International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:10, No:7, 2016

Belt Conveyor Dynamics in Transient Operation for Speed Control

D. He, Y. Pang, G. Lodewijks

Abstract**—**Belt conveyors play an important role in continuous dry bulk material transport, especially at the mining industry. Speed control is expected to reduce the energy consumption of belt conveyors. Transient operation is the operation of increasing or decreasing conveyor speed for speed control. According to literature review, current research rarely takes the conveyor dynamics in transient operation into account. However, in belt conveyor speed control, the conveyor dynamic behaviors are significantly important since the poor dynamics might result in risks. In this paper, the potential risks in transient operation will be analyzed. An existing finite element model will be applied to build a conveyor model, and simulations will be carried out to analyze the conveyor dynamics. In order to realize the soft speed regulation, Harrison's sinusoid acceleration profile will be applied, and Lodewijks estimator will be built to approximate the required acceleration time. A long inclined belt conveyor will be studied with two major simulations. The conveyor dynamics will be given.

Keywords**—**Belt conveyor, speed control, transient operation, dynamics

I. INTRODUCTION

THE belt conveyor is a continuous transportation system and plays an important role in system handling the dry bulk material, especially in areas where there do not exist road or railway tracks or other kinds of infrastructure [1]. Presently, due to the development of motor technology, variable speed drives have already been employed in realizing soft start-up and stop operation. DIN standard (specially DIN22101[2]) further suggests that the applications of variable speed drives can reduce considerable energy consumptions of belt conveyors.

Normally, belt conveyors are running with nominal speed, and the average utilization of belt is less than the design capacity. This can be caused by temporary or cyclic variations in the bulk material flow discharged on the conveyor. In case of advanced belt conveyor system, the actual material flow can be metered by a material mass/volume measurement device. Then, the belt speed is adjusted to match the actual material flow in such a way that the belt is always filled up to a possible peak. This method is speed control whose viability has been proved by recent studies [3]-[6].

The solutions of energy savings via speed control has already been studied for almost 20 years and a series of studies have already obtained promising results. For instance, the methodology of estimating energy savings has been put forward by [7], [8] and methods of optimizing the conveyor speed to achieve more energy savings have been put forward by [6], [9], [10]. However, it is important to note that study of speed control is still in an early stage: rare research of speed control takes the conveyor dynamics in transient operation into account and the potential risks in transient operation have not been studied yet. Even though the belt experts have studied the conveyor dynamic behaviors for a long period, they mainly focus on the realization of soft start-up or stop operations and there are no studies that describe the operation of speed controlled belt conveyors during transient operation. The transient operation includes the acceleration and deceleration operations.

This work mainly focuses on the conveyor dynamic performance in transient operation for belt conveyor speed control. Several important parameters will be discussed in Section II which are responsible for the potential risks in transient operation. Section III will introduce the finite element model which will be employed to calculate the conveyor dynamics. A long inclined belt conveyor will be studied in Section IV and the belt conveyor dynamic behaviors will be analyzed in detail. The last section concludes the results and findings of this study.

II. SPEED CONTROL CONSTRAINTS

Pang and Lodewijks [11] state that the high ramp rate of adjusting the belt speed is not allowed since the stressful continuous acceleration and deceleration of belt conveyors will decrease the service life of conveyor belt and even damage the belt conveyor structure. In transient operation, besides the risk of belt over-tension, there exist several other kinds of risks, such as risk of belt slipping around the drive pulley, risk of motor over-heat, risk of pushing motor into regenerative operation and risk of material spilling away from belt, and so on. In a transient operation of speed control, all the above mentioned risks must be avoided. To discuss these risks, some important parameters are discussed successively.

