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Kalman Filter Preview Control for Energy Savings of Large Scale Cascaded Belt Conveying Systems

Yusong Pang, Gaowei Yan, and Tiezhu Qiao

Abstract— **In various industry productions belt conveyors are widely used for continuous dry bulk material transport. A large scale belt conveying system is generally composed of cascaded single conveyors consuming considerable electric power. According to DIN22101 regulating the belt speed and thereby maximizing the load on the belt may lead to a certain reduction of the needed electrical drive power. To avoid the operational risks, which may be caused by the dynamics of the system, preview control strategy has been proposed for belt conveyor speed control. In case the loading scenarios of a primary conveyor can be measured, the material feeding rate to following conveyors can be previewed. To reduce the influence of noises during material flow measurement and control synchronization, this paper presents the research of adopting Kalman filter to preview control to improve the transient operations of controlled belt conveyors as well as the energy efficiency of the system. Compared to two speed control strategies, the non-constraint preview control and the fuzzy speed control, experimental results show that the proposed Kalman filter based preview control reduces the noise interferences towards softer and safer speed regulation process.**

I. Introduction

Belt conveyors are widely applied in diverse industry fields to continuously transport large amount of dry bulk material such like coal or iron ore. As a main energy consumer, for instance in a dry bulk terminal, a belt conveying system may consume up to 70% of the total electric energy of the overall material handling operation which may equal to 270 million kWh annually [1].

The German standard DIN 22101 [2] indicates that the energy consumption in belt conveyor stable operations can be reduced by regulating the belt speed and thereby maximizing the capacity of the material loaded on the belt, which is the speed control of belt conveyors. Research of belt conveyor speed control can be dated back to the end of last century. A model predictive control method has been proposed to optimize the operating efficiency of belt conveyors [3] and the simulation results showed that both the electrical energy and the operational cost could be considerably reduced. Considering the dynamics of belt conveyors, Pang and Lodewijks [4] proposed a fuzzy control method to adjust the belt speed in a discrete manner. The experimental results proved that discrete control can improve the energy efficiency up to 20%. Further, a fuzzy logic controller was developed aiming at applying fuzzy speed control to belt conveyors [5]. It is important to note that previous researches were mainly based on a hypothesis that material feeding rate to a single belt conveyor is either known or predictable. However, in the most of industry practices and operational situations, the material flow fed to a single conveyor is neither predictable nor controllable. Therefore, previously proposed control methods such as model predictive control are unable to effectively handle the uncertainties of material loading during speed control. Due to the risks in the transient operations of speed control, including belt slippage, belt over-tension, motor overheating and material overloading [6], the speed regulation of such single conveyors is infeasible.

In general, a large scale belt conveying system is composed of cascaded single conveyors, where the material is loaded onto a primary conveyor and further transferred to a secondary and following conveyors. In case the varying loading scenarios of the primary conveyor is known at the beginning of the material conveying process, the material flow rate and control constraints can be previewed for the speed control of the secondary conveyor. Based on this concept a preview control strategy has been proposed to achieve safe speed control towards energy savings [7]. When primary conveyor is fed by upstream uncontrollable loading facilities such as grooves or hoppers, real-time measurement of the loading rate to the primary conveyor is used for the preview control to handle the irregular and sudden changes of material flow which may lead to the operational risks of the secondary conveyor. However, the noises from the real-time measurement and the responses of the controlled conveyors are not concerned in the research. To eliminate the influence of various noises in the control of such complex speed regulation performance, this paper presents the research of applying Kalman filtering to the preview control towards optimizing the transient operations and achieving softer and safer speed control of belt conveyors.

In this paper, Section II explains the energy model and power consumption of belt conveyors according to DIN 22101, which indicate the feasibilities of energy savings by means of belt conveyor speed control. In Section III, after introducing the principle of preview control, the control model for a cascaded belt conveying system is given. Section IV presents the Kalman filter based preview control, followed by the implementation of the control system and the comparison with other control scenarios in Section V. Conclusions are given in Section VI.

