Robust Observer-Based Control of an Aluminum Strip Processing Line

Prabhakar R. Pagilla[1]
School of Mechanical and Aerospace Engineering
Oklahoma State University, Stillwater, OK 74078

Eugene O. King[2]
Alcoa Inc., Technical Center, Pittsburgh, PA 15219

Louis H. Dreinhoefer[3]
Alcoa Inc., FRP Engineering, Knoxville, TN 37902

Srinivas S. Garimella[4]
Alcoa Inc., Technical Center, Pittsburgh, PA 15219

Abstract –*Tension control of an aluminum strip in a strip processing line is the focus of this work. A continuous strip processing line is truly a large-scale complex interconnected dynamic system with numerous control zones to transport the strip while processing it. In this paper, two aspects affecting the tension behavior of the strip in the entire processing line have been studied. First, a model that accurately represents the dynamics of the strip in accumulator spans is derived from the first principles. Second, an estimated decoupled state feedback controller is designed for the linearized dynamics of controlled spans. The state estimates are obtained using a Luenberger observer. Convergence of the state and estimation errors is shown. Some remarks on detection of actuator faults using a linear observer for interconnected systems are also given.*

Nomenclature

A	Cross-sectional area of web
J	Polar moment of inertia of roller
L	Length of span
R	Radius of roller
K	Motor constants
E	Modulus of Elasticity
t_{n0}	Operating value of strip tension
T_n	Change in strip tension force from operating value
t_n	Strip tension force
u_n	Input to driven motor
u_{n0}	Input value at steady state
U_n	Change in input from steady state value
v_n	Strip velocity
v_{n0}	Steady-state operating web velocity
V_n	Change in velocity from steady state
ρ	Density of aluminum strip
M	Mass of the accumulator carriage
t	Time
ϵ	Strain
h	Thickness of web

[1] pagilla@master.ceat.okstate.edu
[2] Eugene.King@alcoa.com
[3] Louis.Dreinhoefer@alcoa.com
[4] Srinivas.Garimella@alcoa.com

1 Introduction

A continuous aluminum strip processing line typically consists of an entry section, a process section, and an exit section. The entry section consists of an unwind stand, tension leveler and an entry accumulator. Operations such as wash, coat and quench on the strip are performed in the wash and coat section. The

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exit section consists of an exit accumulator and a rewind stand. The function of the entry and the exit accumulators is to store/release strip material. The accumulators facilitate continuous operation of the line when either a rewind roll or unwind roll change over takes place. Tension control of the aluminum strip in the entire processing line is crucial to maintaining tension of the strip at desired levels. This further assures the required quality of the finished roll.

The primary motivation for this work stems from observations made on an Alcoa finishing process line. It has been observed that the dynamics of the accumulator plays an important role on the behavior of strip tension in the entire line. Tension disturbance propagation has been noticed due to motion of the accumulator carriage both upstream and downstream of the accumulator. Our first preliminary work reported in this paper was to look at the strip dynamics due to carriage motion. Previous work has ignored the dynamics of the carriage motion on strip tension dynamics. In this work we derive a mathematical model of the strip tension dynamics from the first principles taking into account the time-varying nature of the length of the strip in the accumulator. The derived model reflects not only the time-varying position of the accumulator carriage but also the its speed changes.

The second aspect of this work deals with the design of an observer-based feedback controller. Again the motivation comes from the fact that processing lines do not generally contain adequate number of sensors to measure all the state variables. In some cases, such as hot ovens, it may not be possible to get sensor information. In this work, a model-based Luenberger observer is constructed for the interconnected controlled spans, where only velocity measurements are available. A full-order observer that estimates both tension and velocity has been constructed. It is shown that a decoupled feedback controller using estimated states for feedback results in a stable closed-loop system.

Early work describing the longitudinal dynamics of a web can be found in the book by Campbell, (1958) [1]. Campbell's mathematical model for longitudinal dynamics does not predict tension transfer, as he does not consider tension in the entering span. An historical perspective of lateral and longitudinal behavior of moving webs is given by Young and Reid, (1993)[4]. Wolfermann, (1995) [2], reviews several problems associated with tension control and highlights some focus areas for the future. Mathematical model of multi-span web transport systems with/without dancer subsystems was developed by Shin, (1991)[5]. A large body of research in the area of large-scale interconnected systems has been reported by Siljak in his book entitled "Decentralized Control of Complex Systems" (1991)[6].

