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APPLICATION OF OBSERVER-BASED MONITORING TECHNIQUE IN BELT CONVEYOR SYSTEMS

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Abstract: In this paper an information system is presented, which is developed to meet the requirements on simulation, on-line monitoring, quality management and optimum design of large scale belt conveyor systems. The core of this information system is a mathematical model and an observer. Successful application is also presented to illustrate the proposed approach.

Keywords: Modelling; Simulation; Observers; Fault detection; Uncertain linear systems

1. INTRODUCTION AND PROBLEM FORMULATION

For transporting high mass flows over long distances belt conveyors are widely used in mining and on large-scale building-sites. In order to achieve an optimal operating efficiency, to reduce maintenance costs and to ensure high availability and safety of such complex devices, demands on

- off-line simulation as an effective tool to optimize the plan and construction of the belt conveyor,
- analysis of measurement data aiming at identifying the changes of operation parameters of the belt conveyor in operation and
- on-line monitoring and detection of faults in the belt conveyor during the operation

are continuously increasing during the recent years.

Most of the existing software and information systems were developed aiming at (off-line) simulation of some special types of belt conveyor systems (Grießhaber *et al.*, 1999), and the existing approaches to the data analysis are restricted to the static calculation. For the purpose of on-line monitoring and fault diagnosis only some special kinds of measurement equipments as well as some signal processing approaches like trends analysis or simple statistic tests are used. Due to the complexity the belt conveyor systems, more powerful information systems and simulation and monitoring approaches are needed to fulfill the technical and economic requeirements on such kinds of systems (Jeinsch *et al.*, 2000).

The rapid development in computer technology, control engineering and signal processing offers us advanced methods and technologies to solve such problems, among which the modelling, simulation, model based system monitoring, parameter identification and fault diagnosis are the most powerful tools (Frank and Ding, 1997),(Isermann, 1993).

In this contribution, development of an information system for the purposes of simulation, both on-line and off-line, and monitoring of large scale belt conveyor systems is presented. The core of this system is the application of advanced model-based simulation and monitoring techniques. The background of this work is a R&D project initiated by the companies PC-SOFT GmbH and Lausitzer Braunkohle AG, whose objective is to improve the operating efficiency and reduce maintenance costs.

2. SYSTEM DESIGN

2.1 System structure

The information system developed is multi-layer structured. The core of this system is a mathematical model and an observer. The monitoring system consists of a residual generator and a residual evaluator which are developed on the basis of the observer and used for the purpose of fault detection and diagnosis (Frank and Ding, 1997).

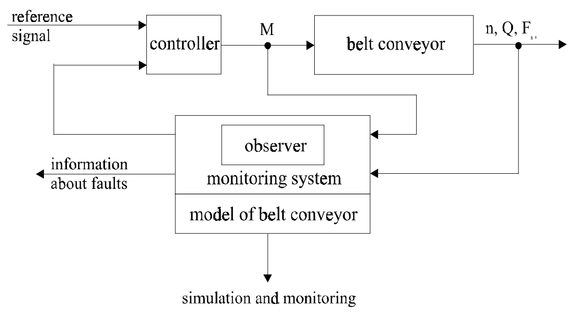

Fig. 1. Possible applications of the developed information system

Figure 1 schematically describes the main applications of the developed information system.

These are, in details,

- simulation of system critical states
- optimization of the design and construction of the belt conveyor
- real time simulation and reconstruction of system operation
- model-based process monitoring and diagnosis (Chen and Patton, 1999),(Frank and Ding, 1997)
- simulation of operational disturbances
- early detection and warning of operational disturbances
- quality management and optimization
- observer based feedback control (Kuo, 1995)

2.2 Mathematical model of belt conveyor systems

The process variables

- torque (engine moment $M(t)$)
- mass flow $Q(t)$.

are used as model inputs. The model delivers, as its outputs, simulation and estimations for

- the speed $n(t)$ of the driving motor
- the belt tension $T_{sp}(t)$
- the driving force $F_{ant}(t)$
- the acceleration of the conveyor belt $a_i(t)$
- the distance $s_i(t)$ of the i-th section
- the resulting belt tension relationship $T_i(t)$ and
- the mass flow $q_i(t)$ over the entire belt conveyor.