II. Energy Model and Energy Savings

In belt conveyor operations, the belt is supported and moves along idler rolls by the driving force on the drive pulley, which overcomes the motional resistance of the system. Generally the belt runs at a constant designed speed,

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as referred to the nominal speed, to satisfy the nominal capacity of the system. In very often operational conditions when the material feeding rate to the conveyor is less than the nominal, the material loaded on the belt can be maximized by reducing the speed of the belt. Although the driving forces increase, the energy consumption of the belt conveyor is expected to be lower due to the reduction of the belt speed. According to DIN22101, the mechanical power P_M required by a belt conveyor at a given speed v is dependent on the total motional resistance and can be determined by

$$P_M = CfLg\left[m'_{roll} + \left(2m'_{belt} + m'_{bulk}\right)\cos\delta\right]v + m'_{bulk}gHv \tag{1}$$

where C is the secondary resistances coefficient, f is the artificial friction coefficient, L represents the conveyor length, g is the gravity acceleration, m'_{roll}, m'_{belt} and m'_{bulk} are the mass per unit length of the idler rolls, the belt and the loaded material, respectively, and δ is the inclination angle of the conveyor with an elevation of H.

When the belt speed is reduced to maximize the material loading on the belt, the material mass per unit length on the belt can be calculated according to the nominal speed v_{nom} and reduced speed v_{var} as

$$m'_{bulk,nom} = \frac{Q}{3.6v_{nom}} \text{ and } m'_{bulk,var} = \frac{Q}{3.6v_{\mathrm{var}}} \tag{2}$$

Reflecting to the potential reduction of energy consumption, the energy saving ratio can be define as [6]

$$\begin{aligned} R_{Pe} &= \frac{P_{e,nom} - P_{e,var}}{P_{e,nom}} \times 100\% \\ &= \frac{(m'_{roll} + 2m'_{belt})(v_{nom} - v_{var})}{(m'_{roll} + 2m'_{belt} + m'_{bulk,nom})v_{nom}} \times 100\% \end{aligned} \tag{3}$$

III. Preview Control for Belt Conveying Systems

Preview control is a control method which can improve the dynamic response of a control system restraining the external disturbances and improving the tracking accuracy [8]. It is especially suitable for controlling systems without known future control targets and disturbances. Preview control strategy fits the requirements of belt conveyor speed control, especially in the situation that the exogenous disturbances of the control system are uncertain and can be previewed beforehand, such as the loading scenarios of the primary conveyor as the disturbances of adjusting the speed of following conveyors in a cascaded belt conveying system .

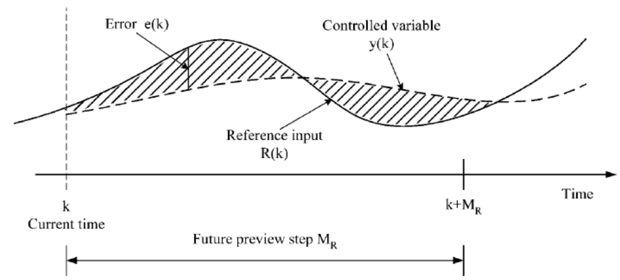
A. Preview Control Principle

Figure 1 presents the principle of preview control [9]. It is assumed that the controlled process can be described by discrete state equations:

$$\begin{cases} \boldsymbol{x}(k+1) = \boldsymbol{A}\boldsymbol{x}(k) + \boldsymbol{B}\boldsymbol{u}(k) + \boldsymbol{E}\boldsymbol{d}(k) \\ \boldsymbol{y}(k) = \boldsymbol{C}\boldsymbol{x}(k) \end{cases} \tag{4}$$

where $\boldsymbol{x}(k) \in \mathbf{R}^n$ is the state variable, $\boldsymbol{y}(k) \in \mathbf{R}^m$ is the output vector, $\boldsymbol{u}(k) \in \mathbf{R}^r$ is control input, $\boldsymbol{d}(k) \in \mathbf{R}^q$ is the disturbance, $\boldsymbol{A} \in \boldsymbol{R}^{n\times n}, \boldsymbol{B} \in \boldsymbol{R}^{n\times r}, \boldsymbol{C} \in \boldsymbol{R}^{m\times n}$ and $\boldsymbol{E} \in \boldsymbol{R}^{n\times q}$ are the matrix of corresponding coefficients ($r \geq m$), assuming that the input of the control system and the relative disturbances are measurable, predictable or controllable.