This paper is organized as follows. In Section 2, a sketch of a typical aluminum strip processing line and its elements are shown. Dynamic model of the unwind, rewind, controlled and free spans are given in Section 3. A dynamic model for tension in accumulator spans is derived in Section 3.1. Section 3.2 contains the linearized dynamics of the controlled fixed spans. In Section 4, a decoupled state feedback controller is designed for a simple two span controlled system. Section 5 gives an adaptive observer based approach to detection of faults. Conclusions and future work are given in Section 6.

2 Aluminum Strip Processing Line

A sketch of a typical continuous strip process line layout is given in Figure 1. It is composed of an entry section that unwinds unprocessed strip, an entry accumulator that releases web into the process section when the the entry section is stopped, a process section where strip processing is performed, and an exit accumulator that stores web when the exit is stopped for a rewind changeover, and an exit section that winds the processed web into rolls. Bridles shown in the figure are driven rolls and

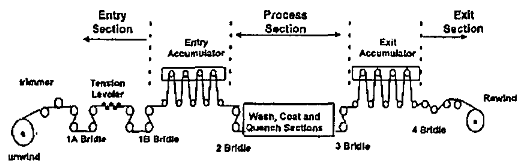

Figure 1: Typical Process Line Layout and Terminology

are either driven by AC or DC drives. Bridle rolls provide transport of the web in the line. Both accumulator carriages are controlled by hydraulic means that provide regulation of tension in the strip when the carriage is in motion.

3 Dynamics of Typical Elements in a Processing Line

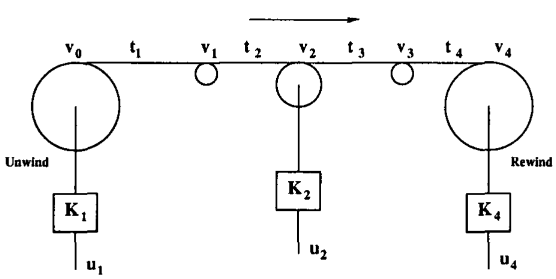

Figure 2: A simplified sketch of an web line

Considering Figure (2), the dynamics [3] of the unwind roller, web spans, and rewind roller is given by

$$J_0(t)\dot{v}_0 = -R_0(t)K_0u_1 + R_0^2(t) \tag{1}$$

$$L_1\dot{t}_1 = EA(v_1 - v_0) - v_1t_1 + \frac{K_1}{R_0(\tau)}v_1u_0 \tag{2}$$

$$J_1\dot{v}_1 = R_1^2(t_2 - t_1) \tag{3}$$

$$L_2\dot{t}_2 = EA(v_2 - v_1) - v_2t_2 + v_1t_1 \tag{4}$$

$$J_2\dot{v}_2 = R_2^2(t_3 - t_2) + R_2K_2u_2 \tag{5}$$

$$L_3\dot{t}_3 = EA(v_3 - v_2) - v_3t_3 + v_2t_2 \tag{6}$$

$$J_3\dot{v}_3 = R_3^2(t_4 - t_3) \tag{7}$$

$$L_4\dot{t}_4 = EA(v_4 - v_3) - v_4t_4 + v_3t_3 \tag{8}$$

$$J_4(t)\dot{v}_4 = -R_4^2t_4 + R_4(t)K_4u_4 \tag{9}$$

where $J_1(\tau)$ and $J_4(\tau)$ denote the time varying inertias of the unwind and rewind, respectively. The time-varying radii of the unwind and rewind rolls are:

$$R_1(t) = \sqrt{R_{1i}^2 - \frac{v_1ht}{\pi}}, \quad R_1(t) = \sqrt{R_{2i}^2 - \frac{v_4ht}{\pi}},$$

R_{1i} and R_{2i} denote the initial radii or unwind and rewind rolls.

