A Model-Based Approach to Fault Detection and Abrasion Depending Maintenance on Belt Conveyor Systems

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Abstract

In this paper an information system is developed to meet the requirements on observer based monitoring and fault detection for large scale belt conveyor systems from a more practical viewpoint to support new abrasion depending maintenance schemes. The core of this information system is a mathematical model, an observer and a fault detection system.

1 Introduction

Nowadays the operations of belt conveyors are faced with increasing requirements on quality and productivity under the presence of many disturbances and strong parameter changes caused by the industrial surroundings, where the belt conveyors are usually in operation. In order to reduce maintenance costs and provide a high availability of such complex devices, it is necessary to achieve the optimal operating efficiency and simultaneously ensure a high level of safety. The existing approaches to the data analysis for detecting system faults are restricted to static calculation and testing methods.

Attention of this paper is focused on the design of an expert system for monitoring and fault detection by applying the probabilistic robustness theory to the determination of thresholds and their integration in the design of observer-based fault detection system. Different from the norm based residual evaluation methods, in which the worst case handling of model uncertainty and disturbances are adopted, the approach proposed here gives less conservative problem solutions in the probabilistic framework.

The background of this work is a R&D project initiated by the companies PC-SOFT GmbH and Vattenfall Europe AG, whose objective is to meet the requirements represented. There are demands on

- system simulation to optimize the design and construction of the belt conveyor,
- on-line monitoring aiming at identifying the changes of operation parameters of the belt conveyor in operation and
- expert system for the detection of faults in the belt conveyor during the operation to adapt abrasion maintenance schemes

are continuously increasing during the recent years

Software and information systems were developed aiming at (off-line) simulation of some special types of belt conveyor systems [4]. To apply modern maintenance schemes, the abrasion states of the system are necessary. Fault diagnosis and on-line monitoring only some special kinds of measurement equipments as well as some signal processing approaches like trends analysis or simple statistic tests are used. However, current applications of monitoring and control on belt conveyor systems are very limited, due to the complexity and the large scale of such systems, as well as the presence of many disturbances and strong parameter changes caused by the industrial surroundings, where the belt conveyors are usually in operation [7].
In this note, the development of an information system for the purposes of simulation, both on-line and off-line, monitoring and fault diagnosis of large scale belt conveyor systems is presented. The use of model-based information about the conditional states and faults can

support the abrasion maintenance for conveyor systems. The problems related to the computation of false alarm rate (FAR) and thresholds, which are often dealing with the design of observer based fault detection systems are presented. The application of the probabilistic robustness technique for the purposes of computing thresholds and FAR are studied.

The core of this system is the application of advanced model-based simulation and monitoring techniques. The rapid development in computer technology, control engineering and signal processing offers us advanced methods and technologies to solve such problems, which the model-based approaches to system simulation, monitoring and fault diagnosis are the most powerful tools [2],[5].

2 System description with model uncertainties

The information 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 [2].

Due to the limited paper length, in the following of this contribution, we shall concentrate on the design of observer based fault detection schemes and their applications to the belt conveyor monitoring system.

In order to model the technical-physical structure, the kinetics and the dynamics of a belt conveyor, the entire plant is generally partitioned into the following three subsystems: driving station, conveyor road and reversing station [13]. The variables

- torque (engine moment of the driving motors $M(t)$),
- mass flow $Q(t)$,

are used as model inputs. As model outputs, simulation and estimations

- 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.

are delivered.

To model 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 [10]. The determination of the friction coefficient

$$f_i = c_1 \cdot k_1 \cdot v_i + c_2 \cdot k_2 \tag{1}$$

where $c1, k1, c2$ and $k2$ are constants affected from environment and technical equipment, are of special importance. To this end, a linear function of the belt velocity is assumed and the influence of the resistance to rolling, pressing in resistance and deformation resistance along a belt section i are taken into account. In [13] the complete dynamic model of a belt conveyor system is presented, which include the calculation of the real mass flow distribution. Mathematically, the model consists of N differential equations of second order with time-dependent coefficients and a number of algebraic equations.

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

$$\begin{aligned} m_i a_i &= k_i s_i + k_{i,v_i}(m_i) v_i + k_{i-1,s_i} s_{i-1} \\ &\quad + k_{i+1} s_{i+1} + k_{i-1,v_i} v_{i-1} \\ &\quad + k_{i+1,v_i} v_{i+1} + k_{i,v_i}(m_i) \end{aligned} \tag{2}$$

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 [7]. Now introduce state vectors and input vector,

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

with u denoting the torque.

The major model uncertainties are

- load of the belt m_i
- kinetic resistances f_i
- environmental influence (wind, temperature,rain)
- measurement disturbances.

and the system fault states are

- operational faults of the belt,
- critical states of the drive and the reversing pulley,
- sensor faults in velocity sensors and
- faults in the driving system and the motors.