Figure 1. Principle of preview control



Using $\boldsymbol{R}(k) \in \mathbf{R}^m$ as the reference of the target value and the error signal $\boldsymbol{e}(k) = \boldsymbol{R}(k) - \boldsymbol{y}(k)$ a general error expansion can be presented as:

$$X_0(k+1) = \emptyset X_0(k) = G\Delta u(k) + G_d\Delta d(k) + G_R\Delta R(k+1) \tag{5}$$

where $X_0 = \begin{bmatrix} e(k) \\ \Delta x(k) \end{bmatrix}$, $\emptyset = \begin{bmatrix} I & -CA \\ 0 & A \end{bmatrix}$, $G = \begin{bmatrix} -CB \\ B \end{bmatrix}$, $G_R = \begin{bmatrix} I \\ 0 \end{bmatrix}$, $G_d = \begin{bmatrix} -CE \\ E \end{bmatrix}$. Eq.(5) indicates that the current moment ($k = 1$) comes into the M_R step where the target value is known. In order to make the output $\boldsymbol{y}(k)$ to track the target value $\boldsymbol{R}(k)$, the control output $\boldsymbol{u}(k)$ needs to be adjusted before the preview step M_R, which presents the control principle as M_R step preview. For the generalized error system, the quadratic performance index is:

$$\boldsymbol{J} = \sum_{k=-M_R+1}^{\infty}\left[\boldsymbol{X_0}^{\mathrm{T}}(k)\boldsymbol{Q}\boldsymbol{X_0}(k) + \Delta\boldsymbol{u}^{\mathrm{T}}(k)\boldsymbol{H}\Delta\boldsymbol{u}(k)\right] \tag{6}$$

where $\boldsymbol{Q}$ and $\boldsymbol{H}$ are the weights as a positive definite matrix. The performance index $\boldsymbol{J}$ concerns the optimal solution with minimum error $\Delta\boldsymbol{u}(k)$ in the control process.

The principle of preview control is to solve the error expansion to make the error between the control reference and the target output as small as possible after the M_R step. Concerning the application of preview control to regulate the speed of belt conveyors, the fundamental requirement of the control system is that the input and the preview steps should be controllable and observable. However, as discussed in Section I, in industry practices, the material feeding rate to a single conveyor is usually neither controllable nor predictable. Due to the operational risks may occur in transient operations, the speed control of single conveyor is sometimes infeasible.

B. Speed Control for Cascaded Belt Conveyors

In large-scale material continuous transport, a belt conveying system is generally composed of a series of single conveyors in cascaded way. These sequentially connected conveyors provide the possibility to apply preview control under the requirements of either observable or predictable inputs for a speed control system. When the loading scenarios of the primary conveyor can be observed or measured, the current belt speed and loading condition can be used as the input of the preview control of the secondary conveyor.

Further the speed control of following conveyors will follow the same control performance of the secondary conveyor.

Figure 2. Schematic diagram of two cascaded belt conveyors

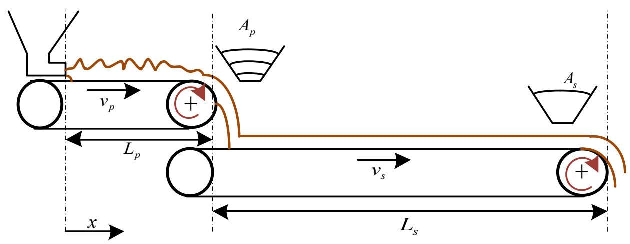
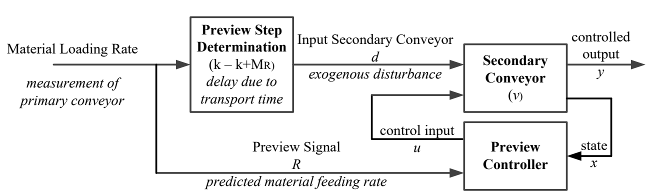