Notice that the dynamics is nonlinear and time-varying. For control design purposes, it is typically assumed that the inertia of the unwind and rewind rolls are changing slowly when compared to the dynamics of the strip. The nonlinearities in the dynamics appear only in the tension dynamics and as bilinear terms in states. Moreover the interconnecting nonlinearities in a controlled span depend only on the neighboring spans. Hence, the strip processing line is a special class of a general large-scale system, wherein the interconnecting nonlinearities depend on neighboring subsystems only.

Also, notice that the span length is assumed to be constant. In accumulators, the span length varies with the motion of the carriage of the accumulator. It is conventional wisdom to just take the dynamics of the fixed length span and make the length of the span time-varying according to the carriage motion. In the following section, it is shown that the longitudinal dynamics of a web span with variable span length is different.

3.1 Dynamics of a Web in Accumulator Spans

Consider the sketch of a simplified accumulator span shown in Figure (3). The law of conservation of mass for a control volume in the first span of Figure (3) gives

$$\frac{d}{dt}\left[\int_{x_1(t)}^{x_2(t)} \rho(x,t)A(x,t)dx\right] = \rho_1(t)A_1(t)v_1(t) - \rho_2(t)A_2(t)v_2(t) \tag{10}$$

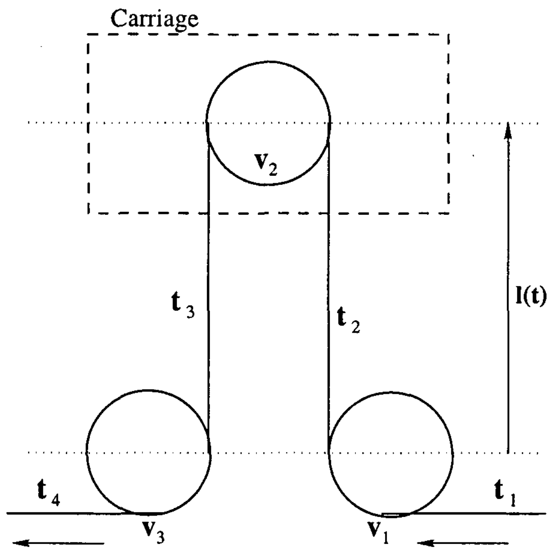

Figure 3: Sketch of an accumulator span

where x_1 and x_2 denote the coordinates or roller 1 and roller 2, respectively, from a fixed reference frame. Notice that for the accumulator case roller 1 is fixed ($x_1(t) = 0$) and roller 2 moves along with the carriage ($x_2(t) = l(t)$), where $l(t)$ denotes the variable length of the span.

If we consider an infinitesimal element of the strip in the machine direction, the geometric relations between unstretched and stretched element are given by

$$dx = (1 + \varepsilon_x)dx_u \tag{11}$$

$$w = (1 + \varepsilon_w)w_u \tag{12}$$

$$h = (1 + \varepsilon_h)h_u \tag{13}$$

where subscript u indicates the unstretched state of the element, w and h denote the width and height of the web, respectively. The elemental mass, dm, in the unstretched and stretched state is equal, which gives

$$dm = \rho\ dx\ w\ h = \rho_u dx_u w_u h_u \tag{14}$$

Combining equations (11)-(14), we obtain

$$\frac{\rho(x,t)A(x,t)}{\rho_u(x,t)A_u(x,t)} = \frac{1}{1+\varepsilon_x(x,t)} \tag{15}$$

Substituting (15) into (10), we obtain

$$\frac{d}{dt}\left[\int_{x_1(t)}^{x_2(t)} \frac{\rho_u(x,t)A(x,t)}{1+\varepsilon_x(x,t)}dx\right] = \frac{\rho_{1u}(x,t), A_{1u}(x,t)v_{1u}(t)}{1+\varepsilon_{x1}(x,t)} - \frac{\rho_{2u}(x,t), A_{2u}(x,t)v_{2u}(t)}{1+\varepsilon_{x2}(x,t)} \tag{16}$$

