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Transverse vibration analysis of inclined conveyor belts

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Abstract

Transverse vibration is an important phenomenon that will affect the working life of a conveyor belt. The impact of some parameters like the speed of the belt, flexural rigidity, and tensile force on the vibration natural frequency is an important matter for designing and operating a conveyor belt. In addition, most conveyor belts are designed to be used for elevating material. In other words, they have an inclination angle. In this article, the effect of speed, tensile force, and flexural rigidity on the vibration frequency for an inclined conveyor belt is investigated. In addition, for a range of spans between idlers, the results are plotted to choose the best results. The results have been compared and suggestions for designing and operating a conveyor belt based on the impact of speed, tensile force, and flexural rigidity on the vibration frequency for an inclined conveyor belt are presented. With the help of this material, it would be easy to control and dampen the vibration.

Keywords: Conveyor Belt; Vibration; Modelling; Transverse Vibration.

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1. Introduction

Conveyor belts are pivotal when raw materials or finished products must be transported. Normally, vibrations occur during the operation of a conveyor belt as a result of dynamical loading. Mostly the vibrations are classified as longitudinal or transverse, depending on their direction relative to the conveyor system. Designing a conveyor belt and calculating the vibrations of a conveyor system are two important concerns for the beneficiary team and engineers as if the conveyor system stops working, results may lead to failure in the production procedure. It is crucial to find a key design factor to optimize the vibration effects on the whole system. The inclination angle, as a designing factor, should be considered for vibration and dynamic motion equations. In addition, for longitudinal vibrations, it is necessary to have a simple simulated model for deriving the amplitude, frequency, and resonances [1-3].

The vibration impact on roller bearings and idler supporters is undeniable and will result in damaging the operating parts. Replacing damaged parts, however, could be a costly procedure. Thus, the vibrations should be considered, and finally be damped to optimize the system operation [4, 5]. The vibrations in a conveyor belt depend on many factors, it is necessary to prevent the resonance in a conveyor system during the design stage. Ensuring that the conveyor structure has sufficient stiffness and damping could be an essential design factor. Indeed, stiffness prevents excessive deflection, while damping dissipates energy and reduces vibrations [6]. Also, calculating the natural frequencies of the conveyor system helps the operators avoid operating near these frequencies to prevent resonance. In addition, understanding the mode shapes of the system is a primary key for modifying the design to avoid modes with high vibration amplitudes [7]. There are some operating parameters that can affect the conveyor system vibrations such as belt tension, speed, and load distribution [8]. In addition, there are ways to control the vibration by damping methods like using Tuned Mass Dampers or Viscous Dampers [9, 10].

Previously, Piotr Baranowski et al [11], worked on the transverse vibration of conveyor belts. They determined the transverse vibration frequency of a conveyor belt using theoretical relationships based on the assumption that the belt acts as a stationary elastic string. Belt vibrations share similarities with other tension member systems, such as power transmission belts. Based on some research, for shorter belt sections, a beam model provides a more accurate description of vibration compared to a string model. Most experimental studies have focused on stationary belts, but this article presents vibration measurements for a moving steel-cord belt under various operating conditions and idler support configurations. Continuously, the results were compared with both string and beam models, revealing that belt speed has negligible influence, while tensile force significantly impacts vibration frequency. Depending on idler spacing, the belt behaviour approximates a beam or a string model. Finally, it is suggested that a beam model is more suitable for analysing vibrations in the upper strand of the belt. In contrast, a string model is preferable for vibrations in the lower strand.

Kibria et al [12], studied extensive utilization of tubular belt conveyors that face limitations due to insufficient validation of conveyor parameters. They derive equilibrium equations for the load on the inclined tubular conveyor belt based on the theory of limiting equilibrium states for bulk materials. They assume the belt to be a rigid cylinder filled with bulk material in a state of extreme equilibrium. Using these equilibrium equations, they establish analytical relationships between the conveyor’s limiting angle of inclination (with a tubular belt) and the degree of belt unfilled with bulk load, as well as the properties of the conveyed material. Notably, the limiting angle of inclination is influenced by the angle of internal friction of the transported load, the angle of friction between the load and the conveyor belt, and the degree of belt unfilled, but it remains independent of the conveyor belts radius.