Figure 2 presents a part of such a cascaded belt conveying system which contains only the primary and the secondary conveyors. The primary conveyor, which receives the material (at point x) from the upper stream of material handling process for instance a loading hopper, consists of a belt operating at its nominal speed (v_p).The operational speed of the secondary conveyor (v_s) is to be controlled and adjusted based on the changes of the material feeding rate of the primary belt (A_p). The target of the control system is to maximize the material loading rate of the secondary conveyor to reach up to its nominal loading capacity (A_s). Based on the preview of the input signal and disturbance of the control system, the material feeding situation to the secondary conveyor can be anticipated. During the time (L_p/v_p) the material is transported from the tail end (the material loading area) to the head end (the material discharging area) of the primary conveyor, the target speed of the secondary conveyor can be calculated and the control requirements can be determined. In such case, the measurement of the primary material feeding rate is used as the input signal and the fluctuation of the feeding rate can be considered to be the disturbance for preview control. By regulating the speed of the secondary conveyor to match the received material feeding rate from the primary conveyor, the loading on the secondary conveyor can be maximized to match the target of speed control. Further, the energy savings of the secondary conveyors can be achieved. Figure 3 shows the principle and the model of applying preview control for the speed control of the belt conveying system.

Figure 3. Model of preview control for cascaded belt conveyors



When the loading scenario of the primary conveyor varies frequently, the speed of the secondary conveyor may need to be regulated accordingly. However, the frequent speed adjustment of a belt conveyor causes not only a great burden on the motor and the reduction of its service life, but also increases risks during transient operations. To avoid such phenomenon, the sum of loaded materials over a period of time is used as the condition for determining the preview inputs for the secondary conveyor. Assume that the material feeding rate of the primary conveyor at a location x is $A(x,t)$, the total mass of the material in a period $[0,\ t_0]$ is:

$$m_{t_0} = \int_0^{t_0} A(x,t)dt \tag{7}$$

The corresponding belt speed of the secondary conveyor can be determined with a maximally loaded belt:

$$\bar{v}_s = \frac{m_{t_0}/\rho}{S_{s,\max}\cdot t_0} \tag{8}$$

where $\bar{v}_s$, $S_{s,max}$ and ρ are the secondary belt speed, the cross section area of the material on the secondary belt and the material density, respectively. In this situation, although the material is transported continuously, for the practical reasons during belt conveyor transient operations discrete speed adjustment is preferred rather than continuous speed control. Therefore, fuzzy control, as a control philosophy, applying fuzzy logic to provide discontinuous control strategies has been applied for belt conveyor speed control to avoid the stressful continuous acceleration of belt conveys, when the material flow fluctuates considerably [4]. In this fuzzy control method, the controlled speed is determine as

$$v_{i\_act} = b_{i+1}\cdot v_{nom} \tag{9}$$

where v_{i_act} is the ith adjusted belt speed for maximum belt load, which is a percentage of the nominal belt speed. This percentage is determined by comparing the fuzzy values $f_{b_i}(x)$ and $f_{b_{i+1}}(x)$ of material loading rates at the control moments, following the fuzzy member function

$$f_{b_{i+1}}(x) = \frac{-1}{b_i - b_{i+1}}x + \frac{b_i}{b_i - b_{i+1}} \tag{10}$$

This fuzzy control method contains few limitations. Firstly, the speed adjustment relies on the variance of material loading degree. The setting of fuzzy ranges and boundaries are hardly derived from a proper fuzzy membership function. Secondly, with respect to the variances of the patterns and the magnitudes of material loading, when short-term excessive loading happens, the number of stress cycles need to be limited to prevent unnecessary and sometimes harmful acceleration to the belt conveying system [10]. Compared to the fuzzy control method, the speed of the secondary conveyor $\bar{v}_s$ in preview control can be determined by the measurement of the primary conveyor to provide future target information and the needed error tracking information. As shown in Figure 2, the measured primary loading rate is converted into the information of future control target for the secondary conveyor. Further, preview control enables the match between the belt speed and the feeding rate of the secondary conveyor, to achieve the final control goal of maximizing the loading on the belt and taking the operational constraints of the control system into account.

IV. Kalman Filter Based Preview Control

In material handling applications under harsh industrial environment, the data and information acquired from a large scale cascaded belt conveying system may have mixed noises, which result in inaccurate signal acquisition and affect the speed regulation and control performance. Further, the synchronization of speed control for multiple cascaded conveyors is an important issue to be taken into account, which means that the speeds of all the cascaded conveyors should be adjusted simultaneously to avoid material spillage and belt overload. If the control of the serial conveyors are not synchronized well, the deviation of the speeds of different conveyors can be considered to be the noise of the overall speed control system. To optimize the speed control of a belt conveying system composed of multiple single conveyors, Kalman filtering algorithm can be added into the preview control to reduce the influences of the measurement noise and the synchronization noise.