A. Belt Tension

Lodewijks and Pang [12] suggests that in the transient operation, it is important to maintain the belt tension into a proper level, and the reasons for this are twofold:

The first reason considers the belt strength. The strength property of belt is mainly depending on the properties of carcass. According to the standard DIN, the ratio between the belt nominal rupture force and the actual maximum belt tension is named as safety factor. When designing a belt conveyor system, the selection of belt must satisfy the following formula:

D. He, Y. Pang, G. Lodewijks are with Department of Marine and Transport Technology, Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, Mekelweg 2, 2628 CD, Delft, the Netherlands (e–mail: D.He@tudelft.nl, Y.Pang@tudelft.nl, G.Lodewijks@tudelft.nl).

$$k_N \geq \frac{ST_{\max}}{B} \tag{1}$$

where k_N is the strength capacity per unit width, S is the safety factor, $T_{\max}$ is the maximum belt tension in operation, and B is the belt width. DIN suggests that the required safety factor varies from 4.8 to 9.5 to satisfy different operation conditions. For normal operation, the demanded minimal safety factor is 5.4 in transient operation ($S_{A,\min}$). Considering the risk of belt over-tension, the permitted belt tension in the transient operation is:

$$T_{\max} = \frac{k_N B}{S_{A,\min}} \tag{2}$$

Another reason to maintain the belt tension is for limiting the belt sag. The belt tension is responsible for the belt sag, and the belt will significantly drop between the idlers if the belt tension is excessively low. Too much sag may create large friction between the belt and idlers. DIN states that in steady operating condition, the belt sag must be less than 1% of the idler pitch. CEMA [13] further states that the bulk material may be spilled away from the belt when the belt sag ratio is more than 3%. Therefore, with respect to the risk of material spillage, the minimal belt tension $T_{\min}$ on the carrying side must be constrained by:

$$T_{\min} \geq \frac{g\left(m'_{belt} + m'_{bulk}\right)L_c}{8h_{rel}} \tag{3}$$

where g is the gravitational acceleration, m'_{belt} and m'_{bulk} are the mass of belt per unit length and the mass of specified bulk materials on belt per unit length, respectively, L_c is the distance between the idler centers in the carrying side, and h_{rel} is the maximum permitted belt sag ratio.

B. Driving Force Exerted on the Drive Pulley(s)

Besides the constraint of belt tension, the forces exerted on the drive pulley should also be limited. For a specified belt conveyor system, the potential driving force is not only depending on the property of drive motor, but also the parameters of conveyor. These parameters mainly include the frictional coefficient μ between the belt and the drive pulley, the wrap angle α of belt around the drive pulley, and the belt tension T_2 after the drive pulley.

The belt tensions around the drive pulley are shown in Fig. 1 in which T_1 is belt tension before the drive pulley and T_d is the driving forces exerted on the drive pulley:

$$T_1 = T_2 + F_d \tag{4}$$

According to the Euler-Eytlewein formula [14]:

$$\frac{T_1}{T_2} \leq e^{\mu\alpha} \tag{5}$$

The permitted driving force exerted on the drive pulley is:

$$F_{d,\max} = T_2\left(e^{\mu\alpha} - 1\right) \tag{6}$$

to ensure that sufficient driving force can be transferred onto the belt. Otherwise, the belt will slip around the drive pulley. As shown in Fig. 1, in case of a belt conveyor that is tensioned by gravity take-up device with mass m_T, the belt tension T_2 equals

$$T_2 = \frac{1}{2}m_T g \tag{7}$$

which does not take the acceleration of take-up device into account. Then, (6) can be recast by:

$$F_{d,\max} = \frac{1}{2}m_T g\left(e^{\mu\alpha} - 1\right) \tag{8}$$

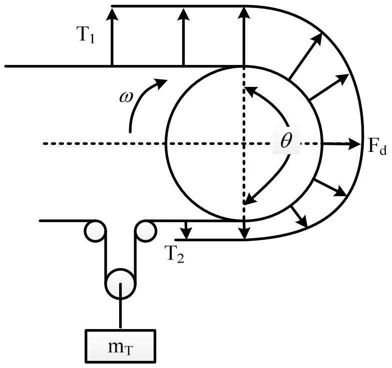


Fig. 1 Belt tension distribution in transient operation

C. Motor Driving Torque

Due to the belt's elasticity, the driving force exerted on the drive pulley is fluctuating before the belt conveyor is working in a steady operating condition. In case of heavy fluctuations, the excessive driving torque might be generated by driving motor. Although in transient operation the driving torque can be larger than the nominal torque $\tau_{motor,nom}$ for a short time, the maximum motor service torque $\tau_{motor,\max}$ must be constrained by:

$$\tau_{motor,\max} \leq i_{sf}\tau_{motor,nom} \tag{9}$$

to prevent the risk of motor overheat. In (9), the mark i_{sf} represents the motor service factor which indicates the motor's ability of tolerating the overload without overheating. For instance, the standard service factor for open drip-proof motors is 1.15 [15].