Shangguan et al [13] introduced a method for modelling and calculating the natural frequencies of a belt span and the transverse vibration displacement at a point within that span for an accessory drive system. The model simplifies the belt between adjacent pulleys as an axial moving viscous-elastic string, and it describes the relationship between stress and strain using a standard viscous-elastic constitutive model. The calculated natural frequencies from this axial moving string model are compared with estimated results from a pulley–string belt coupled model. Remarkably, the natural frequencies can be directly obtained from the axial moving string model. Experimental measurements of natural frequencies and transverse displacements in a generic engine front-end accessory drive system align well with the calculated results, validating the presented modelling and calculation methods. Additionally, the study investigates how the elastic stiffness and damping of the belt impact transverse deflections within a belt span. Notably, increasing the elastic stiffness and damping leads to reduced transverse deflections in the belt.

Piotr Bortnowski et al [14] investigated transverse vibration analysis that relies on theoretical models or stationary tests. In this study, the vibration frequency of an operational conveyor was measured both when the belt was unloaded and when it carried material. The tests were conducted while the conveyor was in motion, using a specially designed device placed on the belt. The distribution of transverse vibration frequencies along the entire conveyor length was identified. By leveraging belt vibration characteristics, the increase in tension force in the upper belt strand was quantified. Comparing the measured tension force increments with values obtained through computer simulation demonstrated the method’s high accuracy.

Hiroharu Tokoro et al [15], observed generating mechanism and the reduction method of belt transverse vibration as a cause of timing belt noise. Two main processes have been described. Firstly, the belt resonance frequency varies with the tension and the amplitude increases when the frequency equals the belt meshing frequency. Secondly, an excitation source exists in the belt tooth crest and bottomland, whose influence varies with the tension. Petru Razvan Scurtu et al [16], considered the nonlinear effect of the transversal vibration of the belt under transversal excitation without considering the coupling effect between the transversal and longitudinal vibrations under longitudinal excitation.

Serge Abrate [17] discussed the models available free and forced vibration of the belt considering the effects of initial tension, transport velocity, bending rigidity, support flexibility, large displacements, and belt and pulley imperfections. Beikman et al [18] focused on fundamental modelling issues that are central to predicting accessory drive vibration. A prototypical drive is evaluated, which is composed of a driven pulley, a driving pulley, and a dynamic tensioner. Harrison et al [19] explained the evolution of stresses in belts using solutions to the one-dimensional elastic wave equation by developing techniques to measure and analyse these transient stresses in the belt using belt velocity characteristics. You-fu Hou et al [20] tested two types of belts, a steel reinforced belt and a fabric-reinforced belt under conditions appropriate for the ISO/DP9856 standard. Also, the test equipment was built to provide data appropriate for designing belt conveyors and suggest that the proper and safe design of conveyor belts requires careful consideration of transverse vibration. Accurate determination of vibration frequencies is crucial to prevent hazardous operating conditions and premature component wear.

Thus, in this paper, we suggest an improved model in which the belt inclination angle and speed of the belt are also considered. For this model, transverse vibration frequency has been calculated and the equations have been solved using theoretical relationships based on dynamical equations. First, we solve the continuous transverse vibrational equations for different inclination angles of the unloaded conveyor belt and obtain the natural vibration frequency and resonances for both modelling the belt as a string and as a beam. In the following, the same work has been done for the conveyor belt with the maximum possible load and tension. Finally, the results have been compared with each other and the best results have been chosen.

2. Modelling and governing of equations

The object of the design was a single drive belt conveyor as shown in figure 1. The belt includes a drive pulley, a tale pulley, idlers and a take up section has an inclination showing as θ. In this designed system, the pulling force is applied to the belt by the drive unit situated at the head pulley, which consists of a unique drive pulley mounted on the output shaft of the motor-gearbox assembly [21]. As it is obvious that the belt is a tension member, there are some analogous behaviours between a conveyor belt and the transverse vibrations of a power transmission belt [5, 15, 16, and 18].

