Diagnosis of Fluid Systems utilizing Gröbner Bases and Filtering of Consistency Relations

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Diagnosis of Fluid Systems utilizing Gröbner Bases and Filtering of Consistency Relations

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Performed for **ABB Automation Systems AB**
in cooperation with **ABB Corporate Research AB**

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Titel Diagnos av fluidsystem utnyttjande Gröbner baser och filtrerade konsistensrelationer

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Sammanfattning
Abstract

The objective of this master's thesis is to develop a method for automatic design of diagnostic systems for pulp and paper industry. General models for fluid systems are presented. The models simulate slow dynamics based on object-oriented sub-models. The sub-models are tanks, pipes, control valves, pumps, mixers and dividers. The diagnostic systems are based on hypothesis tests and decision structures. The hypothesis tests are formed as tests with thresholds. The tests are constructed as normalized residuals. Consistency relations are used to construct the residuals. The consistency relations are extracted from model equations. Through calculations of Gröbner bases, good decision structures are achieved.

To evaluate the methods, they are applied to a stock preparation and broke treatment system from a paper mill. Three different simulations including three different faults are presented. A semi-automatic algorithm, with the ability to construct diagnostic systems for arbitrary fluid systems, is presented. The diagnostic system, constructed with the semi-automatic algorithm, can detect and isolate faults. Arbitrary slow dynamic faults can be detected and isolated.

Nyckelord
Keywords

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Preface

This master's thesis has been performed for *ABB Automation Systems AB* in cooperation with *ABB Corporate Research AB* and *Vehicular Systems* at *Linköpings Universitet* during summer-fall 2001.

Thesis outline

The thesis consists of six chapters.

Chapter 1: Introduction to the thesis.

Chapter 2: Short introduction to model based diagnosis and Gröbner bases.

Chapter 3: Description of the models used in fluid systems.

Chapter 4: Presentation of two methods to construct diagnostic systems for fluid systems.

Chapter 5: Application of the methods, presented in chapter 4, on a stock preparation and broke treatment part of a paper mill.

Chapter 6: Conclusions and topics for further studies.

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I would like to thank my supervisors *Carl-Fredrik Lindberg* and *Mattias Krysander* for valuable help during the work with this thesis. Further, I would like to thank *Erik Frisk, Mattias Nyberg, Bengt Oldberg* and *Xiaojing Zhang* for aiding me in various areas.

Jonas Biteus

Linköping, 23rd October 2001

Contents

Chapter 1

Introduction

Background

In the pulp and paper industry the costs for an unplanned stop is very high. An hour stop can cause up too tens of thousands euros in unnecessary costs.

In an automation system, *diagnosis* is the discovery and identification of what is wrong in the system. The diagnosis will give a *diagnose* that includes the information of what is wrong. A *diagnostic system* is a system that performs a diagnosis.

ABB supplies the pulp and paper industry with a complete platform for use in process automation. The platform includes sensors, actuators, control systems and simulators. To further increase the services that can be offered to the customer, ABB's goal is to produce diagnostic systems that can be included in the platform.

Objectives

The objective for the thesis is to find *methods* that can be used to construct *diagnostic systems*. The demands on the *methods* are that they shall be:

- Easy to adapt for a specific system.

The objectives for the *diagnostic system* are to:

- Detect all faults;
- Isolate all faults;
- Be robust w.r.t. disturbances and model faults.

Assumptions

It is assumed that a physical model have been found and identified. This includes the environment that affects the system. Further, it is assumed that only one fault is present. The fault dynamics are assumed slower than the disturbance dynamics.

Chapter 2

Theory

This chapter will describe the needed theory concerning model-based diagnosis. The theory is only included to give the reader a basic understanding. Section 2.1 will describe tests and isolation, for more information see [1, 2]. Section 2.2 will describe the concept of Gröbner bases, for more information see [3, 4, 5].

2.1 Model based diagnostic system

If the diagnostic system is based on an explicit model, it is called *model based diagnostic system*.

Figure 2.1 shows a schematic figure of how a model based diagnostic system can be achieved. In the figure the *system* is controlled by input u and gives output y, known disturbance w, unknown disturbance v and *Fault* are acting upon the system. The *model identification* identifies the system and the *diagnostic system* performs *diagnosis* which produces a *diagnose*. In case of a difference between the model and the system, an alarm will be included in the diagnose. One of the following reasons can have caused the difference:

- There is a model fault in the model;
- A fault is acting upon the system;
- Unknown disturbances are acting upon the system.

The first reason is connected to the model identification problem and will not be considered in this paper. It is the second and last reason that will be studied.

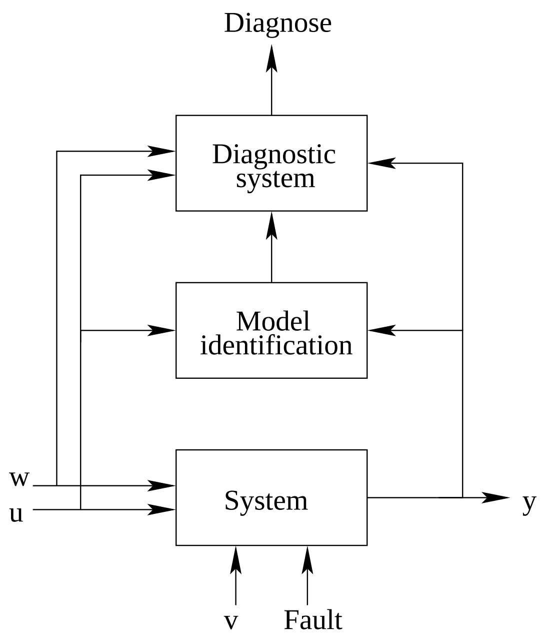

Figure 2.1: Schematic picture of a model based diagnostic system.

2.1.1 Fault modes

When a fault is acting upon the system the system will be in a *fault mode*. In the fault free case the system is in the *no fault mode* $\mathcal{NF}$. The set of all fault modes

$$\Omega \quad = \quad \{\mathcal{NF}, \mathcal{F}_1, \dots, \mathcal{F}_n\}.$$

A sub-set of Ω,

$$M_i \subseteq \Omega.$$

The goal of a diagnostic system is to decide which fault mode $\mathcal{F}_p \subset \Omega$ that can explain the observations (y, u, w). In this report it is assumed that $|\mathcal{F}_p| = 1$.

2.1.2 Different tests to detect fault modes

A test reacts to a sub-set of fault modes M_i. A test can for example be:

- Limit checking of sensors (the “classic” approach);
- Linear and non-linear observers that approximate the fault;

- Fault sensitive residuals.