To describe the steel cable belt and modelling the dynamic behavior of the whole belt conveyor the steel cable belt is first divided into N sections with an identical length L_o, and each of them is then modelled as a spring-mass-damper system, since the stress and extension behavior is mainly determined by the elastic characteristics of the steel cable as well as the internal material absorption (Schulz, 1995).

Figure 2 schematically shows the complete dynamic model of a belt conveyor system, which, as mentioned above, mainly consists of the following blocks

- N spring-mass-damper systems
- transfer functions for transmissions, clutch, brake, drive and reversing wheel
- calculation of the real mass flow distribution

Mathematically, the model consists of N differential equations of second order with time-dependent coefficients as well as a number of static (algebraic) equations.

Let a_i, v_i, m_i, s_i denote the acceleration, velocity of the i-th section of the conveyor belt, the mass and the distance of the mass of the i-th section, respectively. Then the dynamics of the i-th-section can be generally described by

$$\begin{aligned} m_i a_i = & k_i s_i + k_{i,v_i}(m_i) v_i + k_{i-1,s_i} s_{i-1} + k_{i+1} s_{i+1} \\ & + k_{i-1,v_i} v_{i-1} + k_{i+1,v_i} v_{i+1} + k_{i,v_i}(m_i) \end{aligned}$$

where $k_i, k_{i-1,s_i}, k_{i-1,v_i}$ and k_{i+1,v_i} are constants which are known, $k_{i,v_i}(m_i)$ is assumed to be a known function of m_i (Jeinsch *et al.*, 2000). We now introduce the state and input vectors,

$$s = \begin{bmatrix} s_1 \\ \vdots \\ s_N \end{bmatrix}, v = \begin{bmatrix} v_1 \\ \vdots \\ v_N \end{bmatrix}, u = \begin{bmatrix} M_1 \\ \vdots \\ M_p \end{bmatrix}$$

with M denoting the torque, the overall system model can then be expressed in terms of a state space equation

$$\begin{bmatrix} \dot{s}(t) \\ \dot{v}(t) \end{bmatrix} = A(m) \begin{bmatrix} s(t) \\ v(t) \end{bmatrix} + B(m)u(t) \in R^{2N} \quad (1)$$

Since only the velocity at the 1st- and the N-th sections is measured, the output equation is given by

$$\begin{aligned} y(t) &= \begin{bmatrix} v_1(t) \\ v_N(t) \end{bmatrix} = C \begin{bmatrix} s(t) \\ v(t) \end{bmatrix} \\ &= \begin{bmatrix} O & 1 & 0 & \cdots & 0 \\ O & 0 & \cdots & 0 & 1 \end{bmatrix} \begin{bmatrix} s(t) \\ v(t) \end{bmatrix} \end{aligned} \quad (2)$$

2.3 Observer design

The mass $m(t)$ and its distribution are unknown in the on-line implementation. Indeed, the mass flow is subject to

$$\begin{aligned} \dot{m}_i(t) = &Q_{in,i-1}(m_{i-1}(t), v_{i-1}(t)) \\ &-Q_{out,i}(m_i(t), v_i(t)) \end{aligned} \quad (3)$$

i.e. it is time-variant and also depends on the velocity of each section of the belt conveyor. If $m_i(t)$ is considered as a state variable, then we have in fact, (1) and (3) together, a nonlinear system model. It is well known that in contrast to the well-established linear observer theory, there exist no general solutions to the nonlinear observer design problem (O'Reilly, 1983). It is just this fact that makes the observer design for the belt conveyor system very difficult. Taking into account these, we formulate the main tasks of the observer design as follows:

- The estimation error dynamics of the observer should be linearized (O'Reilly, 1983);
- The observer should be easily on-line implementable.