The overall system model considering the uncertainties and faults can then be expressed in terms of a state space equation

$$\begin{aligned} \dot{x}(t) &= A(m)x(t) + B(m)u(t) + E_d(m)d(t) + E_f\ f(t) \\ y(t) &= Cx(t) + F_d d(t) + F_f\ f(t) \end{aligned} \quad (3)$$

where $x \in R^n$, $u \in R^{k_u}, y \in R^m, f \in R^{k_f}$ and $d \in R^{k_d}$ denote the state, input, output and unknown input vectors respectively. We assume d and u are L_2-norm bounded

$$\|d(t)\|_2 \leq \delta_d \quad (4)$$

A, B, C, E_d and F_d are matrices with appropriate dimensions and E_f, F_f represents model uncertainties and multiplicative and additive faults in the plant.

3 Robust observer design

The mass $m(t)$ and its distribution are unknown in the on-line implementation.

$$\begin{aligned} \dot{m}_i(t) &= Q_{in,i-1}(m_{i-1}(t), v_{i-1}(t)) \\ &\quad -Q_{out,i}(m_i(t), v_i(t)) \end{aligned} \quad (5)$$

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 get in fact, (1) and (5), a nonlinear system model. It is well known that in contrast to the well-established linear observer theory, there exist no general solution to the nonlinear observer design problem [9]. 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 [9];
- The observer should be easily on-line implementable.

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

$$\begin{aligned} A(m) &= A + \Delta A, \quad B(m) = B + \Delta B, \\ E_d(m) &= E_d + \Delta E_d \end{aligned}$$

where A, B and E_d are constant matrices, ΔA, ΔB and ΔE_d represent model uncertainties which can be expressed by $[\Delta A \quad \Delta B \quad \Delta E_d] = E\,\Sigma(t)\,[F_1 \quad F_2 \quad F_3]$ where E, F_1, F_2 and F_3 are known matrices. Denote

$$\begin{aligned} \Omega_A &: = \left\{\Delta A \,|\, \Delta A = E\,\Sigma(t)\,F_1, \Sigma^T(t)\Sigma(t) \leq I\right\} \\ \Omega_B &: = \left\{\Delta B \,|\, \Delta B = E\,\Sigma(t)\,F_2, \Sigma^T(t)\Sigma(t) \leq I\right\} \\ \Omega_{E_d} &: = \left\{\Delta E_d \,|\, \Delta E_d = E\,\Sigma(t)\,F_3, \Sigma^T(t)\Sigma(t) \leq I\right\} \end{aligned}$$

$A + \Delta A$ is assumed to be asymptotically stable for all $\Delta A \in \Omega_A$. Then (3) can be re-written as the

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

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 $\hat{y} \in R^m$ represent the state and output estimation vector respectively. The design parameter is the observer gain matrix H. Then the estimation error dynamic is governed by

$$\begin{aligned} \dot{e}(t) &= (A + HC)\,e(t) + \Delta Ax(t) + \Delta Bu(t) \\ &\quad +(E_d + \Delta E_d + HF_d)d(t) \\ z(t) &= Ce(t) + F_d d(t) \end{aligned} \quad (6)$$

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 (6) that $G_{zu}u$ can be expressed as follows:

$$\begin{aligned} &G_{zu}u = C\,(sI - A - HC)^{-1}\,\varphi_u \\ &\varphi_u = \Delta A x_u + \Delta B u \\ &x_u = (sI - A - \Delta A)^{-1}\,(B + \Delta B)\,u \end{aligned} \quad (7)$$

The transfer function $G_{zd}d$ from the unknown inputs d to the residual signal z is

$$\begin{aligned} &G_{zd}d = C\left(sI - A - HC\right)^{-1}\varphi_d + F_d d \\ &\varphi_d = \Delta A x_d + (E_d + \Delta E_d + HF_d)d \\ &x_d = \left(sI - A - \Delta A\right)^{-1}\left(E_d + \Delta E_d\right)d \end{aligned} \tag{8}$$

Note that

$$\begin{aligned} &\Delta A(x_u + x_d) + \Delta B u + \Delta E_d d = ... \\ &...E\Sigma\begin{bmatrix} F_1 & F_2 & F_3 \end{bmatrix}\begin{bmatrix} x_u + x_d \\ u \\ d \end{bmatrix} = E\Sigma\varphi_\Delta \\ &\varphi_\Delta = F_1(sI - A - \Delta A)^{-1}([B + \Delta B \quad E_d + \Delta E_d] \\ &\quad + [F_2 \quad F_3])\begin{bmatrix} u \\ d \end{bmatrix} \end{aligned}$$