The third test-type, *fault sensitive residuals*, can be based on dynamic models and arbitrary model expressions. Therefore, it is *fault sensitive residuals* that will be used in this report.

2.1.3 Residuals

A residual is an output, from a stable filter, that in the fault free case are small. Residuals can be constructed from consistency relations. Consistency relations are any relations between known or measured variables that, in the fault free case, always holds. A consistency relation is typically a model-equation that only includes parameters, actuators and sensors.

Example 1
Consider a nonlinear model description

$$\begin{aligned}\dot{y}_1 &= x_1 - x_2 \\ y_1 &= \frac{1}{u^2}x_1^2 + f \\ y_2 &= x_2^2 \\ x_1, x_2, y_1, y_2 &> 0\end{aligned}$$

where f is some unknown fault. If y_i is measurable and $\dot{y}_i$ can be estimated then a consistency relation is

$$\dot{y}_1 - u\sqrt{y_1} + \sqrt{y_2} = 0.$$

The consistency relation is true if $f = 0$. A residual can be realized as

$$\int_{t-\tau}^{t} (\dot{y}_1 - u\sqrt{y_1} + \sqrt{y_2})dt. \tag{2.1}$$

The residual is low pass filtered to reduce sensitivity from disturbances. If (2.1) is larger than some limit, it follows that the fault is large.

2.1.4 Influence structure and fault isolation

An influence structure describes the logical connection between different components. In this case, it is connections between tests and fault modes. The influence structure is represented by a two dimensional matrix. Let m_{ij} be the element at row i and column j. If test T_i logically reacts to fault mode $\mathcal{F}_j$ this will be represented by “1” at m_{ij}, otherwise “0”. To be able to isolate all fault modes the tests have to react to different sub-sets of fault modes. The influence structure will show if it is possible to logically isolate all fault modes.

Example 2
In the influence structure test T_1 reacts to fault mode $M_1 = \{\mathcal{F}_2\}$, T_2 to $M_2 = \{\mathcal{F}_2, \mathcal{F}_3\}$ and T_3 to $M_3 = \{\mathcal{F}_1, \mathcal{F}_3\}$. It is clear that it will be possibly to isolate all fault modes.

	$\mathcal{F}_1$	$\mathcal{F}_2$	$\mathcal{F}_3$
T_1	0	1	0
T_2	0	1	1
T_3	1	0	1

If T_1 and T_2 reacts,

$$\mathcal{F}_p \subseteq M_1 \cap M_2 \cap M_3^C = \{\mathcal{F}_2\} \cap \{\mathcal{F}_2, \mathcal{F}_3\} \cap \{\mathcal{F}_2\} = \{\mathcal{F}_2\},$$

i.e. the fault mode is $\mathcal{F}_2$.

2.1.5 Thresholds, hypothesis tests and decision structure

Section 2.1.4 described that it is possible to isolate a fault by using tests and influence structure. However, it is not possible to use this structure direct in a diagnostic system due to disturbances and model faults. To avoid false alarms the tests have to be compared to a threshold. A *hypothesis test* compares the test T_i to a *threshold* J_i,

$$\delta_i : T_i > J_i.$$

When the test is compared to a threshold, it might occur that even if a fault is present in the system, the hypothesis test is false. The fault will be undetected. This problem introduces the concept of *decision structure*. A decision structure is a relaxed form of influence structure. The uncertainty are represented with “X” at m_{ij}. The “X” means that the test “might” react to the fault mode. A result of this is that if the test has not reacted, it is not possible to make any conclusions. Each hypothesis tests have a corresponding sub-decision

$$S_i = \begin{cases} M_i & \text{if } \delta_i \quad \text{is true} \\ \Omega & \text{if } \delta_i \quad \text{is false.} \end{cases}$$

The decision is

$$S = \bigcap_i S_i.$$

Example 3
The tests in example 2 are used to form hypothesis tests δ_1, δ_2 and δ_3. The decision structure will therefore be

	$\mathcal{F}_1$	$\mathcal{F}_2$	$\mathcal{F}_3$
δ_1	0	X	0
δ_2	0	X	X
δ_3	X	0	X

If only δ_2 is true

$$S = \Omega \cap M_2 \cap \Omega = \Omega \cap \{\mathcal{F}_2, \mathcal{F}_3\} \cap \Omega = \{\mathcal{F}_2, \mathcal{F}_3\},$$

i.e. the fault mode $\mathcal{F}_p \subset S$.

2.2 Gröbner bases

The problem of finding consistency relations, so that a good influence structure is found, can be approached with Gröbner bases. Gröbner bases can be used if the equations describing the system can be expressed as non-differential polynomials. The non-differential part means that a variable and its corresponding derivatives will be handled as different variables, e.g. y and $\dot{y}$ are two different variables. A Gröbner base is calculated from a base of polynomials w.r.t. a variable ordering for the included variables. The result is a polynomial base where the variables are excluded from the equations in the base with respect to the given ordering.

Variable ordering

The variable ordering decides in which order variables shall be eliminated. $\succ$ are used to indicate variable priority. For example $x \succ y$ means that x have higher priority than y. If a Gröbner base is calculated with $x \succ y$ this means that x then y shall be eliminated if possible. There exists many different ordering principles; one fundamental is lexicographic ordering. Lexicographic ordering orders the polynomial with respect to the alphabet, this is the ordering used in ordinary lexicon thereby the name lexicographic ordering.

Maple [6, 7] has implemented several different variable orderings. The ordering that are of most interest are *elimination order* called *lexdeg*. Lexdeg takes two orderings $\{v_1, \ldots, v_p\}$ and $\{w_1, \ldots, w_p\}$. A monomial involving any v_i is higher than another monomial involving only w_j. Such a term order is usually used to eliminate $v_1, \ldots, v_p$. The ability to decide which variables that should be eliminated makes it good to use in this report.

Example 4
Consider the following set of equations

$$\begin{aligned} x^2 + y + z - 1 &= 0 \\ x + y^2 + z - 1 &= 0 \\ x + y + z^2 - 1 &= 0 \end{aligned}$$

with the variable order

$$x \succ y \succ z.$$

This means that x, y then z should be eliminated if possible. With maple the Gröbner base γ can be calculated to

$$\begin{aligned} \gamma_1 &= x + y + z^2 - 1 \\ \gamma_2 &= y^2 - y - z^2 - z \\ \gamma_3 &= 2yz^2 + z^4 - z^2 \\ \gamma_4 &= z^6 - 4z^4 + 4z^3 - z^2. \end{aligned}$$

Note that the included variables are excluded in accordance to the variable order.

Chapter 3

Fluid system models

This chapter will describe the models used in general fluid systems. Section 3.1 will describe the model supplied by *ABB*. Section 3.2 will in detail describe the different sub-models and a general fluid system.