To this aim, we consider $m_i(t)$ as model uncertainty and decompose $A(m)$ and $B(m)$ into

$$A(m) = A + \Delta A, \quad B(m) = B + \Delta B$$

where A and B are constant matrices, ΔA and ΔB represent model uncertainty due to the changes of the mass, which can be expressed by $[\Delta A \quad \Delta B] = E\,\Sigma(t)\,[F_1 \quad F_2]$ where E, F_1 and F_2 are known matrices. Denote

$$\begin{aligned} \Omega_A &:= \left\{ \Delta A \,|\, \Delta A = E\,\Sigma(t)\,F_1, \Sigma^T(t)\Sigma(t) \le I \right\} \\ \Omega_B &:= \left\{ \Delta B \,|\, \Delta B = E\,\Sigma(t)\,F_2, \Sigma^T(t)\Sigma(t) \le I \right\} \end{aligned}$$

$A + \Delta A$ is assumed to be asymptotically stable for all $\Delta A \in \Omega_A$. Then (1) and (2) can be re-written as

$$\begin{aligned} \dot{x}(t) &= (A + \Delta A)x(t) + (B + \Delta B)u(t) \\ y(t) &= Cx(t) \end{aligned}$$

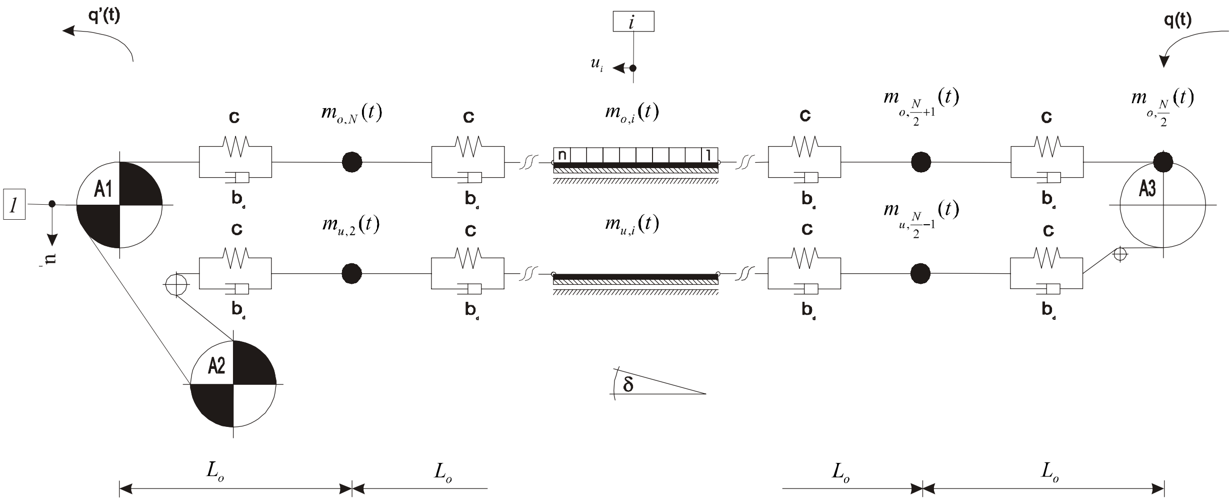

Fig. 2. Schematical description of belt conveyor model

For the purpose of state estimation, the observer is constructed as follows

$$\begin{aligned} \dot{\hat{x}}(t) &= (A + HC)\,\hat{x}(t) + Bu(t) - Hy(t) \\ \hat{y}(t) &= C\hat{x}(t) \end{aligned}$$

where $\hat{x} \in R^n$ and $\hat{y} \in R^n$ represent the state and output estimation vector respectively. The design parameter is the observer gain matrix H. The dynamics of the estimation error is governed by

$$\begin{aligned} \dot{e}(t) &= (A + HC)\,e(t) + \Delta Ax(t) + \Delta Bu(t) \quad (4) \\ z(t) &= Ce(t) \end{aligned}$$

where $e = x - \hat{x}$. First we study the influence of model uncertainties on the system dynamics. Denote the transfer function matrix from the input signal u to the residual signal z by G_{zu}. It follows from (4) that $G_{zu}u$ can be expressed as follows:

$$\begin{aligned} &G_{zu}u = C\left(sI - A - HC\right)^{-1}\varphi \\ &\varphi = \Delta A x_\Delta + \Delta B u \\ &x_\Delta = \left(sI - A - \Delta A\right)^{-1}\left(B + \Delta B\right)u \end{aligned}$$

Note that

$$\begin{aligned} &\Delta A x_\Delta + \Delta B u = E\Sigma \left[\, F_1 \;\; F_2 \,\right] \begin{bmatrix} x_\Delta \\ u \end{bmatrix} = E\Sigma\varphi_\Delta \\ &\varphi_\Delta = \Big(\left(sI - A - \Delta A\right)^{-1}\left(B + \Delta B\right) + F_2 \Big) u \end{aligned}$$