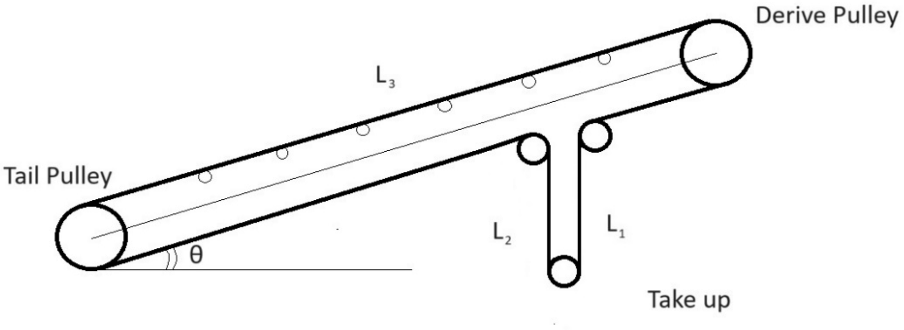

Figure 1. The schematic design of a belt conveyor system.

In figure 1, θ is the belt incline angle that varies between 5 to 12.5 degrees for inclined belts based on the height that materials are going to be transported [3, 6, 22, and 23]. In some cases, modeling a conveyor belt is possible with the help of flexural rigidity. Belt elastic properties and flexural rigidity can be allowed for by using a model of a stationary simply supported beam having a given vibration frequency [24]:

$$f_b = \left(\frac{n\pi}{2l^2}\right)\sqrt{\frac{EI}{m_t.B}} \qquad (1)$$

where EI is flexural rigidity (Nm^2). By considering the beam as a simply supported one, and allowing the tensile force, the beam will have its base vibration frequency as below:

$$f_b = \left(\frac{n\pi}{2l^2}\right)\sqrt{\frac{EI}{m_t.B}}\sqrt{1+\frac{Tl^2}{\pi^2 EI}} \qquad (2)$$

Hence, equation (3) shows the relationship allows for belt speed (for n = 1):

$$f_b = \left(\frac{\pi}{2l^2}\right)\sqrt{\frac{EI}{m_t.B}}\sqrt{1+\frac{(T-Bm_t.v^2)l^2}{\pi^2 EI}} \qquad (3)$$

Flexural rigidity can be expressed as the product of the moment of inertia of the cross-section (I) and the modulus of elasticity (E). The moment of inertia can be calculated as below [24]:

$$I = I_m + 2.I_s \qquad (4)$$

where I_m is the moment of inertia of the central part of the cross-section of the belt (m^4), and I_s is the moment of inertia of the inclined part of the cross-section of the belt (m^4).

3. Materials and Methods

Unlike homogeneous structures, expressing the tensile force as force per area unit of the cross-section could be not easy due to the heterogeneous structure of the cross section of a conveyor belt [25]. Important details of the belt are illustrated in Table 1.

Table 1. Data set derived from the 4th and 5th idlers of observed conveyor belt for beam model.

Parameter	Nominal Value	Value set I	Value set II	Value set III
l (m)	1	0.5	1.5	2
$T\ (N)$	108200	108200	108200	108200
$m_t\ (kg/m^2)$	259.10	107.96	323.875	431.83
EI (Nm^2)	283.93	283.93	283.93	283.93
B (m)	1.2	1.2	1.2	1.2
V (m/s)	1.5	1.5	1.5	1.5

The Flexural rigidity (EI) is calculated based on the given material in Table 1 with the help of equation (4) and given calculations [24]. The inclination angle of the belt (θ) for this belt is 5 degrees, which has a great impact on Tension Force and must be determined.

4. Results and Discussion

As shown in Figure 2, the observations focused on the measurement of vibration frequencies between the carry idler numbers 4 and 5 where the tension is at the lowest value, which means the vibrations would be at the highest rate in this section.

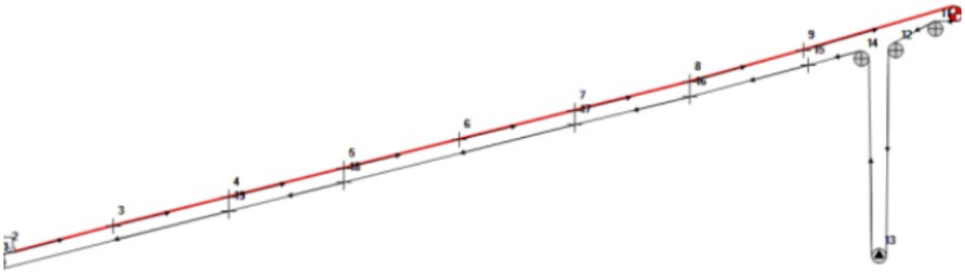

Figure 2. Belt structural design.