3.1 ABB models

ABB have developed models for simulation of fluid systems in the paper industry. These models are object-oriented and based on physical properties for the system. Flow, temperature, pressure, concentration and changes in physical properties can be simulated. This gives very accurate and complex models. The complexity of the model is also its major drawback. To be able to use a physical model in reality its parameters have to be identified. Because of this, new models have been developed. The models are based on the models supplied by ABB.

3.1.1 Simplifications of the complex models

The major differences between the complex models and the simplified are that:

- All energy relations have been removed, e.g. relations concerning temperature;
- The physical properties have been assumed to be constant (density, enthalpy and molar mass);
- It is assumed that the system is working at or around its operating point. E.g. the concentration should not change too much;
- It is assumed that all flows are non-reversible.

Table 3.1: Streams for connection of sub-models.

Stream type	Included variables
Pressure-stream	p
Flow-stream	F, χ

Table 3.2: Stream variables for sub-models.

	Definition	Unit
p	Pressure	Pa
F	Volume flow	m^3/s
χ	Concentration	-

Appendix B gives a short comparison between the complex and the simplified model described in this chapter. It is shown that the differences between the complex and the simplified model are small.

3.2 Model description

Fast dynamics are very difficult to model, because of high frequency disturbances. Therefore, in this report, the models are constructed so that they have good characteristics for slow dynamics. For example, dynamic turbulence, in pipes, has been approximated with static relations. The result of this is that there are only dynamic relations describing the fluid level and concentration in tanks.

A complete model is constructed by connecting non-causal sub-models by streams representing the flow of energy in the system. There are two types of streams, the *intensities* is represented by *pressure-streams* and the *flows* by *flow-streams*. Table 3.1 and 3.2 defines the streams and the corresponding variables. All sub-models have the index and parameters, listed in table 3.3, in common.

Table 3.3: Common parameters for sub-models.

	Value	Definition	Unit
i	-	Number of inputs or outputs	-
g	9.81	Gravitational constant	m/s^2
p^{atm}	101325	Atmospheric normal pressure	Pa
ρ	955	Fluid density	kg/m^3

3.2.1 Tank

The tank is modeled as an open tank with outflow at the bottom. It is assumed that the fluid is perfectly mixed in the tank.

Table 3.4: Variables and parameters for tanks.

	Definition	Unit	Type
L	Level of fluid	m	Variable
p^{tank}	Pressure at tank-bottom	Pa	Variable
A	Cross-section area	m^2	Parameter

Table 3.4 defines variables and parameters. The differential equation for fluid level is

$$\dot{L} = \frac{1}{A}(\sum_i F_i^{in} - F^{out}),$$

and for concentration

$$\dot{\chi}^{out} = \frac{1}{AL}\sum_i F_i^{in}(\chi_i^{in} - \chi^{out}).$$

The hydrostatic outlet pressure at the bottom of the tank,

$$p^{tank} = p^{atm} + g\rho L.$$

3.2.2 Pipe

Figure 3.1 shows a general pipe. The pipe includes a control valve and a pump, added to this is the internal friction. This model relates the flow of an incompressible fluid through a pipe to the difference in pressure across the pipe. The flow in the pipe is affected by friction, a control valve and a pump. The friction and the valve causes a pressure fall while the pump causes a pressure increase. The pump is represented by a centrifugal pump based on a quadratic relationship between differential pressure across the pump and the flow through the pump.

Table 3.5 defines variables and parameters. The pressure fall due to friction is

$$\Delta p_{\text{friction}} = -aF^2$$

and due to the control valve

$$\Delta p_{\text{control valve}} = -\frac{b}{u^2}F^2.$$

The pressure increase from the pump is

$$\Delta p_{\text{pump}} = d_1\sqrt{1 - \left(\frac{F}{d_2}\right)^2}.$$

Table 3.5: Variables and parameters for pipes.

	Definition	Unit	Type
u	Valve input signal	-	Actuator
Δp	Differential pressure	Pa	Variable
a	Friction	$Pa(s/m^3)^2$	Parameter
b	Valve parameter	$Pa(s/m^3)^2$	Parameter
d_1	Maximal pump pressure increase	Pa	Parameter
d_2	Maximal pump flow	m^3/s	Parameter

The pressure fall over a general pipe is

$$p^{down} - p^{up} = \sum_{i \in \text{Components}} \Delta p_i.$$

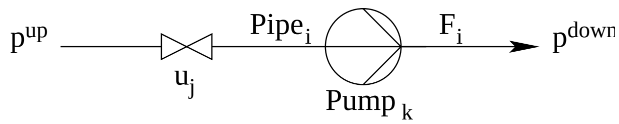

Figure 3.1: A general pipe including friction, control valve and pump.

3.2.3 Mixer and divider

The mixer model takes flows from several inlets and gives an outflow. It is assumed that the fluids are perfectly mixed in the mixer. The flow-equilibrium gives

$$F^{out} = \sum_i F_i^{in}.$$

The equation giving the concentration in the outflow is

$$\sum_i F_i^{in} \chi_i^{in} = F^{out} \chi^{out}.$$

The divider model takes an inlet flow and divides it to several outlets. The flow-equilibrium gives

$$\sum_i F_i^{out} = F^{in}.$$

The concentrations in the outflows are

$$\chi_i^{out} = \chi^{in} \quad \forall i.$$

Table 3.6: Fault modes for the different faults.

Fault mode	Fault
$\mathcal{F}_i^a$	f_i^a
$\mathcal{F}_i^d$	f_i^d
$\mathcal{F}_i^u$	f_i^u
$\mathcal{F}_i^y$	f_i^y

3.3 Faults and fault modes

Different faults can affect the model. For each fault, there will be a corresponding fault mode.

3.3.1 Faults

In this type of system four different types of faults can occur, *increased friction in pipe*, *faulty pump gain*, *actuator fault* and *sensor fault*. To be able to accurately detect and isolate faults it is desired to know the dynamics for the faults. The dynamics are not known in this case. It is assumed that the fault dynamics are slower than the disturbance dynamics, however.

Increased friction in pipe: Increased friction in the pipe f^a result in reduced flow though the pipe. The increased friction in the pipe can be caused by clogging. The fault is modeled as a percentage increase. The reason for this is that it is easy to understand the effect of the fault.

Faulty pump gain: Faulty pump gain f^d results in a deviation of the speed variable from the normalized value 1. This will result in reduced flow through the pump due to decrease in d_1 and d_2. The fault is modeled as a percentage increase. The reason for this is that it is easy to understand the effect of the fault.

Actuator fault: Actuator fault f^u results in higher or lower flow through the valve. The fault is modeled as an *additive fault*. Since the value of u is known the effect of the fault is easy to understand.