The basic idea is to consider $\Delta A x_\Delta$ and $\Delta B u$ as unknown inputs with

$$E_d = E \text{ and } d = \Sigma\varphi_\Delta$$

$$\text{where } \left\|\Sigma\varphi_\Delta\right\|_2 \leq \Delta d$$

are L_2-norm bounded. (4) is expressed as

$$\begin{aligned} &\dot{e}(t) = \left(A + HC\right)e(t) + E_d d(t) \qquad (5) \\ &z(t) = Ce(t). \end{aligned}$$

It thus becomes clear that the objective of selecting H is to make the influence of $d(t)$ on the estimation error as small as possible. To this end, we can use the well-established robust observer theory like H_∞-robust observer or observer design using μ-synthesis (Zhou, 1998).

2.4 Solution of the observer design

We now try to solve the observer design and gives the LMI formulation of H_∞ estimation problem. Notice that this problem can be defined as follows: determine a standard estimator such that H_∞ norm of the transfer function $G_{zd}(s)$ from unknown inputs to the estimation error $z(t)$ of the observer is bounded by a given number $\gamma > 0$, γ being as small as possible and $A_o := A + HC$ is asymptocically stable.

$$\left\|G_{zd}(j\omega)\right\|_\infty < \gamma,\; G_{zd}(s) = C\left(sI - A_o\right)^{-1}E_d$$

The following lemma help converting the H_∞ suboptimal constraints into a matrix inequality.

Lemma 1. (Bounded Real Lemma) Consider the following LTI system

$$\begin{aligned} &\dot{x}(t) = Ax(t) + Bw(t) \\ &z(t) = Cx(t) + Dw(t),\; x(0) = 0 \end{aligned}$$

and A is stable in the continuous-time sense ($\mathrm{Re}\left(\lambda_i\left(A\right)\right) < 0$). Given $\gamma > 0$, then the system is asymptotically stabel and satisfies

$$\int_0^\infty z^T z\, dt < \gamma^2 \int_0^\infty w^T w\, dt$$

if and only if there exist a positive matrix P such that

$$\begin{aligned} PA + A^T P + \Omega^T\left(\gamma^2 I - D^T D\right)^{-1}\Omega + C^T C < 0 \\ \gamma^2 I - D^T D > 0 \\ \left(B^T P + D^T C\right) = \Omega \qquad (6) \end{aligned}$$

Lemma 2. Given constant matrices Ω_1, Ω_2 and Ω_3, where $\Omega_1 = \Omega_1^T$ and $\Omega_2 = \Omega_2^T > 0$, then $\Omega_1 + \Omega_3^T\,\Omega_2^{-1}\,\Omega_3 < 0$ if and only if

$$\begin{bmatrix} \Omega_1 & \Omega_3^T \\ \Omega_3 & -\Omega_2 \end{bmatrix} < 0 \text{ or } \begin{bmatrix} -\Omega_2 & \Omega_3 \\ \Omega_3^T & \Omega_1 \end{bmatrix} < 0$$

Lemmas 1 and 2 to the system described by equation (5) gives asymptotically stable $A_o := A + HC$ and $\left\|G_{zd}(j\omega)\right\|_\infty < \gamma$ if and only if there exists an H_∞ observer gain matrix H given by $H = P^{-1}Q$ where matrices P and Q verify following condition

$$\begin{bmatrix} A^T P + PA + C^T Q^T + QC + I & PE_d \\ E_d^T P & -\gamma^2 I \end{bmatrix} < 0$$

with $P = P^T > 0$ and $\gamma > 0$. This optimisation problem can be solved numerically with the LMI-Toolbox available on Matlab.