Assuming the density (ρ) and the modulus of elasticity (E) of the web in the unstretched state are constant over the cross-section, (16) can be written as

$$\frac{d}{dt}\left[\int_{x_1(t)}^{x_2(t)} \frac{1}{1+\varepsilon_x(x,t)}dx\right] = \frac{v_1(t)}{1+\varepsilon_{x1}(x,t)} - \frac{v_2(t)}{1+\varepsilon_{x2}(x,t)} \tag{17}$$

Assuming that the strain is very small, $\varepsilon_x <<< 1$, we can neglect higher order terms and write $1/(1+\varepsilon_x) \approx (1-\varepsilon_x)$. Then, (17) can be written as

$$\frac{d}{dt}\left[\int_{x_1(t)}^{x_2(t)} (1-\varepsilon_x(x,t))dx\right] = v_1(t)[1-\varepsilon_{x1}(x,t)] - v_2(t)[1-\varepsilon_{x2}(x,t)] \tag{18}$$

Assuming that the strain does not vary with x, i.e. $\varepsilon_x(x,t) \approx \varepsilon_x(t)$, the left-hand-side of (18) can be written as

$$\frac{d}{dt}\left[\int_{x_1(t)}^{x_2(t)} (1-\varepsilon_x(t))dx\right] = \left[\int_{x_1(t)}^{x_2(t)} dx\right]\frac{d}{dt}(1-\varepsilon_x(t)) + (1-\varepsilon_x(t))\frac{d}{dt}\left[\int_{x_1(t)}^{x_2(t)} dx\right] \tag{19}$$

Notice that the second term in the right-hand-side of (19) is differentiation of an integral with variable limits of integration. Hence, the integral can be differentiated using Leibnitz rule[1]

[1] Leibnitz rule

$$\frac{d}{dt}\left[\int_{\phi(t)}^{\psi(t)} f(x,t)dx\right] = \int_{\phi(t)}^{\psi(t)} \frac{\partial f(x,t)}{\partial t}dx - \frac{d\phi}{dt}f(\phi(t),t) + \frac{d\psi}{dt}f(\psi(t),t)$$

of differentiating an integral. For simplicity, taking the accumulator case given by Figure (3), i.e., $x_1(t) = 0$ and $x_2(t) = l(t)$, applying Leibnitz rule for (19) gives

$$\frac{d}{dt}\left[\int_0^{l(t)}(1-\varepsilon_x(t))dx\right] = \left[\int_0^{l(t)} dx\right]\frac{d}{dt}(1-\varepsilon_x(t)) + (1-\varepsilon_x(t))\frac{d}{dt}\left[\int_0^{l(t)} dx\right] \quad (20)$$

Substituting (20) into (18) and using Hooke's law, i.e., $t_2(t) = AE\epsilon_x(t)$, gives

$$\dot{t}_2(t) = \frac{AE}{l(t)}[v_2(t) - v_1(t)] + \frac{1}{l(t)}[t_1(t)v_1(t) - t_2(t)v_2(t)] + \frac{AE}{l(t)}\dot{l}(t) - \frac{1}{l(t)}t_2(t)\dot{l}(t) \quad (21)$$

Notice that the last two terms in (21) appear in the tension dynamics of the strip due to the variable length of the spans in accumulators. In fact the dynamics of this variable length is given by the accumulator carriage dynamics, i.e., $M(d^2l(t)/dt^2) = \sum$ forces on the carriage. It should also be observed from (21) that the dynamics of the accumulator carriage is well reflected in the tension dynamics of the spans.

3.2 Linearized Dynamics of controlled spans

The linearized dynamic model around an operating point of a controlled span given by equations (4) and (5) is

$$\dot{T}_n = -\frac{v_{n0}}{L_n}T_n + \frac{AE}{L_n}V_n + \frac{v_{n-10}}{L_n} \quad (22)$$

$$\dot{V}_n = -2\frac{R^2}{J}T_n - \frac{B_f}{J}V_n + \frac{R^2}{J}T_{n-1} + \frac{R^2}{J}T_{n+1} \quad (23)$$

