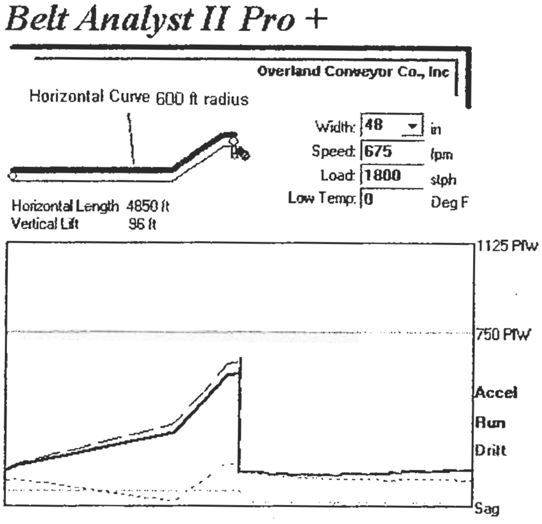
The long-term operating efficiency needed by mines and other large-scale material handling facilities is most impacted by the initial design for belt conveyors. The design can develop in a number of ways but in the end a simulation model is developed to predict the conveyor operating loads and path stability which ultimately control operating reliability and cost. Simulating the interaction of various sets of components leads one to an optimized design if pursued in an iterative fashion. With short, straight conveyors the models can be very simple and intuition tells us the worst-case operating conditions to evaluate.

Computer Modeling

With long, complicated conveyors, intuition becomes less reliable and the mathematical models much more complicated. Computer modeling of conveyors with various commercial software packages is commonplace and has simplified the analysis procedure and lets the designer look at a wide range of loading and other operating parameters within one design configuration. Unfortunately, the computer does not reduce the need for accurate constitutive model algorithms but, as discussed above, the designs now possible require improved accuracy and understanding of range of applicability due to the wide range of interactions that develop.

Examples

The following examples describe the results of two analysis models to illustrate effects described above. The same basic conveyor is used for all of the comparisons. The layout and basic parameters are shown in Figure 1 with a graph of expected operating tensions under fully loaded operation at steady state as well as during startup and shutdown.



Width: 48 in
Speed: 675 fpm
Load: 1800 stph
Low Temp: 0 Deg F
Horizontal Length 4850 ft
Vertical Lift 96 ft