3. APPLICATIONS TO REAL BELT CONVEYOR SYSTEMS

In this section, we shall present some results achieved by applying the information system to the simulation, on-line monitoring and state estimation of a real belt conveyor in an open mine of Lausitzer Braunkohle AG. A belt conveyor with a length of over 2300 *meter* has been modeled and simulated. The measured data of load and driving motor torque for monitoring tools and the calculated velocity $v_{estimate}$ and measured velocity $v_{measure}$ are shown next. This results will demonstrate the performance of the information system for on- as well as off-line applications at static and dynamic states of operation. Due to the fact that the described system in this application is not observable, a transformation matrix T has to be defined such that the given system is decomposed into an observable and nonobservable subsystem.

$$\begin{aligned} &\dot{\bar{x}}(t) = \left(\bar{A} + \Delta\bar{A}\right)\bar{x}(t) + (\bar{B} + \Delta\bar{B})u(t) \\ &y(t) = \bar{C}\bar{x}(t) \end{aligned}$$

with $\bar{A} = T^{-1}AT$; $\bar{B} = T^{-1}B$; $\bar{C} = CT$ and $\bar{x}(t) = \begin{bmatrix} \bar{x}_u(t) \\ \bar{x}_o(t) \end{bmatrix} = T^{-1}x(t)$ where $\bar{x}_o(t)$ is the observable state vector. Introducing the transformation matrix

$$T = \begin{bmatrix} -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

gives the following linearized system dynamic equations of a real belt conveyor in an open mine of Lausitzer Braunkohle AG

$$\dot{\bar{x}}(t) = \begin{bmatrix} 0 & 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & 1 \\ 1.56 & 0 & 1.56 & -0.70 & 0.35 & 0 & 0.35 \\ -5.40 & 2.70 & 0 & 0.60 & -1.22 & 0.60 & 0 \\ 2.01 & -4.01 & 2.01 & 0 & 0.45 & -0.91 & 0.45 \\ 0 & 2.05 & -4.11 & 0.46 & 0 & 0.4 & -0.93 \end{bmatrix} \bar{x}(t) + \Delta\bar{A}\bar{x}(t)$$
$$+10^{-5} \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 6.28 & 6.28 & 6.28 & 6.28 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} u(t) + \Delta\bar{B}u(t)$$
$$y(t) = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \bar{x}(t)$$

Where $\bar{x}(t) = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 \end{bmatrix}^T$, $x_{1...3}$ are the running differences of each belt section to section one $s_{2...4}(t) - s_1(t)$ and $x_{4...7}$ are the velocities at each section $v_{1....4}(t)$. $u(t)$ represent the torques $M_{1...4}(t)$ acting on the driving pulleys. By consider $\Delta\bar{A}$ and $\Delta\bar{B}$ as unknown inputs designate E_d with

$$E = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}^T,$$
$$F_1 = \begin{bmatrix} -2.01 & 4.01 & -2.01 & 0 & -0.45 & 0.89 & -0.45 \\ 0 & -2.05 & 4.11 & -0.46 & 0 & -0.46 & 0.91 \end{bmatrix},$$
$$F_2 = \begin{bmatrix} 0.003 & -0.020 \end{bmatrix}, \ |\Sigma(t)| \leq 1$$

By using the proposed design approach, we get for $\gamma = 0.15$ the observer gain matrix

$$H = \begin{bmatrix} -53.37 & -1.37 \\ -612.7 & -20.15 \\ -4.42 & -10.61 \\ -23.08 & -0.89 \\ -544.2 & -16.98 \\ -1853 & -70.70 \\ -91.98 & -69.63 \end{bmatrix}$$

On-line monitoring and state estimation are based on measured data from a real belt conveyor system. As shown in Figure 3 the load of the belt conveyor alter within a large range even during static and dynamic operation states. Figure 4 shows the measured torque of each driving motor. Due to the complexity of the belt conveyor system, the information system enables the monitoring of the belt-stress and provides information for on-line analysis aiming at identifying the changes of operational parameters.