Another important reason to detect the driving torque is to ensure that the motor is not trying to be pushed into regenerative operation. When engineers design a conveyor system, the function of driving system is determined by the conveyor working condition and the configuration of belt conveyor system. In case a conveyor system without special demand, for example, rapid stop, the motor driving system normally does not have regenerating function and cannot act as a generator to produce negative torque. It means that in transient operation, especially in the motor-controlled deceleration operation, the minimum driving torque should be no less than zero. Otherwise, a large mechanical jerk will occur due to a sudden loss of driving force.

D. Belt Speed

In transient operation, the belt's elasticity results in the fluctuation of belt speed. Although Kolonja et al. [16] state that the conveyor can bear a short period overload (belt cross-section utilization can reach up to around 115%), an excessive percentage error of speed can result in the material spillage nearby the loading area. Therefore, either in the steady operating conditions or in transient operations, the percentage error ε of speed must be limited by the boundary

$$\varepsilon = \frac{V_{act} - V_{ref}}{V_{ref}} \geq -15\% \tag{10}$$

where V_{act} is the actual instantaneous speed of belt near the tail pulley and V_{ref} is the expected speed after speed adjustment.

III. Dynamic Model

In this paper, the simulations are based on the finite element model, which is presented in detail by Lodewijks [17]. Lodewijks overviews the development of modelling belt conveyor dynamics and examples an application to present the detailed procedure of setting up a finite element method of a belt conveyor. The application is a typical long belt conveyor whose geometry is shown in Fig. 2. The endless belt (a) is supported by a number of rotating idler rollers (b). The belt is driven by a head pulley (c). The tension of the belt is generated by using a sliding pulley (d), which is tied to a gravity take-up unit (e).

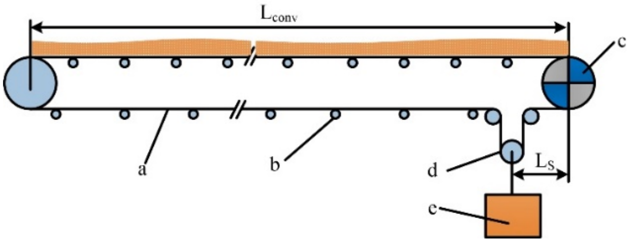


Fig. 2 Typical belt conveyor geometry

Fig. 3 illustrates the belt finite element model. The conveyor is divided into a number of finite elements: N-1 segments with N nodes. The sum of the belt mass, idler mass, bulk material mass (on the belt carrying side) is treated as a singular lumped mass on each node. On the carrying side, the dump-mass of the node equals the sum of equivalent belt mass, equivalent idler mass and the equivalent bulk material mass. On the return side, the dump-mass of node equals the sum of belt mass and the idler mass.

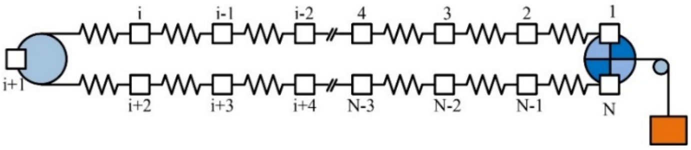


Fig. 3 Lump-mass spring-dampened finite element method

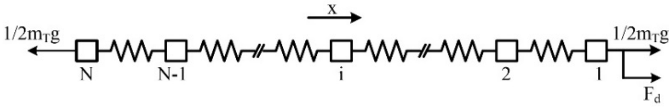


Fig. 4 One dimensional model of belt conveyor system

In Fig. 2, the mark L_S presents the horizontal distance between the drive pulley and the take-up pulley, and the mark L_{conv} stands for the distance between the drive and tail pulley. In case of conveyor with take-up pulley installed nearby the head pulley, the value of L_S is far less than L_{conv}. So in Fig. 3, it is eligible to combine the drive pulley and take-up pulley into one. In case of a belt conveyor with gravity take-up device, the belt tension after the drive pulley is assumed to remain constant and equals '$1/2m_Tg$'. If we suppose the belt is laid in x-direction and the belt only moves towards one direction, Fig. 4 illustrates the simplified belt conveyor system. In this system, the conveyor driving system and the tensioning system are replaced by two forces, which are marked as 'F_d' and '$1/2m_Tg$', respectively.