Assuming that a covariance matrix of the synchronizing noise and measurement noise is $\boldsymbol{W}$, which does not change with the change of the system state. The covariance matrix of the system state vector is $\boldsymbol{P}(k)$ with the gain of $\boldsymbol{K}_g(k)$. For the discrete preview belt speed control system represented by equation (4), the discrete recursive algorithm for Kalman filtering include:

Optimal filter estimation equation:

$$x(k) = Ax(k-1) + K_g(k)[y(k) - CAx(k-1)] \tag{11}$$

Optimal gain matrix equation:

$$K_g(k) = \frac{P(k)C^T}{CP(k)C^T + R(k)} \tag{12}$$

Single-step preview error covariance equation:

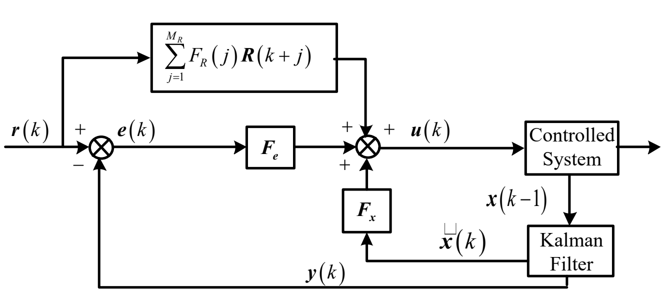
$$P(k) = AP(k-1)A^T + BW(k)B^T \tag{13}$$

Filtered preview error covariance equation:

$$P(k) = [I_n - K_g(k)C]P(k) \tag{14}$$

Figure 4 presents the improved speed control system that combine the non-constraint preview control shown in Figure 3 with Kalman filter algorithm. The Kalman filter based preview control optimizes the determination of the secondary belt speed by taking more considerations of the influences from the material flow fluctuation of the primary conveyor as well as reducing the synchronization noise towards the speed control of following conveyors.

Figure 4. Preview control with Kalman Filter



V. Simulation

To implement the Kalman filter based preview control, a belt conveying system is used for case study as shown in Figure 2. The measurement of the material flow rate at the tail end (the point *x*) of the primary conveyor is used as the input of the preview control system and the flow rate fluctuation as the disturbance. Further, due to the limitation of implementing the control system onsite, simulation is applied for the speed control of the secondary conveyor showing the effects of the preview control as well as the improved energy efficiency. The belt conveying system is composed of more than two cascaded conveyors. The speed control of following conveyors remains the same control principle as of the studied secondary conveyor. The main parameters of the secondary conveyor are given in TABLE I.

TABLE I. Prameters of Controlled Secondary Conveyor

Conveyor length/width	*1000m/1.2m*	Friction coefficient	*0.018*
Nominal speed of belt	5.2*m/s*	Roll mass per unit	$m'_{roll} = 14.86 + 7.72\, kg/m$
Nominal capacity	*2500t/h*	Belt mass per unit	$m'_{Belt} = 14.28 * 2\, kg/m$
Secondary resistance coefficient	*C=1.09*	Material mass per unit	$m'_{Bulk} = 133.54\, kg/m$

A. Control Procedure

In the speed control system, the material flow from the primary conveyor is considered to be the preview information for the speed regulation of the secondary conveyor. The target value of preview control can be determined by foreseeing the input and current belt speed so that the loading situation of the controlled conveyor can reach up to its nominal loading capacity. The control procedure is as follows:

Step 1: According to the loading rate of the primary conveyor, to calculate the target speed of the secondary conveyor $\bar{v}_s(i)$ as of Equation (8);

Step 2: to obtain an expected speed $v'_s(i)$ at time *i*. If $v'_s(i)$ is less than $v_{nom,\max}$, $v'_s(i)$ is the current target value of speed control. Otherwise, speed adjustement is not needed;