The influence of the uncertainties to the system dynamic follows as

$$\begin{aligned} &G_{zu}u + G_{zd}d \\ = &\left[C\left(sI - A - HC\right)^{-1}\left(\bar{E}_d + H\bar{F}_d\right) + \bar{F}_d\right]\bar{d} \end{aligned} \tag{9}$$

The basic idea is to consider the model uncertainties as unknown inputs with

$$\bar{E}_d = [E \quad E_d], \quad \bar{F}_d = [0 \quad F_d] \text{ and } \bar{d} = \begin{bmatrix} \Sigma\varphi_\Delta \\ d \end{bmatrix}$$

where the unknown input vector $\left\|\bar{d}(t)\right\|_2 \leq \Delta_d$

are L_2-norm bounded. (6) is expressed as

$$\begin{aligned} \dot{e}(t) &= (A + HC)\,e(t) + (\bar{E}_d + H\bar{F}_d)\bar{d}(t) \\ z(t) &= Ce(t) + \bar{F}_d\bar{d}(t). \end{aligned} \tag{10}$$

It thus becomes clear that the objective of selecting H is to make the influence of $\bar{d}(t)$ 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 [11].

4 Design of observer based fault detection (FD) system

In this section, we present the design of observer based fault detection system applied at the above-described large scale belt conveyor system with model uncertainties. The FD system consists of a residual generator and a residual evaluation stage including an evaluation function and a threshold [1],[3],[2].

4.1 Residual generator design

For the purpose of residual generation, observer-based fault detection system of the following form

$$\dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t) + H\left(y(t) - \hat{y}(t)\right) \tag{11}$$
$$\hat{y}(t) = C\hat{x}(t) \tag{12}$$
$$r(s) = R(s)\left(y(s) - \hat{y}(s)\right) \tag{13}$$

are considered, where r is the residual vector and the design parameters are the observer gain H and $R(s) \in RH_\infty$ is the so-called post-filter which is an arbitrarily selectable parametrization matrix [2]. It can be derived that the dynamics of the residual generator (13) is governed by

$$r(s) = R(s)M_u(s)\left(G_{\bar{d}}(s)\bar{d}(s) + G_f(s)f(s)\right) \tag{14}$$

with

$$M_u(s) = I + C(sI - A - HC)^{-1}H$$

$$\begin{aligned} G_{\bar{d}}(s) &= C\left(sI - A\right)^{-1}\bar{E}_d + \bar{F}_d \\ G_f(s) &= C\left(sI - A - \Delta A\right)^{-1}E_f + F_f \end{aligned}$$

where the transfer function matrices from d, f to y are denoted as $G_d(s)$ and $G_f(s)$ respectively. The solution of this problem provide the optimal parameter of the fault detection filter [14].To evaluate the residual, the 2-norm of the residual signal r is used as the evaluation function and the decision logic is the mostly used on

$$\begin{aligned} &\|r\|_2 > J_{th} \Longrightarrow fault \\ &\|r\|_2 \leq J_{th} \Longrightarrow no\ fault \end{aligned} \tag{15}$$

The main objective of designing residual generators is to improve the sensitivity of the FD system to faults without loss of the robustness to disturbances. Thus the selection of the design parameters H and $R(s)$ can be formulated as an optimization problem

$$\min_{R(s),H} \frac{\left\|R(s)M_u(s)\bar{G}_{zd}(s)\right\|_\infty}{\sigma_i(R(s)M_u(s)\bar{G}_{zf}(s))} \tag{16}$$

where $\sigma_i(R(s)M_u(s)\bar{G}_{zf}(s))$ denotes some nonzero singular value of $R(s)M_u(s)\bar{G}_{zf}(s)$. The determination of adaptive threshold considering the design of the residual generator is to improve the results on fault detection and isolation.[12]

4.2 Probabilistic approach to the threshold selection

Different from the norm-based residual evaluation methods, where J_{th} is the threshold selected as

$$J_{th} = \sup_{d,f=0}\|r\|_2 = \left\|R(s)M_u(s)\bar{G}_{zd}(s)\right\|_\infty \Delta_d \tag{17}$$

and the threshold determination is based on the worst-case handling of model uncertainty and unknown inputs, the probabilistic robustness theory is applied for the purpose of calculating thresholds and false alarm rate. This approaches will lead to a more practical design of observer based fault detection systems.