Sensor fault: Sensor fault f^y is modeled as an *additive fault*. Since the value of y is known the effect of the fault is easy to understand.

3.3.2 Fault Modes

To each fault, there is a corresponding fault mode. Table 3.6 lists the different fault modes and the corresponding faults.

3.4 General model description

This section will describe a general model of a fluid system. Let the system include k tanks, l pipes, m pumps, n control valves, q mixers and dividers and r Sensors.

3.4.1 Variables

Let x_{li} denote the level of fluid in tanks i and x_{ci} the concentration. Variable F is the flow in the pipes and p the pressure in the mixers and the dividers. Variables x_l, x_c, F and p will include all state variables that exist in the system. The r sensors will measure one or several of these variables.

$$y = C[x_l, x_c, F, p]^T + Df$$

where C and D are matrices.

3.4.2 Complete model

For each tank, there will be two differential equations. Resulting in equations g_l and g_c with dimension k,

$$\begin{aligned} \dot{x}_l &= g_l(F) \\ \dot{x}_c &= g_c(F, x_l, x_c). \end{aligned}$$

For each pipe there will be one algebraic constrain equation

$$h_p(x_l, u, F, p, f) = 0.$$

Mixers and dividers will introduce constrains upon the flows

$$h_m(F) = 0.$$

The complete system is

$$\dot{x}_l = g_l(F) \tag{3.1a}$$
$$\dot{x}_c = g_c(F, x_l, x_c) \tag{3.1b}$$
$$0 = h_p(x_l, u, F, p, f) \tag{3.1c}$$
$$0 = h_m(F) \tag{3.1d}$$
$$y = C[x_l, x_c, F, p]^T + Df. \tag{3.1e}$$

Polynomials

In section 2.2 it is said that a requirement for use of Gröbner bases, is that the equations are polynomials. In the system given above it is seen that the equations are polynomials with exception for the pumps that have a square-root part. To be able to use polynomial methods these have to be removed. This can be done in two ways:

- Since there are only one pump in each equation it will be possible to move the square-root to r.h.s. and square the equation;
- With help variables and equations the square-root can be transformed to a variable.

The second approach will be used in this report (for no specific reason). If there are k pumps, k help equations will occur

$$
\begin{array}{rcl}
z_i & = & d_1\sqrt{1-\left(\dfrac{F}{d_2}\right)^2} \\
 & \Longleftrightarrow & \\
z_i^2 & - & d_1^2(1-\left(\dfrac{F}{d_2}\right)^2) = 0 \\
 & \Longleftrightarrow & \\
h_{zi}(F,z) & = & 0.
\end{array}
$$

The complete system will now be

$$
\begin{aligned}
\dot{x}_l &= g_l(F) && (3.2a)\\
\dot{x}_c &= g_c(F, x_l, x_c) && (3.2b)\\
0 &= h_p(x_l, u, F, p, z, f) && (3.2c)\\
0 &= h_m(F) && (3.2d)\\
0 &= h_z(F, z, f) && (3.2e)\\
y &= C[x_l, x_c, F, p]^T + Df. && (3.2f)
\end{aligned}
$$

Chapter 4

Fluid system diagnosis

The diagnostic system will be constructed from residuals. The residuals will be constructed from non-linear consistency relations. The model equations given in section 3.4.2 shall be used to produce a set of consistency relations. The consistency relations shall have such an influence structure so that all fault modes can be isolated. Each test shall have a threshold so that the probability for false alarm and missed detection is small.

This chapter will describe how diagnostic systems can be constructed for fluid systems. Two different methods to extract consistency relations are presented. The *direct extraction of consistency relations* method will use a direct and computer intense approach. This method is described in section 4.1. The *find flows to extract consistency relations* method uses an indirect approach. This method is described in section 4.2. Section 4.3 describes the construct of the diagnostic system based on consistency relations. Appendix A describes how a semi-automatic algorithm for construction of diagnostic systems can be implemented, based on the flow method.

4.1 Direct extracting of consistency relations

The direct extracting of consistency relations method directly eliminates the unknown variables from the model equations (3.2). The variables are eliminated through the calculation of a Gröbner base. A specific sub-set of the calculated Gröbner base will consist of consistency relations.

Denote the unknown variables ζ. In section 2.1.4 it is said that to be able to isolate all faults, it is desired that tests reacts to different sub-sets of faults. Choose the variable ordering as

$$\zeta_1 \succ \cdots \succ \zeta_n \succ f_i \succ \ldots \tag{4.1}$$

Calculate the Gröbner base with the variable ordering (4.1). The resulting Gröbner base $\gamma(y, u, \zeta, f)$ can be divided into two sub-sets

$$\begin{aligned} \gamma_\zeta &= h_1(y, u, \zeta, f) \\ \gamma_\zeta^C &= h_2(y, u, f_1, \ldots, f_{i-1}, f_{i+1}, \ldots, f_n). \end{aligned}$$

By including f_i in the variable ordering the equations in γ_ζ^C will not react to the specific fault f_i. If Gröbner bases for all f are calculated, $dim(f)$ bases will be calculated. The complete set of consistency relations is

$$\Gamma(y, u, f) = \bigcup_i \gamma_{\zeta i}^C.$$

From Γ consistency relations can now be chosen so that a good influence structure can be achieved.

Remark: It is not sure that all faults can be isolated.

4.1.1 Limits with this method

The algorithms used to find the Gröbner bases are computer intense. The complexity of the problem increases when the number of equations and variables increases. The complexity can fast increase to such a high degree that the computation of the Gröbner bases becomes impossible[1].

The stock preparation and broke treatment system in chapter 5 have been used to test this method. Due to the complexity of the problem it was not possible to achieve any relevant result (see section 5.2).

4.2 Find flows to extract consistency relations

The direct approach suggested in section 4.1 can not be used in reality due to the complexity of the problem. If it would be possible to decrease the workload, the basic idea might still be usable.

One such way is to decrease the number of fault modes that exists in the system. This will of course reduce the possibility to isolate specific fault modes. The idea here is to use the pressure equations (3.1c) to evaluate all flows. When the flows are known, consistency relations can be constructed from the equations corresponding to mixers, dividers and tanks. A good influence structure might be achieved when Gröbner bases are calculated.

[1]At least with the limited computers that exist today.

Assumptions

This method assumes that:

- All physical parameters are known, including the parameters connecting the system to the environment;
- There are fluid level and concentration sensors in all tanks;
- Concentration sensors are only placed in tanks (or in the pipes leading from the tanks);
- There are no sensors measuring the flows.