IV. Test Case

A long inclined belt conveyor in an underground mining is studied. The conveyor has a conveying length 753 m with lifting height 11.9 m. The conveying capacity is 6000 t/h at the nominal speed 4.5 m/s. It is driven by three 355 kW frequency controlled drive units. The detail of conveyor parameters is shown in TABLE I. According to the practical demand, the minimum conveyor speed is 2 m/s. Then, taking the largest speed regulation range into account, two major transient operations will be studied: an acceleration operation from 2 m/s to 4.5 m/s, and a deceleration operation from 4.5 m/s to 2 m/s.

TABLE I
BELT CONVEYOR SYSTEM PARAMETERS FOR THE CASE STUDY

Parameters (symbol, unit)	value
Conveyor length (L_{conv}, m)	753
Lifting height (H, m)	11.9
Nominal capacity (C_{des}, t/h)	6000
Nominal speed (V_b, m/s)	4.5
Belt type	ST 1600
Belt width (B, m)	1.800
Belt modulus (E_b, N/m)	115000
Cross section area of belt (A_{belt}, m^2)	0.1607
Nominal rupture force of belt per unit width (k_N, kN/m)	1600
Mass of belt per unit length (m'_{belt}, kg/m)	48.6
Mass of idler per unit length on the carrying side ($m'_{roll,c}$, kg/m)	44.64
Mass of idler per unit length on the return side ($m'_{roll,r}$, kg/m)	11.16
Mass of gravity take-up device (m_T, kg)	14000
Friction coefficient between drive pulley and conveyor belt (μ, -)	0.3
Wrap angle of the belt on the drive pulley (α, °)	340
Motor torque rating ($\tau_{nom,motor}$, Nm)	2279*3
Motor service factor (i_{sf}, -)	1.15
Reduction factor of gearbox (i_{rf}, -)	18

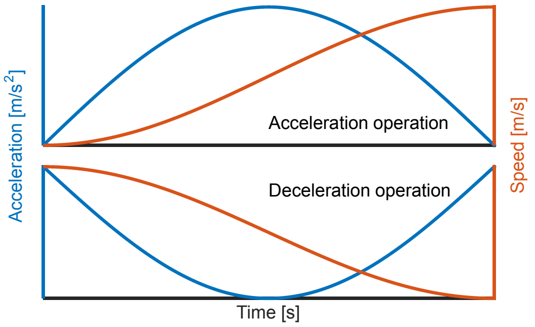


Fig. 5 Acceleration profiles and speed curves

A. Speed Regulation Procedure

In order to realize soft speed regulations, Harrison [18] suggested a sinusoid acceleration profile which has been proved to help reduce the mechanical jerk. The related acceleration and speed curves are shown in Fig. 5 and the mathematical expression of acceleration and speed is:

$$\left.\begin{aligned} a(t) &= \frac{\pi}{2}\frac{\Delta v}{t_a}sin\frac{\pi t}{t_a} \\ v(t) &= v_0 + \frac{\Delta v}{2}\left(1-cos\frac{\pi t}{t_a}\right) \end{aligned}\right\} 0 \le t \le t_a \tag{11}$$

Then, in case of belt conveyors with a small inclined angle, as suggested by Lodewijks [17] that the acceleration time t_a can be estimated by:

$$t_a = \frac{|\Delta v|}{Cfg}\left(\frac{S_{A,\min}}{S_{B,\min}-S_{A,\min}}\right) \tag{12}$$

where Δv is the speed regulation range, C is secondary resistance factor, f is the artificial frictional factor, and $S_{B,\min}$ is the suggested minimum safety factor in stationary operation. Accordingly, it requires 21 s to speed up from 2 m/s to 4.5 m/s or to lower speed from 4.5 m/s to 2 m/s for this specific belt conveyor.