The result of having different tensile forces in terms of the length of the belt on frequencies has been measured and the result of changing the shape of the belt which changes the Flexural rigidity (EI) has been calculated. In the following, the result of enhancing the velocity in terms of the width (B) of the belt has been figured.

As has been discussed the string model does not bring accurate outcomes for a belt conveyor simulation because strings cannot carry much load on them in a real matter, and the transverse vibration calculations may have errors and be inaccurate if a conveyor belt is simulated by a string. On the other hand, the beam model shows more trustable and realistic answers which makes it a good model for calculations of a conveyor belt. Results shown in the diagrams of Figure 3-6 provide answers that speed, Tension force, and the width of the belt could have a profound influence on the frequency. Showing a non-linear pattern for increasing the frequency has been observed. The inclination of the belt is another considerable parameter that changes the results. Considering the belt angle made the calculations more accurate and realistic. In Figure 3, it has been shown that the lower speeds of a conveyor belt may provide high natural frequencies to the belt. If the span between two idlers becomes greater the results may show different values. As a result, if the length of the span between two idlers is long, speeding up the belt may cause fewer transverse vibration frequencies. The results shown in Figure 4 give us answers to the question about the impact of tensile force on the belt vibration. As shown, high frequencies are the result of more tensile force. However, when the idlers are set to be at a short span the natural frequencies do not differ at a high rate.

On the other side, long idler spans may have higher frequency differences showing that for long span sets it would be better to have not much high tensile force. The plotted data in Figure 5 shows that the effect of the shape of the belt may have a huge influence on the natural frequency range. Data is not much different but flatted designs may cause more transverse vibrations. For more optimal operation, it is better to design the belt in a shape that has a lower flexural rigidity value. Furthermore, in Figure 6, the effect of applying different speeds on the belt in terms of different widths has been plotted. Results show that it may not have as much effect on the transverse vibration and natural frequencies as Length. However, it can be considerable when it comes to having an optimal design. For reducing, the number of vibrations controlling the natural frequencies and damping the vibrations further research is essential. However, redesigning the shape of the belt, controlling the speed of the belt, and changing the tensile force may change the condition and increase the system's possible working hours without being damaged. The noise and vibration meter allows for clear results only for high vibration.

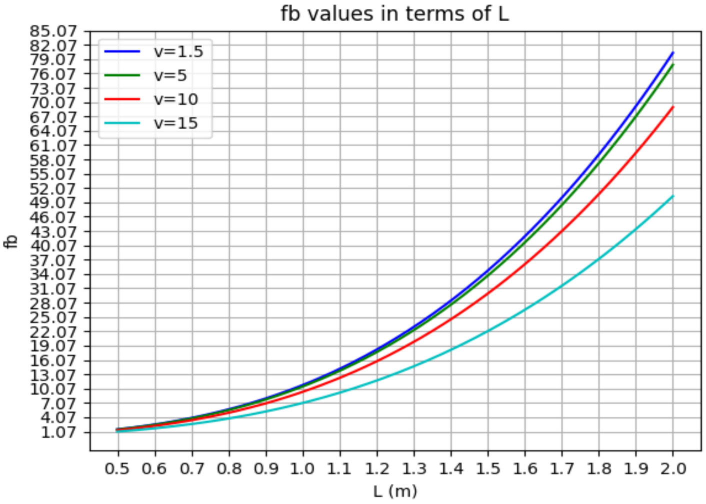

Figure 3. Frequencies in terms of L for different velocities.