Step 3: based on the difference between $v'_s(i)$ and $v'_s(i+1)$, determine the maximum allowed acceleration $\bar{a}_s(i)$. If $\bar{a}_s(i)$ is less than $a_{\max}$, speed is adjusted by $\bar{a}_s(i)$. Otherwise, $a_{\max}$ is acceptable for speed control. According to [6] a_{max} is determined by the maximum allowed driving force on the belt taking the risks in transition operations into account;

Step 4: for the next moment after M_R preview steps, to determine the target value $\bar{v}_s(i+1) = \Delta t a_{max} + \bar{v}_s(i)$;

Step 5: to calculate the speed for the next moment $v'_s(i+1)$ for speed control. To maximize the load on the belt the smaller value of $\bar{v}_s(i+1)$ and $v'_s(i+1)$ is the determined speed at moment $i+1$.

The procedure above enables the control system to determine the speed to be regulated according to the acceleration requirements. The implementation of the speed control of this research concerns three control scenarios which compare the speed regulation under fuzzy speed control, non-constraint preview control and Kalman filter based preview control.

B. Control scenarios

One of the purposes of this research is to explore the applicability of Kalman filter preview control for belt conveying systems and further to investigate the improvement of energy efficiency under different scenarios of the three control scenarios mentioned above. To achieve the belt conveyor speed control for energy savings, the material feeding rate and the expected amplitude of the change of the belt speed are two fundamental parameters.

The first control scenario is based on the belt conveyor fuzzy speed control [4], as presented by Equation (10). The principle of the fuzzy control is to fuzzify the material loading condition within a period of time as the input of the control system. Then the speed adjustment is based on the defuzzified expected belt speed according to the lower boundary of the fuzzy ranges and the predefined fuzzy membership function.

The second scenario is of the non-constraint preview control for speed regulation according to Equation (4), which does not take the influence of both measurement noise and synchronizing noise into account. Such preview control has proved its applicability to achieve energy savings in belt conveyor speed control [7].

The third scenario to be implemented is the proposed Kalman filter preview control system.

C. Simulation results

In order to compare the system behaviors of the different control scenarios and the improvement of energy efficiency via speed control, various speed control setups, acceleration curves and required energy consumption are applied to the secondary conveyor under different control scenarios as well as an operational scenario without speed control applied.

Figure 5. Comparison of material loading situations

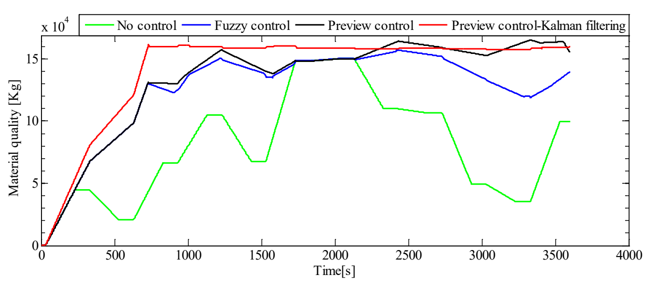


Figure 5 shows the material loading situations under four operational situations. For the no control operations (green line), the material loading rate on the secondary conveyor follows the actual measurement of the material feeding rate to the primary conveyor. Three other control scenarios enable the secondary conveyor to maintain a high loading capacity by adjusting the belt speed. Preliminarily, the experimental results show that the preview control with Kalman filtering (red line) not only adjusts the belt speed more quickly and accurately but also eliminates the adverse effects of noises in the speed regulation process, making the material more stably and evenly distributed along the belt of the secondary conveyor.

Figure 6. Comparison of speed regulation

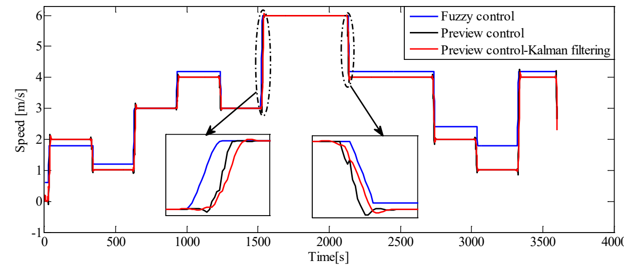
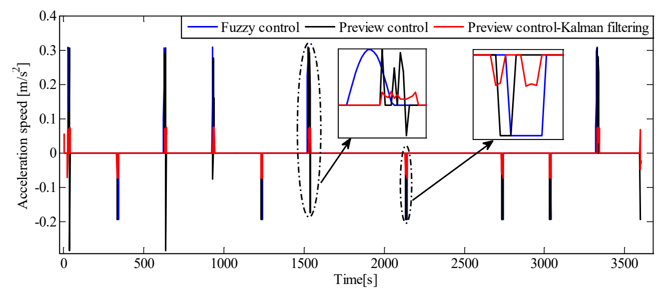