B. Parameter Monitoring

To calculate the transient operation, the belt tension, the pulley driving force, the motor driving torque and the belt speed are monitored. Based on (2), the belt tension in transient operation is expected to be lower than the top boundary:

$$T_{1,\max,overtension} = \frac{k_N B}{S_{A,\min}} = 533.3\,kN \tag{13}$$

with respect to the risk of belt over-tension. Based on (6), the driving force exerted on the drive pulley is expected to be less than the top boundary:

$$F_{da,\max,\text{slippage}} = T_2\left(e^{\mu\alpha}-1\right) = \frac{1}{2}m_T g\left(e^{\mu\alpha}-1\right) = 338.2\,kN \tag{14}$$

with respect to the risk of belt slippage around the drive pulley. Subsequently, the maximum belt tension before the drive pulley is constrained by:

$$T_{1,\max,slippage} = F_{da,\max,\text{slippage}} + T_2 = 406.8\,kN \tag{15}$$

Then, comparing (13) and (15) yields that in this case the phenomenon of belt over-tension will not happen due to the occurrence of belt slippage.

Based on (9), the driving torque generated by motor should be less than the top boundary:

$$\tau_{motor,\max} = i_{sf}\tau_{nom,motor} = 7.862\,kNm \tag{16}$$

with respect to the risk of motor overheat. If ignoring the mass inertia of gearbox and drive pulley, we can also replace the detection of motor driving torque by the detection of driving force exerted on the drive pulley and the top boundary of driving force is:

$$F_{da,\max,overheat} = \frac{i_{rf}\tau_{motor,\max}}{R_d} = 235.8\,kN \tag{17}$$

Then, the comparison between (14) and (17) yields that in this certain case, the risk of motor overheat should be taken more attention than the risk of belt slippage. Based on (3), the belt tension on the carrying side is expected to be higher than the bottom boundary:

$$T_{\min} = \frac{g\left(m'_{belt}+m'_{bulk}\right)L_c}{8h_{rel}} = 21.3\,kN \tag{18}$$

with respect to the risk of material spillage caused by the excessive belt sag. In addition, based on (10), the belt speed nearby the tail pulley in deceleration operation is expected higher than the bottom boundary:

$$v_{act,\min} = 1.7\, m/s \tag{19}$$

with respect to the risk of material spillage caused by the excessive percentage error of speed.

Accordingly, the driving force should be larger than 0 and less than 235.8 kN, the value of belt tension on the carrying side should be larger than 21.3 kN and the speed nearby the loading area should be no less than 1.7 m/s in deceleration operation.

C. Simulation Results

Two major simulations are carried out for analyzing the conveyor dynamic performances in transient operation: one is about acceleration operation and another about deceleration operation. The simulations are based on the following suppositions:

i. The conveyor belt is fully loaded during the whole operation due to the speed control
ii. The belt tension after the drive pulley, which is also the take-up tension, remains constant

Fig. 6-Fig. 8 illustrate the conveyor dynamics in acceleration operation with the acceleration time 21 s. The conveyor deceleration operation performs from 1 s. Fig. 6 presents the driving force exerted on the drive pulley. The figure shows at the beginning of acceleration, and the driving force increases smoothly. At time point 11.5 s, the driving force reaches the peak 214.5 kN which is less than the boundary caused by risk of motor overheat. After that, the driving force decreases gradually. After the acceleration operation, the driving force begins to cyclically fluctuate around 140.8 kN. This fluctuation damps out after the passage of several tension waves.

Fig. 7 illustrates the belt tension at each nodal point. As the figure shows, the maximum belt tension occurs in the first node at time point 11.5 s, and the minimum belt tension at the carrying side occurs at the 11th node after the deceleration operation. According to the figure, it clearly shows that the risk of belt over-tension is prevented and the risk of material spillage caused by excessive belt tension is also avoided. The figure further shows with respect to the belt's elasticity, the belt tension at each node is fluctuating for a certain period after the acceleration operation. The fluctuation of the amplitude of belt speed at the carrying side is less than that at the return side. Meanwhile, with respect to the belt's viscosity property, the amplitude damps out in time.

Fig. 8 illustrates the belt speed at each node. In the speed adjustment process, the speed of belt at each node increases successively. As the figure shows that the belt speed increases gradually and the speed curve is virtually following the 'S' profile. Similar with the belt tension curve, the speed is fluctuating after the acceleration operation with decreasing amplitude. Accordingly, the risk of material spillage caused by excessive speed fluctuation is prevented.