In matrix form, linearized dynamics is given by

$$\dot{X}_n = \mathbf{A}_n X_n + \mathbf{B}_n U_n + \mathbf{A}_{n,n-1}X_{n-1} + \mathbf{A}_{n,n+1}X_{n+1} \quad (24)$$

$$Y_n = \mathbf{C}_n X_n \quad (25)$$

where

$$X_n = \begin{bmatrix} T_n \\ V_n \end{bmatrix}; \; \mathbf{B}_n = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

$$\mathbf{A}_n = \begin{bmatrix} -\frac{v_{n0}}{L_n} & \frac{AE}{L_n} \\ -2\frac{R^2}{J} & -\frac{B_f}{J} \end{bmatrix}; \; \mathbf{A}_{n,n-1} = \begin{bmatrix} \frac{v_{n-1,0}}{L_n} & 0 \\ \frac{R^2}{J} & 0 \end{bmatrix};$$

$$\mathbf{A}_{n,n+1} = \begin{bmatrix} 0 & 0 \\ \frac{R^2}{J} & 0 \end{bmatrix}; \; \mathbf{C}_n = \begin{bmatrix} 0 & 1 \end{bmatrix}$$

Notice that $(\mathbf{A}_n, \mathbf{B}_n)$ is controllable and $(\mathbf{A}_n, \mathbf{C}_n)$ is observable.

4 Observer Based Feedback Controller

The control objective can be stated as follows: if there is a perturbation in the tension and/or velocity of a span due to some disturbances, then find the perturbation in control input that brings the states to their operating values. For controller design, we assume that only velocity measurements are available. The output equation given by (25) reflects this choice. For simplicity, we show the design of an observer based controller considering two controlled spans. Generalization can be carried out with a little more work. Consider the dynamics of the two spans.

Span 1:

$$\dot{X}_1 = \mathbf{A}_1 X_1 + \mathbf{B}_1 U_1 + \mathbf{A}_{10} X_0 + \mathbf{A}_{12} X_2 \quad (26)$$

$$Y_1 = \mathbf{C}_1 X_1 \quad (27)$$

Span 2:

$$\dot{X}_2 = \mathbf{A}_2 X_2 + +\mathbf{B}_2 U_2 + \mathbf{A}_{21} X_1 + \mathbf{A}_{23} X_3 \quad (28)$$

$$Y_2 = \mathbf{C}_2 X_2 \quad (29)$$

Notice that if the span lengths and the radii of the rollers are same, then the matrices $\mathbf{A}_1$ and $\mathbf{A}_2$ are same. Consider the following observers:

$$\dot{\hat{X}}_1 = \mathbf{A}_1\hat{X}_1 + \mathbf{B}_1 U_1 + \mathbf{L}_1(Y_1 - \hat{Y}_1) \tag{30}$$

$$\dot{\hat{X}}_2 = \mathbf{A}_2\hat{X}_2 + \mathbf{B}_2 U_2 + \mathbf{L}_2(Y_2 - \hat{Y}_2) \tag{31}$$

where $\mathbf{L}_i, i = 1,2$ denotes observer gain matrix. Defining $e_i = X_i - \hat{X}_i$, we obtain the observer error dynamics to be

$$\dot{e}_1 = (\mathbf{A}_1 - \mathbf{L}_1\mathbf{C}_1)e_1 + \mathbf{A}_{12}X_2 \tag{32}$$

$$\dot{e}_2 = (\mathbf{A}_2 - \mathbf{L}_2\mathbf{C}_2)e_2 + \mathbf{A}_{21}X_1 \tag{33}$$

Since the pairs $(\mathbf{A}_1, \mathbf{C}_1)$ and $(\mathbf{A}_2, \mathbf{C}_2)$ are observable, the eigenvalues of matrices $\mathbf{A}_1 - \mathbf{L}_1\mathbf{C}_1$ and $\mathbf{A}_2 - \mathbf{L}_2\mathbf{C}_2$ can be arbitrarily placed by choosing the observer gain matrices $\mathbf{L}_1$ and $\mathbf{L}_2$. Now consider the following controllers based on estimated feedback,

$$U_1 = -\mathbf{K}_1\hat{X}_1 \tag{34}$$

$$U_2 = -\mathbf{K}_2\hat{X}_2 \tag{35}$$

where $\mathbf{K}_1$ and $\mathbf{K}_2$ are feedback gain matrices. With these control laws the dynamics becomes

$$\dot{X}_1 = \mathbf{A}_1 X_1 - \mathbf{B}_1\mathbf{K}_1\hat{X}_1 + \mathbf{A}_{12}X_2 \tag{36}$$

$$\dot{X}_2 = \mathbf{A}_2 X_2 - \mathbf{B}_2\mathbf{K}_2\hat{X}_2 + \mathbf{A}_{21}X_1 \tag{37}$$