FIGURE 1 Example belt conveyor with modeled belt tensions

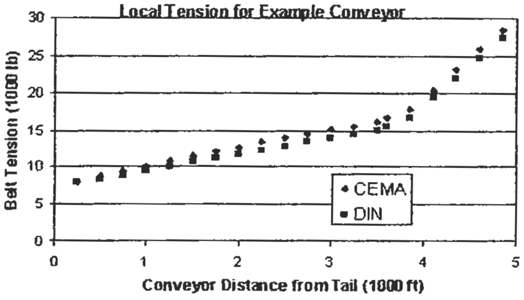


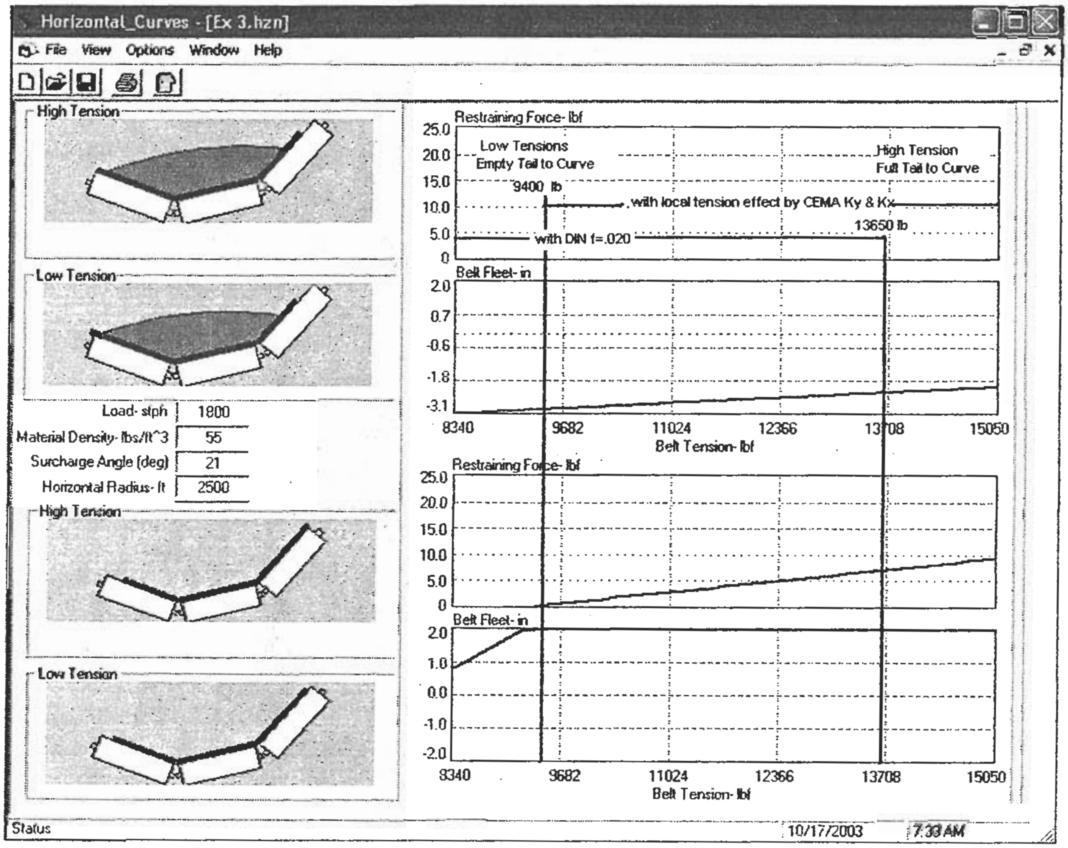
FIGURE 2 Local belt tensions at steady state fully loaded for two different "friction" models

Vertical curve design. To illustrate the sensitivity of tension calculation to vertical curve design, conveyor tensions were modeled assuming a constant friction factor of 0.20 as indicated for common belt conveyors in DIN 22101 (2002). The required vertical curve radii were evaluated with various loading conditions including loaded, empty load of/load on steps and worst-case assumptions of loading in the incline only. The design was then "locked in" and the "friction" model changed to one similar to CEMA's method (1997) with similar load combinations and with the same net power requirement. Figure 2 shows the difference in tensions that developed due to higher local friction at the low-tension portions of the conveyor.

Table 1 shows the net effect on required radius. The improved sensitivity of the CEMA model predicts that the belt would lift off of the idlers if the conveyor had been designed to the constant friction model.

TABLE 1 Comparison of operating requirements for conveyors designed with two separate friction loss models

Friction Model	Max Required Power	Concave Curve Radius Required
Constant f=0.20 (DIN)	356kW (478 hp)	585m (1,920 ft)
Varies with Tension (CEMA)	355kW (476 hp)	625m (2,050 ft)



Load- stph 1800
Material Density- lbs/ft^3 55
Surcharge Angle (deg) 21
Horizontal Radius- ft 2500

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FIGURE 3 Horizontal curve analysis showing effect of tensions from Figure 2 tension differences

Horizontal curve design. The effect of the same tension differences on a horizontal curve in the previous example conveyor are illustrated in Figure 3.

This shows that side restraining rolls would be in use to restrain the empty belt if the constant friction assumption were used with the original conveyor design and actual operating tensions varied per CEMA's trends. Unlike the vertical curve analysis, extra conservancy on the tension calculations is not desirable since it can cause excess belt fleet or shifting in the opposite direction. Alternatively, compromises to the belt capacity caused by concerns for curve instabilities will be needed to tolerate the expected inaccuracy in the original design. Energy losses due to temperature fluctuations from 25°C (80°F) to −25°C (−10°F) or from idler drag significantly different than expected at the design stage are effected by a comparable amount to that calculated above with similar net results.

It should be noted that a simplified example was used for clarity and the results are magnified for more complex configurations.

CONCLUSION

The lack of total understanding of local tension around the belt circuit has not stopped the development of long complex belt paths but continues to compromise the range and efficiency of installations. Standardized improvement in this understanding can allow more flexibility in installations as well as reducing installed and operating costs without complicating commercial issues and making each design into a research project.

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