4.2.1 Find flows

To find the flows, the equations (3.1c) will be used. These equations include only one unknown flow for each equation. If there are pressure points that are unmeasured by pressure sensors there will be unknown variables p included. These variables have to be eliminated in order to decide the flow. To eliminate the variable extra equations have to be used. These equations are the constrain-relations from the mixer or dividers without pressure sensors, a sub-set of (3.1d).

4.2.2 Basic consistency relations

When the flows have been found, no unknown variables are left in the system. *Basic* consistency relations can be constructed from the remaining equations in (3.1),

$$e = \{\dot{x}_l - g_l(F), \dot{x}_c - g_c(F, x_l, x_c), h_m(F) - 0\} \tag{4.2}$$

where

$$\begin{aligned} e &= 0 \\ \begin{bmatrix} x_l \\ x_c \end{bmatrix} &= C^{-1}y \end{aligned}$$

in the fault free case.

4.2.3 Gröbner bases

The equations (4.2) can directly be used to construct residuals. The consistency relations might however not be able to isolate all fault modes. With the use of Gröbner bases, consistency relations so that all fault modes can be isolated might be found. To find a good isolation structure of the influence structure the variable ordering is chosen as

$$F_i \succ \dots \tag{4.3}$$

With the variable ordering (4.3) l(see section 3.4) different Gröbner bases $\gamma = 0$ are calculated. The complete set of consistency relations

$$\Gamma(F, y) = \bigcup_i \gamma_i \cup \bigcup_i e_i. \tag{4.4}$$

The basic consistency relations (4.2) are added because it is desired that the consistency relations are as simple as possible.

Remark: Gröbner bases are used to achieve a decision structure that might isolate all fault modes, i.e. eliminate one fault each time. However, in this case, it might exist much simpler methods to achieve a good decision structure.

4.2.4 Fault modes

Since the different flows will be calculated explicitly, it will not be possible to isolate all fault modes, only sub-sets of fault modes. The fault mode for a general pipe i, with sensors up and down stream measuring the flow is

$$\mathcal{F}_i^p = \{\mathcal{F}_i^a, \mathcal{F}_i^d, \mathcal{F}_i^u, \mathcal{F}_{up}^y, \mathcal{F}_{down}^y\},$$

where the included fault modes corresponds to friction, pump, actuator and sensor faults, see section 3.3. The sensor faults have to be included because the flow will be calculated with help of the sensors measuring level or pressure. The fault modes corresponding to concentration sensor faults can still be isolated. The reason for this is that the concentration sensors are not used when the flows are calculated.

4.2.5 Limits with this method

The flow variables are used explicitly when the Gröbner bases are calculated. This give as a result that it is not possible to isolate exactly which fault that are present, only in which flow the fault is present.

4.3 Diagnostic system based on consistency relations

4.3.1 Choosing consistency relations

Theoretically, all consistency relations can be used to form the residuals. However, if a consistency relation is very complex this will mean that it is sensitive to disturbances. Since the risk for false alarm shall be small, a high threshold has to be used. This will lead to a small possibility to detect a fault. The consistency relation will be useless. Since the relation is useless, it can be removed.

4.3.2 Sensor filtering and approximations of derivative

To reduce the sensitivity to disturbances, y is filtered with a low-pass filter, e.g. low-pass Butter-worth filter. The sensors derivative are approximated with a backward difference approximation. This simple approximation can be used since the sensors have been low-pass filtered.

4.3.3 Residuals, tests and hypothesis tests

The residuals are formed as the floating mean square value of the consistency relations

$$r_i(t) = \int_{t-\tau}^{t} \Gamma_i^2 dt.$$

The residuals are sensitive to faults in the time-window τ. To use a threshold is equivalent to normalize the residual. The tests are constructed as normalized residuals

$$T_i(t) = \frac{1}{J_i} r_i(t).$$

The thresholds for the hypothesis tests are 1,

$$\delta_i(t) : T_i(t) > 1.$$

Choosing τ and J_i

τ and J_i shall be chosen so that the probability for false alarm and missed detection are small. Simulations and experiments can be used to decide τ and J_i.

Disturbances relation to detection and isolation

If perfect models were available, it would be possible to construct perfectly functioning diagnostic systems. However, model faults and disturbances are in reality acting upon the system. One of the objectives for the diagnostic system, is that it shall be robust w.r.t. disturbances and model faults (chapter 1). This means that the risk for false alarm shall be small. From this it follows that the thresholds should be high (with low thresholds, disturbances might produce false alarms). However, if the thresholds are high, the probabilities to detect and isolate faults are reduced and the other objectives are missed.

The conclusion from this is that, use high thresholds to avoid false alarms, low thresholds to detect and isolate all faults. The thresholds have to be decided through simulations and experiments.

4.3.4 Influence and decision structure

Each fault corresponds to a fault mode. The influence structure can therefore be found by inspection of the consistency relations. If the flow method is used the fault modes will be sub-sets of "old" fault modes. The decision structure are found by replacing "1" with "X" in the influence structure.

Chapter 5

Application of the diagnostic systems

In chapter 4 two different methods to construct diagnostic systems was presented. This chapter will show how the methods can be applied to diagnosis a system. The system is a part of a paper mill. The paper mill produces linerboard paper used to produce cardboard paper.

Section 5.1 gives a description of the system. Section 5.2 describes how the direct method unsuccessfully have been tried. Finally section 5.3 describes the successfully implementation of the flow method. It is the algorithm in appendix A, based on the flow method, that has been used.

5.1 Description of the system

The system used to test the diagnostic methods is the *stock preparation and broke treatment* part of the mill. Figure 5.1 shows the schematic structure of the system. The stock preparation and broke treatment part is used to prepare paper mixture for use in the paper machines. The system starts with recycled paper and water. The recycled paper will be simulated as a fluid with a high concentration of paper fibers. The two parts are mixed in the *pulper* tank. When the concentration is right the fluid is moved through *pipes* to a *tank* with the use of a *pump*. From this tank the mixture is pumped to a *cyclone*.

The cyclone separates paper fiber and water from waste such as gravel. This is done by spinning the fluid inside the cyclone. The result is that large particles are collected at the bottom where they can be removed. In the top of the cyclone the mixture is clean and can be transported to the next stage. From the cyclone, there is a pipe back to the tank. The return of fluid increases the concentration in the

Table 5.1: The different sub-models used in the stock preparation and broke treatment system.

Name	Sub-model type
Pulper	Tank
Tank	Tank
Pump 1,2	Pump
Mixer	Mixer
Pipe 1, ... ,10	Pipe
Control Valve 1, ... ,6	Control valve
Cyclone	Divider
Divider	Divider

Table 5.2: Sensors in the stock preparation and broke treatment system.