Figure 6 compares the speed control of the secondary conveyor under three control scenarios. From the zoom-in details of the speed adjustment during an acceleration process at time 1500s and a deceleration process at time 2200s, it can be found that the Kalman filter preview control has a later acceleration, remaining the same acceleration curve as the same as the non-constraint preview control, which both are better than the acceleration processes of the fuzzy control. Such an observation indicates that the Kalman filter preview control can achieve more the energy savings with less operational risks.

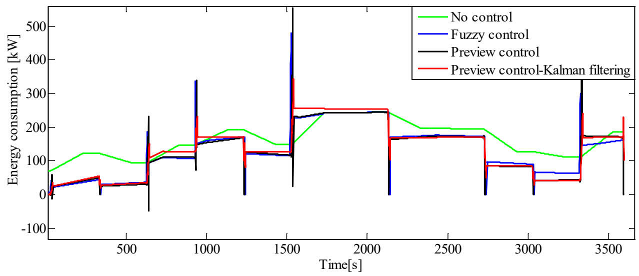
Figure 7. Comparison of material loading situations



Further regarding the operational risks of belt over-tensioning and motor overheating, Figure 7 shows the experimental results of each acceleration process of the secondary conveyor. Due to the fact that these two risks do not concern with deceleration, the control profiles during acceleration is more important for proper speed control. As shown in the zoom-in acceleration in Figure 7, both fuzzy control and non-constraint preview control generate much higher acceleration during the speed control. On one hand, higher acceleration may lead to higher risks of belt rupture and motor overload. On the other hand, the high mechanical jerks happened during the acceleration may lead to the damage of system components and the reduction of the motor lifetime. The Kalman filter preview control takes these risks into account so that the softer and safer speed regulation with lower acceleration rates can be achieved. This is the fundamental requirement of belt conveyor speed control, for both start-up procedures and in transient operations.

From energy saving point of view, the implementations of three speed control scenarios do not lead to a significant difference with respect to the improvement of the energy efficiency of the belt conveying system. Figure 8 presents the overall energy consumption of the three different control scenarios.

Figure 8. Comparison of acceleration in different phases of speed control



Compared with the belt conveyor operation without speed control, the similar as other two control scenarios, the Kalman filter preview control can improve the energy efficiency up to 20% based on a 7/24 (seven days per week and 24 hours per day) material transport operational condition. Such estimated energy savings matches the experimental results of the most of previous researches [1][5][6].

Further experimental results of the Kalman filter preview control show that the energy savings almost equal to the implementation of a previous research of preview control [7]. In a typical dry bulk terminal operations with 30% belt conveyor occupancy of the available time of 360 days per year and 24 hours per day, the annual energy savings of the belt conveying system can be more than100 MWh, leading to CO2 reduction of more than 60 tons and direct economic benefit of more than €10k. The most direct advantage of the Kalman filter preview control is its abilities to take the noises into account towards softer transient operations during speed control with less operational risks.

VI. Conclusion

Belt conveyor speed control can be realized by different control methods. The control philosophy to regulate the speed of belt conveyors matches the principle of preview control. This research aims to introduce Kalman filter based preview control strategy for the speed control of the belt conveying systems composed of serial cascaded single belt conveyors. The measurement of the material feeding rate on the primary conveyor is considered to be the previewed input information to control the speed of secondary conveyors. Kalman filtering algorithm is applied to deduce the influences of measurement noises and synchronization noises of the control system. A case study is given to show the advantages of the Kalman filter preview control compared to other control strategies. Taking the operational risks into account as the constraints of the control system, the proposed preview control system is able to achieve soft control profiles for the speed regulation during transient operations. Such soft acceleration processes are the fundamental requirements for belt conveyor systems with respect to system dynamics and healthy operations. Experimental results prove the improvement of energy efficiency of belt conveying systems by means of preview control.

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