Applying the norm based residual evaluation methods, the threshold J_{th} should cover all possible changes in the residual vector caused by the model uncertainty and unknown inputs. It is evident that threshold setting in the way of (17) ensures no false alarms. Unfortunately, this is often achieved at the cost of a high threshold which may result in that the number of undetectable faults becomes very large. This problem can also be formulated from the probabilistic viewpoint. The false alarm rate (FAR) is defined as the conditional probability that $\|r\|$ is larger than the threshold in the fault free case.

$$FAR = \Pr ob \left\{ \|r\| \text{ffl} J_{th} \quad | \ f = 0 \right\} \tag{18}$$

and the threshold be $J_{th} = \sup_{d,f=0} \|r\|$, where $f = 0$ indicate the fault-free case, then we have

$$\Pr ob \left\{ \|r\| \le J_{th} \quad | \ f = 0 \right\} = 1 \Rightarrow$$

$$\begin{aligned} FAR &= \Pr ob \left\{ \|r\| \ge J_{th} \quad | \ f = 0 \right\} \\ &= 1 - \Pr ob \left\{ \|r\| \le J_{th} \quad | \ f = 0 \right\} = 0 \end{aligned}$$

there $\Pr ob \left\{ \alpha \le \beta \right\}$denotes the probability of $\alpha \le \beta$. We now set the threshold J_{th} smaller than $\sup_{d,f=0} \|r\|$, it turns out

$$\begin{aligned} FAR &= \Pr ob \left\{ \|r\| \text{ffl} J_{th} \quad | \ f = 0 \right\} \\ &= 1 - \Pr ob \left\{ \|r\| \le J_{th} \quad | \ f = 0 \right\} \end{aligned}$$

If $\Pr ob \left\{ \|r\| \le J_{th} \quad | \ f = 0 \right\} \prec 1$,then FAR will be larger than zero. Decreasing the threshold leads to increasing the number of detectable faults. For this reason, it is in practice often the case that a compromise between the FAR and the miss detection rate is made. The idea of this study is to make use of the knowledge of random matrix Σ (i.e. its probability distribution) to establish a relationship between the FAR and the threshold and to achieve a suitable determination of the threshold for the information system of the belt conveyor. Due to the limitation of this note we will show first results of this idea used for two problems are often met in practice for the application of the fault detection system, i.e. to estimate FAR if $J_{th} \le \sup_{d,f=0} \|r\|$ and to find the threshold J_{th} at a given system and FAR_{α} such $FAR = \Pr ob \left\{ \|r\| \text{ffl} J_{th} \quad | \ f = 0 \right\} \le FAR_{\alpha}$.

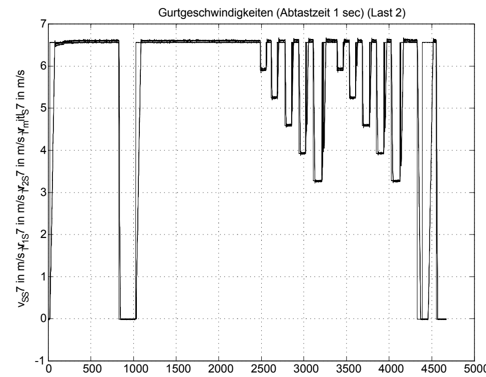

Figure 1: Conveyor monitoring and state estimation

5 Applications and Conclusion

In this section some results presented, achieved by applying the information system to the simulation, on-line monitoring, state estimation and fault detection on a real belt conveyor in an open mine of Vattenfall Europe AG. The measured velocity $v_{measure}$ and the calculated velocity $v_{estimate}$ of one belt section are shown in Figure 1, including static and dynamic states of operation.

Aiming at system monitoring, state estimation and fault detection, an observer is designed on the basis of the above described model. Apply the introduced observer-based fault detection to the developed information system and evaluate the residual using the evaluation function given above by using real data of a conveyor system is shown in Figure 2. It displays the result of the evaluated residual $r(t)$ corresponding to a logged fault event of the conveyor control system. This demonstrates the successful fault detection. 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 detect certain kinds of faults and
- improve the maintenance and thus enhance the quality and performance of the belt conveyor system.

The main attentions have been devoted to the robust observer design and fault detection. We used the well-established linear observer theory which ensures the

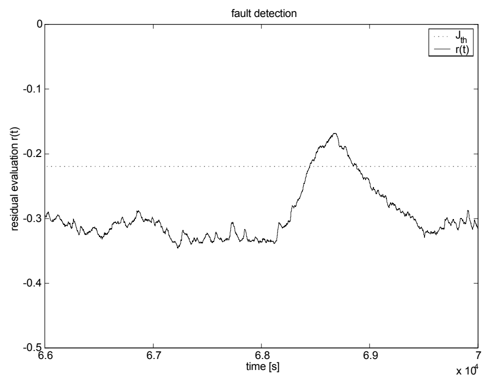

Figure 2: Evaluated residual $r(t)$ and threshold J_{th}

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. Aiming at solving more practical fault detection problems at the belt conveyor, study on application of probabilistic robustness theory are mentioned to improve the performance of the developed information system. One further application is to use the knowledge about the fault states and the probability of false alarm rate to adapt the control schemes of the belt driving unit, to avoid faults and critical system states in order to reduce the abrasion and maintenance costs.

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