Sensor	Sub-model	Variable	Unit	Type
y_1	Pulper	L	m	Fluid level
y_2	Tank	L	m	Fluid level
y_3	Pipe 6	p^{down}	Pa	Pressure
y_4	Pipe 8	p^{down}	Pa	Pressure
y_5	Pipe 3	χ	-	Concentration
y_6	Pipe 6	χ	-	Concentration

tank. To maintain a proper concentration, the mixture is mixed with more water before going back to the cyclone. There are no chemical reactions or phase changes in the process.

ABB does not have any good model for the cyclone, therefore it is modeled as a divider. The result is that the pressure in the inlets and outlets of the cyclone are equal, as opposed to a real cyclone where the pressures out of the cyclone are higher. The concentrations out of the cyclone equals the concentration in, as opposed to a real cyclone were the concentrations out of the cyclone are different from the concentration in.

5.1.1 Model specifications

Table 5.1 lists the different sub-models used to construct the model. Table 5.2 lists the sensors in the system. Note that there are no flow sensors. There are six actuators in the model, u_1–u_6. The model parameters are assumed known.

Connection between the model and the environment

There are five pipes connected to the environment (pipe 1,2,5,7 and 9). To simulate the system the pressures connecting these parts to the

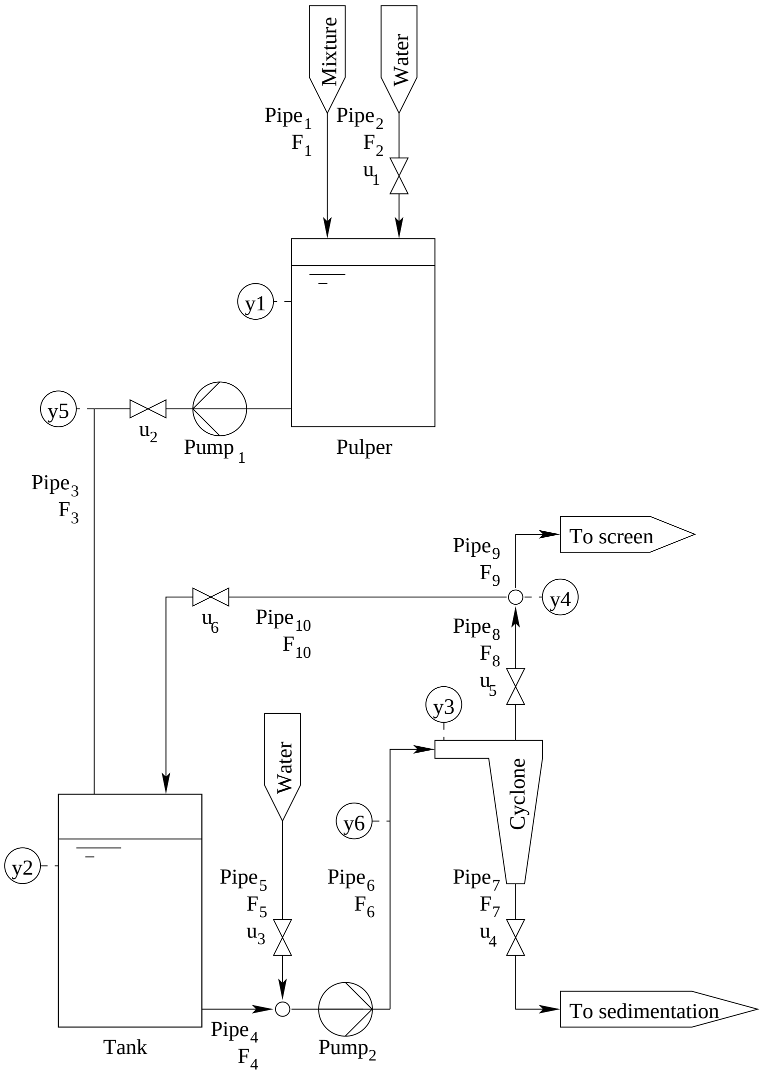

Figure 5.1: Schematic picture of stock preparation and broke treatment system.

Table 5.3: Environment in-data to the stock preparation and broke treatment system.

Pipe	Variable	Denoted	Unit
1	p^{up}	p_1^{up}	Pa
1	χ	χ_1	-
2	p^{up}	p_2^{up}	Pa
2	χ	χ_2	-
5	p^{up}	p_5^{up}	Pa
5	χ	χ_5	-
7	p^{down}	p_7^{down}	Pa
9	p^{down}	p_9^{down}	Pa

environment have to be known. This can for example be the pressure from the atmosphere or hydrostatic pressure in an external tank. The concentration of the fluids that leads into the system must also be known. Table 5.3 shows the required parameters.

Concentration sensor y_6

The concentration sensor y_6 measures the concentration in pipe 6 (see figure 5.1). To perform a diagnosis of the sensor a consistency relation sensitive to a fault in the sensor has to be found. This means that the concentration in the tank and in pipe 5 must be known. The concentration in pipe 5 is known. The concentration in the tank is however unknown and has to be found indirectly. The expression can be found. It will however include flow derivatives. This means that it can not be used with the methods suggested in chapter 4, because in the methods the flow derivatives are not calculated. Sensor y_6 will therefore be ignored when constructing the diagnostic system.

5.1.2 Model equations

From the model description given in chapter 3, figure 5.1 and the data given in section 5.1.1, it is now possible to build a complete model. Replace the state space variables in the equations with its corresponding sensors (if the state space variables are measured).

Differential equations describing the change in fluid level (3.1a) in the tanks,

$$\dot{y}_1 = \frac{1}{A_1}(F_1 + F_2 - F_3) \tag{5.1a}$$

$$\dot{y}_2 = \frac{1}{A_2}(F_3 + F_{10} - F_4). \tag{5.1b}$$

From the pulper it is possible to find an equation describing the changes in concentration (3.1b),

$$\dot{y}_5 = \frac{1}{A_1 y_1}((\chi_1 - y_5)F_1 + (\chi_2 - y_5)F_2). \tag{5.2}$$

The pressure loops (3.1c) are found by inspection of the figure

$$\begin{aligned}
h_{p1}(F_1) &= -a_1 F_1^2 + p_1^{up} - p^{atm} \\
h_{p2}(F_2) &= -(a_2 + \frac{b_1}{u_1^2})F_2^2 + p_2^{up} - p^{atm} \\
h_{p3}(F_3) &= -(a_3 + \frac{b_2}{u_2^2})F_3^2 + d_{11}\sqrt{1 - \left(\frac{F_2}{d_{21}}\right)^2} + \rho g y_1 - p^{atm} \\
h_{p4}(F_4, p_{mixer}) &= -a_4 F_4^2 + \rho g y_2 - p_{mixer} \\
h_{p5}(F_5, p_{mixer}) &= -(a_5 + \frac{b_3}{u_3^2})F_5^2 + p_5^{up} - p_{mixer} \\
h_{p6}(F_6, p_{mixer}) &= -a_6 F_6^2 + d_{12}\sqrt{1 - \left(\frac{F_6}{d_{22}}\right)^2} + p_{mixer} - y_3 \\
&\vdots
\end{aligned}$$

In this system there is one unknown pressure variable p_{mixer} in the mixer. The flow constrains from mixers and dividers (3.1d) are

$$h_{m1}(F) = F_4 + F_5 - F_6 \tag{5.3a}$$
$$h_{m2}(F) = F_6 - F_7 - F_8 \tag{5.3b}$$
$$h_{m3}(F) = F_8 - F_9 - F_{10}. \tag{5.3c}$$

5.1.3 Simulation software

To simulate the system *gPROMs* [8] has been used. gPROMs is an object-oriented simulation software. With gPROMs the system have been simulated and different faults have been introduced. To simulate disturbances and model faults band limited noise have been added to the output.