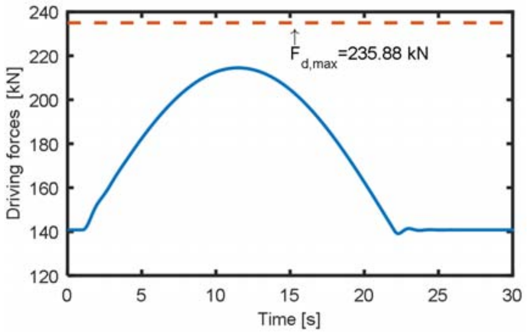


Fig. 6 Driving force exerted on the drive pulley in deceleration operation

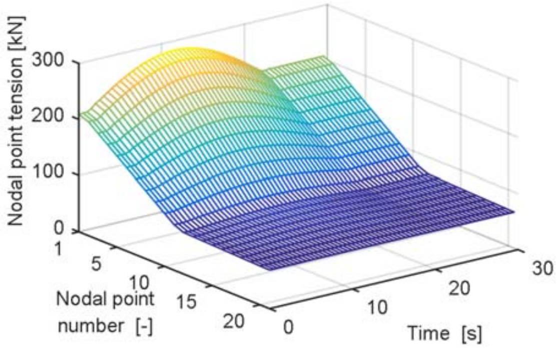


Fig. 7 Belt tension at each nodal point

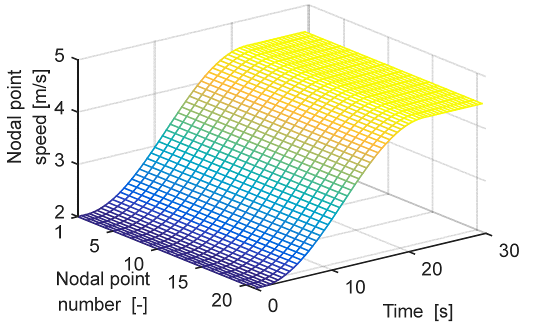
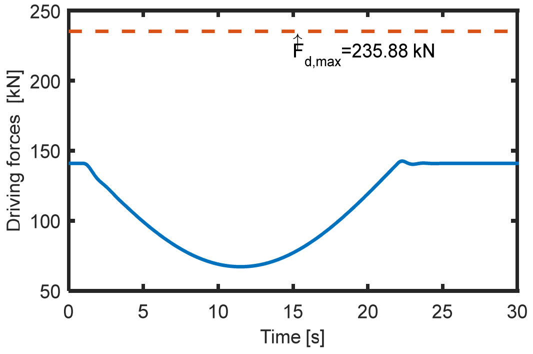
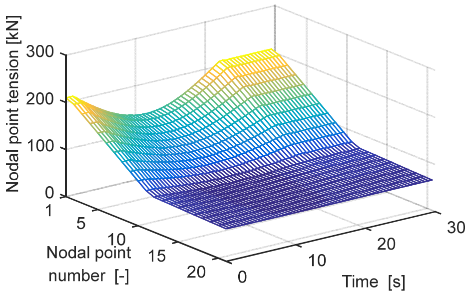


Fig. 8 Belt speed at each nodal point

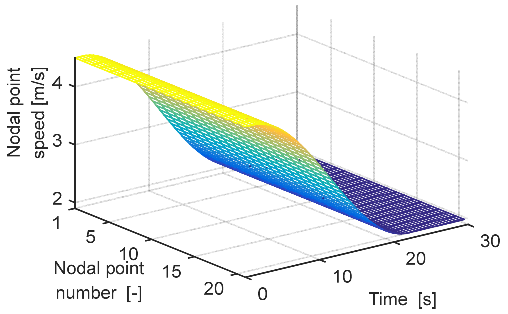
The conveyor dynamic performance in deceleration operation is shown in Fig. 9. As the figure shows in deceleration operation, the driving force and belt tension decrease gradually. As a consequence, smooth speed curves are achieved.