Define the following:

$$\bar{e}_1 = \begin{bmatrix} X_1 \\ e_1 \end{bmatrix}, \quad \bar{e}_2 = \begin{bmatrix} X_2 \\ e_2 \end{bmatrix}$$

Then the closed-loop dynamics becomes:

$$\dot{\bar{e}}_1 = \bar{\mathbf{A}}_1\bar{e}_1 + \bar{\mathbf{A}}_{12}\bar{e}_2 \tag{38}$$

$$\dot{\bar{e}}_2 = \bar{\mathbf{A}}_2\bar{e}_2 + \bar{\mathbf{A}}_{21}\bar{e}_1 \tag{39}$$

where

$$\bar{\mathbf{A}}_i = \begin{bmatrix} \mathbf{A}_i - \mathbf{B}_i\mathbf{K}_i & \mathbf{B}_i\mathbf{K}_i \\ \mathbf{0} & \mathbf{A}_i - \mathbf{L}_i\mathbf{C}_i \end{bmatrix}$$

$$\bar{\mathbf{A}}_{12} = \begin{bmatrix} \mathbf{A}_{12} & \mathbf{0} \\ \mathbf{A}_{12} & \mathbf{0} \end{bmatrix}, \quad \bar{\mathbf{A}}_{21} = \begin{bmatrix} \mathbf{A}_{21} & \mathbf{0} \\ \mathbf{A}_{21} & \mathbf{0} \end{bmatrix}$$

We now show convergence of the closed-loop errors $\bar{e}_1$ and $\bar{e}_2$ to zero. Let $\bar{\mathbf{T}}_i$ be a similarity transformation for $\bar{\mathbf{A}}_i$, i.e., $\bar{\mathbf{\Lambda}}_i := \bar{\mathbf{T}}_i^{-1}\bar{\mathbf{A}}_i\bar{\mathbf{T}}_i$ is diagonal. The matrix $\mathbf{\Lambda}_i$ is negative definite. Define $\bar{\bar{e}}_1$ and $\bar{\bar{e}}_2$ such that $\bar{e}_1 = \bar{T}_1\bar{\bar{e}}_1$ and $\bar{e}_2 = \bar{T}_2\bar{\bar{e}}_2$. The error dynamics in $\bar{\bar{e}}_1$ and $\bar{\bar{e}}_2$ becomes

$$\dot{\bar{\bar{e}}}_1 = \bar{\mathbf{\Lambda}}_1\bar{\bar{e}}_1 + \bar{\mathbf{T}}_1^{-1}\bar{\mathbf{A}}_{12}\bar{\mathbf{T}}_2\bar{\bar{e}}_2 \tag{40}$$

$$\dot{\bar{\bar{e}}}_2 = \bar{\mathbf{\Lambda}}_2\bar{\bar{e}}_2 + \bar{\mathbf{T}}_2^{-1}\bar{\mathbf{A}}_{21}\bar{\mathbf{T}}_1\bar{\bar{e}}_1 \tag{41}$$

The error dynamics (40) and (41) can be written in matrix form as

$$\begin{bmatrix} \dot{\bar{\bar{e}}}_1 \\ \dot{\bar{\bar{e}}}_2 \end{bmatrix} = \underbrace{\begin{bmatrix} \bar{\mathbf{\Lambda}}_1 & \bar{\mathbf{T}}_1^{-1}\bar{\mathbf{A}}_{12}\bar{\mathbf{T}}_2 \\ \bar{\mathbf{T}}_2^{-1}\bar{\mathbf{A}}_{21}\bar{\mathbf{T}}_1 & \bar{\mathbf{\Lambda}}_2 \end{bmatrix}}_{\bar{\bar{\mathbf{A}}}} \begin{bmatrix} \bar{\bar{e}}_1 \\ \bar{\bar{e}}_2 \end{bmatrix} \tag{42}$$

The matrix $\bar{\bar{\mathbf{A}}}$ can be made negative definite by proper choice of the eigenvalues of $\bar{\mathbf{\Lambda}}_1$ and $\bar{\mathbf{\Lambda}}_2$. Hence, the errors converge to zero.