5.2 Direct extracting of consistency equations

As described in section 4.1 the direct method is to from the model equations directly eliminate the unknown variables. The elimination is achieved when Gröbner bases are calculated.

Table 5.4: Fault modes for stock preparation and broke treatment system.

"New" fault mode	Included fault modes
$\mathcal{F}_{4,5,6}$	$\{\mathcal{F}_4^a, \mathcal{F}_5^a, \mathcal{F}_6^a, \mathcal{F}_3^u, \mathcal{F}_2^d, \mathcal{F}_2^y, \mathcal{F}_3^y\}$
$\mathcal{F}_1$	$\{\mathcal{F}_1^a\}$
$\mathcal{F}_2$	$\{\mathcal{F}_2^a, \mathcal{F}_1^u\}$
$\mathcal{F}_3$	$\{\mathcal{F}_3^a, \mathcal{F}_2^u, \mathcal{F}_1^d, \mathcal{F}_1^y\}$
$\mathcal{F}_7$	$\{\mathcal{F}_7^a, \mathcal{F}_4^u, \mathcal{F}_3^y\}$
$\mathcal{F}_8$	$\{\mathcal{F}_8^a, \mathcal{F}_5^u, \mathcal{F}_3^y, \mathcal{F}_4^y\}$
$\mathcal{F}_9$	$\{\mathcal{F}_9^a, \mathcal{F}_4^y\}$
$\mathcal{F}_{10}$	$\{\mathcal{F}_{10}^a, \mathcal{F}_6^u, \mathcal{F}_4^y\}$
$\mathcal{F}_{y5}$	$\{\mathcal{F}_5^y\}$

This direct method has been tried on the stock preparation and broke treatment system. However, it has not been possible to calculate the Gröbner bases. The reason for this is that the model equations are so complex that the computation load becomes extremely high. Only if a very limited part of the system was used, it was possible to calculate the Gröbner bases, resulting in almost useless consistency relations.

5.3 Find flows to extract consistency relations

As described in section 4.2 the flow method is to first calculate the flow. When the flow is known the consistency relations can be calculated from the equations not used to find the flows.

5.3.1 Fault modes

As is described in section 4.2.4 there will be new fault modes. In this system there will be 9 different fault modes. Table 5.4 defines the "new" fault modes. Figure 5.2 shows the system with the fault modes marked.

5.3.2 Flows

As described in section 4.2 the first problem to solve is to find analytic or numeric expressions for all flows. For all flows, with exception of F_4, F_5 and F_6, an expression for the flows can be found analytically. To find the flows matlab's [9] *solve* function from the symbolic toolbox

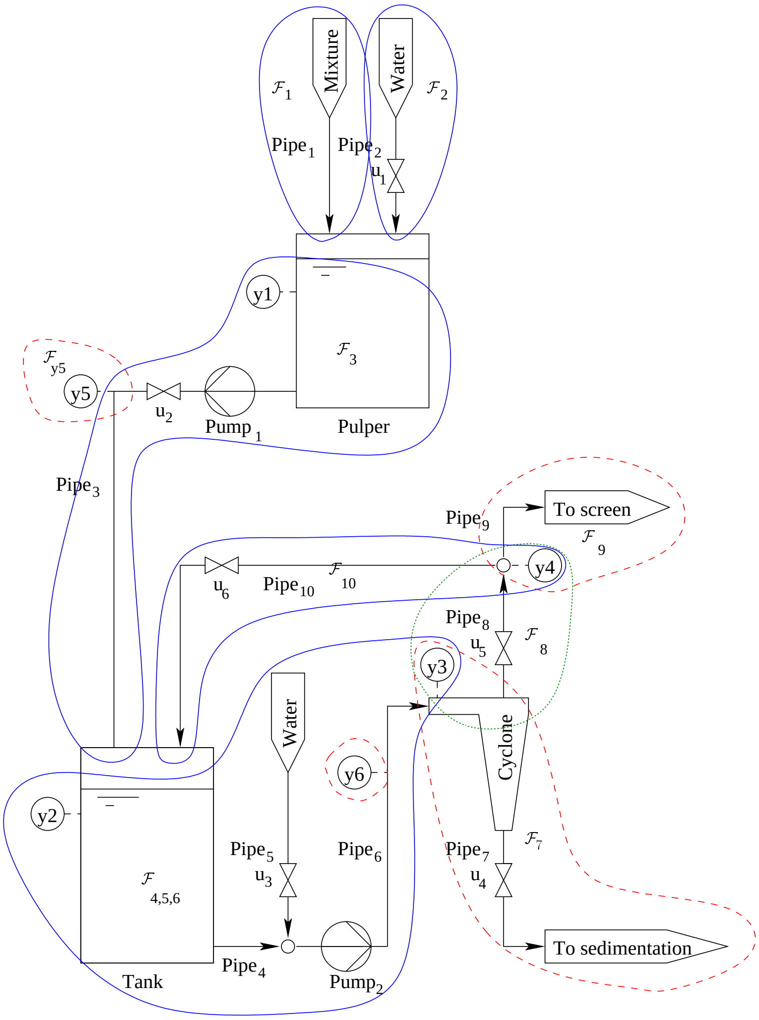

Figure 5.2: Fault modes for stock preparation and broke treatment system.

is used,

$$\begin{aligned}
F_1 &= 0.22607 \\
F_2 &= 4\,\frac{\sqrt{315760\,u_1{}^2 + 16774750}u_1}{1280\,u_1{}^2 + 68000} \\
F_3 &= 1/25\,\sqrt{5}\sqrt{\frac{-6250\,u_2{}^2 + 19907\,y_1 + 316170\,y_1\,u_2{}^2 + 50\,\sqrt{\alpha}}{72900\,u_2{}^4 + 9180\,u_2{}^2 + 289}}u_2 \\
&\vdots
\end{aligned}$$

where

$$\begin{aligned}
\alpha &= 45578125\,u_2{}^4 - 99535\,y_1\,u_2{}^2 - 1580850\,u_2{}^4 y_1 + \\
&+ 5737500\,u_2{}^2 + 180625.
\end{aligned}$$