(a) Driving force



(b) Belt tension



(c) Belt speed

Fig. 9 Conveyor dynamics in deceleration operation

V. CONCLUSION

This paper analyzed several important parameters of belt conveyor which were responsible for the belt conveyor risks in transient operation. In order to monitor those parameters, a non-linear model was built to calculate the conveyor dynamic performance in transient operation, both in acceleration and deceleration operations. That model was based on an existing finite element model. A long inclined belt conveyor at an underground mining was studied. To realize the soft speed regulation, Harrison's sinusoid acceleration profile was used and Lodewijks estimator was built to calculate the required acceleration time. Two major simulations were carried out to analyze the conveyor dynamic behaviors. The simulation results showed in transient operation, the driving force, and belt tension varied gradually in such a way the belt speed was regulated smoothly. That means in transient operation, all potential risks could be prevented with proper selection of acceleration time and speed profile.

ACKNOWLEDGEMENT

The China Scholarship Council (CSC) (File No.201306990010) is gratefully acknowledged for funding the first author.

REFERENCES

[1] A. J. G. Nuttall, "Design aspects of multiple driven belt conveyors," TU Delft, Delft University of Technology, 2007.

[2] DIN22101, "Continuous conveyors-Belt conveyors for loos bulk materials-Basics for calculation and dimensioning," ed, 2002.

[3] W. Daus, M. Koerber, and N. Becher, "Raw coal loading and belt conveyor system at Nochten opencast mine - a new conveying and loading system based on drives controlled and adjusted by frequency converter," *Braunkohle Surf Min,* 1998.

[4] ABB, "Variable-speed drives for belt-conveyor systems," 2000.

[5] J. Hiltermann, "Reducing the Eletrical Power Consumption of Troughed Belt Conveyors by Speed Control," July 4 2008.

[6] Y. Pang, G. Lodewijks, and D. L. Schott, "Fuzzy Controlled Energy Saving Solution for Large-Scale Belt Conveying Systems," *Applied Mechanics and Materials,* vol. 260, pp. 59-64, 2013.

[7] J. Hiltermann, G. Lodewijks, D. L. Schott, J. C. Rijsenbrij, J. A. J. M. Dekkers, and Y. Pang, "A methodology to predict power savings of troughed belt conveyors by speed control," *Particulate science and technology,* vol. 29, pp. 14-27, 2011.

[8] S. Zhang and X. Xia, "A new energy calculation model of belt conveyor," in *AFRICON, 2009. AFRICON'09.*, 2009, pp. 1-6.

[9] L. Ristic, M. Bebic, D. Jevtic, I. Mihailovic, S. Statkic, N. Rasic*, et al.*, "Fuzzy speed control of belt conveyor system to improve energy efficiency," in *Power Electronics and Motion Control Conference (EPE/PEMC), 2012 15th International*, 2012, pp. DS2a. 9-1-DS2a. 9-7.

[10] L. B. Ristic and B. I. Jeftenic, "Implementation of Fuzzy Control to Improve Energy Efficiency of Variable Speed Bulk Material Transportation," *Industrial Electronics, IEEE Transactions on,* vol. 59, pp. 2959-2969, 2012.

[11] Y. Pang and G. Lodewijks, "Improving energy efficiency in material transport systems by fuzzy speed control," in *Logistics and Industrial Informatics (LINDI), 2011 3rd IEEE International Symposium on*, 2011, pp. 159-164.

[12] G. Lodewijks and Y. Pang, "Belt de-tensioning in dips," *Beltcon 17,* pp. 1-17, 2013.

[13] C. E. M. A. E. Conference, *Belt conveyors for bulk materials*: CEMA, 1997.

[14] G. Kuhnert and G. Schulz, "L. Euler or JA Eytelwein? The Origins of the" Rope Friction Equation"," *Bulk Solids Handling,* vol. 15, pp. 261-264, 1995.

[15] A. Emadi, *Energy-Efficient Electric Motors, Revised and Expanded*: CRC Press, 2004.

[16] B. Kolonja, B. Jeftenić, and D. Ignjatović, "The application of frequency converters for the regulation of belt conveyor drives in surface mining," *Transport i logistika,* pp. 11-26, 2003.

[17] G. Lodewijks, *Dynamics of belt systems*: TU Delft, Delft University of Technology, 1996.

[18] A. Harrison, "Criteria for minimising transient stress in conveyor belts," *Mechanical Engineering Transactions, Vol. ME8,* pp. 129-134, 1983.