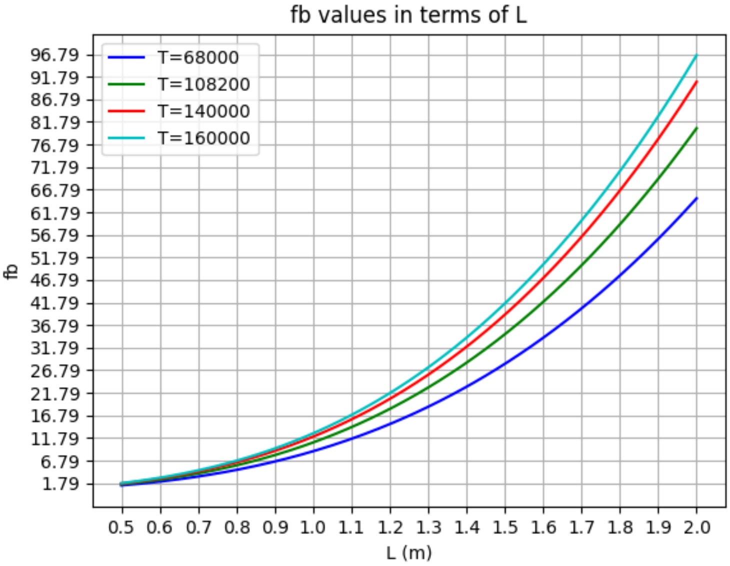

Figure 4. Frequencies in terms of L for different Tensile Forces.

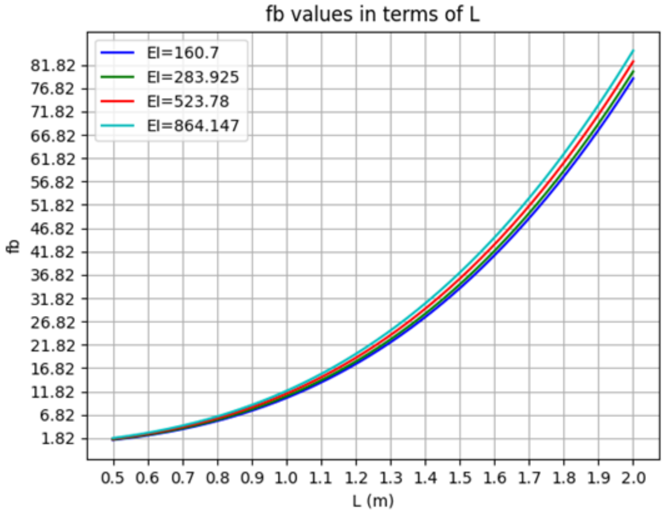

Figure 5. Frequencies in terms of L for different Flexural Rigidities.

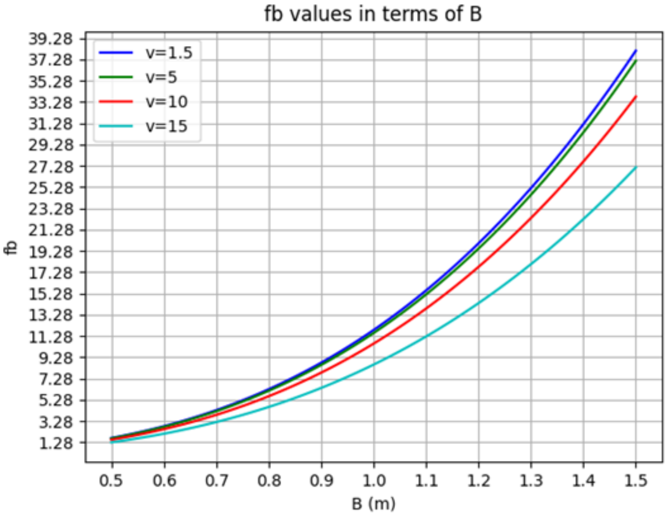

Figure 6. Frequencies in terms of B for different Velocities.

5. Conclusion

In conclusion, the observed data exhibit a non-linear pattern as the tensile force, speed, and flexural rigidity in the belt increase, similar to the vibration frequency. The parameter that influences the agreement between model predictions and measurements is the idler spacing. Notably, the beam model demonstrates lower errors across various idler spacing values. When the idler spacing exceeds one meter, resulting in relatively high vibration amplitudes, the obtained spectra can be precisely interpreted because they exhibit clear maxima. However, at smaller idler spacing, the spectra are less distinct due to lower vibration amplitudes. The effect of parameters may be different; however, in this article, the effect of three main parameters has been shown. The impact of speed, tensile force, and flexural rigidity. Previously, the researched conveyor belt was considered flat but, in this article, the inclination of the belt also has been included and the results show that inclined belt calculations have more realistic outcomes and are more accurate. The effect of inclination on speed and tensile force is more important when it comes to having an accurate simulation. Finally, results showed that the longer the span between two idlers is the more the behaviour of a conveyor belt becomes similar to a string. Hence, the string model can be helpful when the spacing between two idlers is longer. For calculating the natural frequency, it is important to choose which mathematical relation.

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