4.1 Remarks on Detecting Faults

It is well known that the Luenberger observers given by (30) and (31) can be used to detect faults. It can be shown that such an approach does not work for interconnected systems because the states of the neighboring subsystems appear in the observer error dynamics. Consider the modification of equations (26) and (28) to reflect actuator faults:

$$\dot{X}_1 = \mathbf{A}_1 X_1 + \mathbf{B}_1 g_1(t) U_1 + \mathbf{A}_{10}X_0 + \mathbf{A}_{12}X_2 \tag{43}$$

$$\dot{X}_2 = \mathbf{A}_2 X_2 + +\mathbf{B}_2 g_2(t) U_2 + \mathbf{A}_{21}X_1 + \mathbf{A}_{23}X_3 \tag{44}$$

In the above equations, $g_1(t) = 1$ and $g_2(t) = 1$ means the actuators are healthy. The observer error dynamics becomes,

$$\dot{e}_1 = (\mathbf{A}_1 - \mathbf{L}_1\mathbf{C}_1)e_1 + \mathbf{A}_{12}X_2 + \mathbf{B}_1(g_1(t) - 1)U_1(t) \tag{45}$$

$$\dot{e}_2 = (\mathbf{A}_2 - \mathbf{L}_2\mathbf{C}_2)e_2 + \mathbf{A}_{21}X_1 + \mathbf{B}_2(g_2(t) - 1)U_2(t) \tag{46}$$

Fault detection can be carried out as follows: if $\|\mathbf{C}_i e_i(t)\| \leq \gamma_i$ then no fault occurs in actuator i; if $\|\mathbf{C}_i e_i(t)\| > \gamma_i$, for any $t \geq t_f$ then fault has occurred at time t_f, where γ_i is a pre-specified threshold value. Notice that $\mathbf{C}_i e_i(t) = Y_i - \widehat{Y}_i$, and hence is known. This type of fault detection approach cannot be used to conclude an actuator fault in a particular span, because the error $\|Y_i - \widehat{Y}_i\|$ might have exceeded a pre-specified threshold value due to the interconnection terms X_{i-1} and X_{i+1}. Moreover, in the linearized dynamics, (43) and (44), the control input U_i is a perturbation to the actual control input u_{i0}. Hence the linearized dynamics given above may not actually detect actuator faults.

5 Conclusions and Future Work

In this paper, a dynamic model for strip tension dynamics in accumulator spans is developed. This model reflects the motion dynamics of the accumulator carriage. A Luenberger observer is proposed for the linearized dynamics of interconnected spans. An estimated state feedback controller is designed for the linearized dynamics. Convergence of the states and estimation errors is shown.

Our future work will focus on considering the entire process line to investigate tension disturbance propagation from one span to others that are downstream and upstream. In this paper, we mentioned that the strip processing line is truly a large-scale interconnected system. Although we have not worked with the dynamics of the entire line in this work, future work will focus on casting the entire process line dynamics as a large-scale interconnected system. It appears that such a framework may not only help in predicting tension disturbance propagation in the entire line but also in the supervision and fault diagnosis of the entire processing line.

Further, using linear observer based strategies for detection and diagnosis of faults is not conclusive for interconnected systems. Focusing on the nonlinear dynamics to construct nonlinear observers may open up new avenues. Also, notice that this dynamic model for strip dynamics assumes only one-dimensional motion of the carriage. It has been observed that accumulator carriage may sway during its motion. This may cause a moment on the strip in contact with the rollers on the accumulator carriage. We plan to investigate the effects of this on the strip dynamics in the future. Also, this model does not include the slip effects on the roller and its role in strip dynamics in accumulator spans. We also plan to explore this in our future work.

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