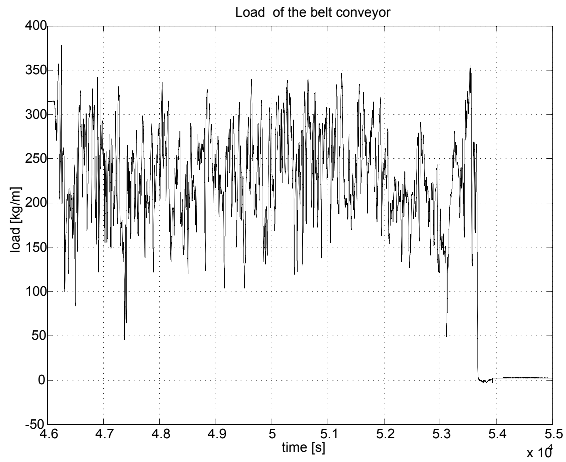

Fig. 3. Load of the belt conveyor

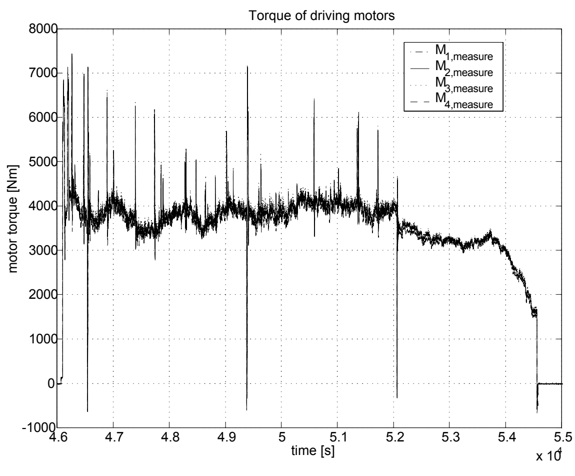

Fig. 4. On-line monitoring of real belt conveyor

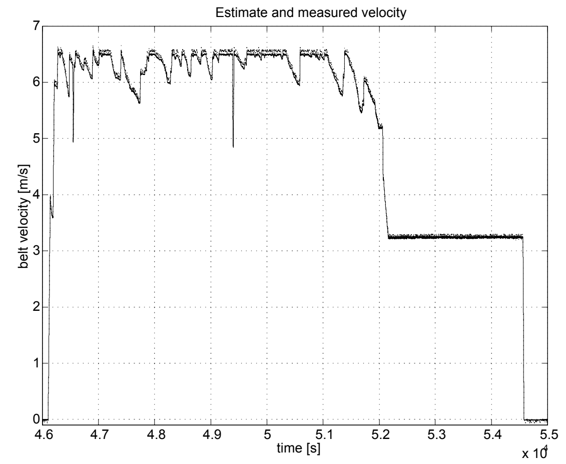

Fig. 5. On-line monitoring and state estimation of real belt conveyor

The results achived in state estimation, by using the observer gain matrix H following the proposed design approach are represented in Figure 5. It shows the measured velocities v_1 and v_2 together with the estimated velocities under the influence of unknown inputs.

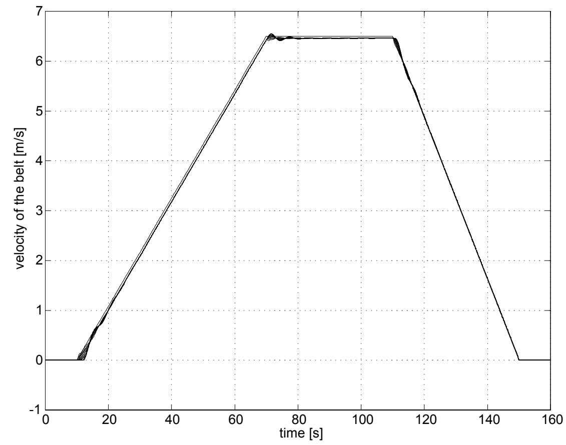

Fig. 6. Simulated velocities of the belt

Furthermore the developed information system provides the effective tool for off-line simulation of belt conveyors especially the critical dynamic states of operation. Figure 6 demonstrates the calculated velocities of each belt section during one period from the state start to stop.

4. CONCLUSION

Aiming at system monitoring, state estimation and fault detection, an observer is designed on the basis of the above described model. The application results presented above demonstrate that

- the observer delivers satisfactory estimation results so that we can get more on-line information about the operating condition,
- the information system provides a powerfull basis for the detection of certain kinds of faults and
- the information system improves the maintenance and thus enhance the quality and performance of the belt conveyor system.

The main attentions have been devoted to the development of the mathematical model and innovative observer design. We used the well-established linear observer theory which ensures the desired performance for a nonlinear mass depending belt conveyer system. The on-line implementation and the required on-line computations for the observer are at an acceptable level so that they do not cause any trouble for a successful industrial application.

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