The flows above are easy to calculate. It is however not so easy to find expressions for F_4, F_5 and F_6 excluding p_{mixer}. To be able to find an expression for the flows only including known variables, p_{mixer} has to be eliminated. This sub problem has four unknowns and three equations, which mean that one extra equation has to be used. The extra equation is of course the mixer equation (5.3a). The flows into the mixer are too complex to be solved explicitly and therefore they have to be solved numerically. This can be done in several different ways. All equations can be solved numerically with the matlab function *fsolve*[1]. Another solution is first to simplify the equations by finding analytic expressions for one or several of the flows, then solve the remaining equations numerically. In this example, the second method has been used because it gives the fastest computations. First F_4 and F_5 have been solved analytically,

$$\begin{aligned}
F_4 &= F_6 - F_5 \\
F_5 &= 1/2\,\frac{-3000\,F_6\,u_3 + 20\,\sqrt{\beta}}{278500\,u_3{}^2 + 1700000}u_3
\end{aligned}$$

where

$$\begin{aligned}
\beta &= 4200000\,F_6{}^2 u_3{}^2 + 93784875\,u_3{}^2 - 26089880\,y_2\,u_3{}^2 + 572475000 + \\
&+ 25500000\,F_6{}^2 - 159256000\,y_2.
\end{aligned}$$

Left to be solved is a very complex function $\xi(F_6, u_3, y_2, y_3) = 0$. This equation is solved numerically. This shows that it is, for this example, possible to find expressions for all flows. Thereby elimination of all unknown variables has been achieved.

[1]The function fsolve takes one or several equations and solve these equations numerically w.r.t. the unknown variable or variables.

Remark: It would in this example be possible to solve *all* equations numerically to find F. fsolve is however relatively slow so to get a acceptable fast system the flows are solved analytically. There is also a risk that fsolve degenerates.

5.3.3 Basic consistency relations

The equations used to form the basic consistency relations (4.2) are (5.1,5.2,5.3b) and (5.3c),

$$
\begin{aligned}
e = & \{30\dot{y}_1 - F_1 - F_2 + F_3, \\
& , 40\dot{y}_2 - F_3 - F_{10} + F_4, \\
& , 30000\dot{y}_5 y_1 - F_1(57 - 1000y_5) - F_2(1 - 1000y_5), \\
& , F_6 - F_7 - F_8, \\
& , F_8 - F_9 - F_{10}\}.
\end{aligned}
$$

The mixer equation is excluded because it is used in solving the flows (for all times it will be logical true).

5.3.4 Gröbner bases

To find a good isolation structure 10 different Gröbner bases are calculated. In each base, a different flow is eliminated. Maple's *gbases* function from the *Groebner* package are used to calculate the bases. The ordering is chosen as *lexdeg* (see section 2.2) where

$$
\begin{aligned}
v &= F_i \\
w &= \{\dot{y}_1, \dots\}.
\end{aligned}
$$

This means that the Gröbner base will if possible eliminate F_i first,

$$\gamma_i = \text{gbases}(e, \text{lexdeg}(\{F_i\}, \{\dot{y}_1, \dots\})).$$

The complete set of consistency relations (4.4) is

$$\Gamma = \bigcup_i \gamma_i \cup \bigcup_i e_i.$$

Maple gives Γ with dimension 14. This means that there are 14 consistency relations that can be used to construct residuals.

5.3.5 Choosing consistency relations

As is said in section 4.3.1 consistency relations that are very complex can be removed since they will be almost useless. In this example

$\Gamma_{5,6,8,14}$ are found to be very complex and are therefore removed. The consistency relations that will be used are

$$\begin{aligned}
\Gamma_1 &= F_8 - F_9 - F_{10} \\
\Gamma_2 &= F_6 - F_7 - F_8 \\
\Gamma_3 &= 300000\,\dot{y}_5\,y_1 - F_1\,(570 - 10000\,y_5) - F_2\,(10 - 10000\,y_5) \\
\Gamma_4 &= -40\,\dot{y}_2 + F_3 - F_4 + F_6 - F_7 - F_9 \\
\Gamma_7 &= 1000\,F_3\,y_5 - 30\,\dot{y}_1 + 30000\,y_5\,\dot{y}_1 - 56\,F_1 + 30000\,\dot{y}_5\,y_1 - F_3 \\
\Gamma_9 &= -57\,F_3 + 1000\,F_3\,y_5 + 56\,F_2 - 1710\,\dot{y}_1 + 30000\,y_5\,\dot{y}_1 + \\
&+ 30000\,\dot{y}_5\,y_1 \\
\Gamma_{10} &= 30\,\dot{y}_1 - F_1 - F_2 + F_3 \\
\Gamma_{11} &= 40\,\dot{y}_2 - F_3 - F_{10} + F_4 \\
\Gamma_{12} &= -40\,\dot{y}_2 + 40000\,y_5\,\dot{y}_2 - 30\,\dot{y}_1 + 30000\,y_5\,\dot{y}_1 - 56\,F_1 + F_{10} - \\
&- 1000\,y_5\,F_{10} - F_4 + 1000\,y_5\,F_4 + 30000\,\dot{y}_5\,y_1 \\
\Gamma_{13} &= F_9 + F_{10} - F_6 + F_7
\end{aligned}$$

5.3.6 Residuals, tests and hypothesis tests

The residuals r_i are formed as the floating mean square value of the consistency relations

$$r_i(t) = \frac{1}{\tau}\int_{t-\tau}^{t} \Gamma_i^2 dt,$$

where τ shall be chosen so that disturbances are eliminated and faults detected. Simulations shows that $\tau = 375$ s gives a good result. Normalized residuals are used to form the tests

$$T_i(t) = \frac{1}{J_i} r_i(t).$$

The thresholds shall be chosen so the risk for false alarm and missed detection is small. The thresholds J_i are chosen so that $\max(T_i) < 0.4$ for a fault free simulation. The hypothesis test is

$$\delta_i(t) \quad : \quad T_i(t) > 1.$$

5.3.7 Decision structure

Directly from the consistency relations, the influence and thereby the decision structure can be found. Table 5.5 shows the decision structure.

Table 5.5: Decision structure for stock preparation and broke treatment system (“0”:s have been excluded for typographic reasons).

	Fault mode									
	$\mathcal{NF}$	$\mathcal{F}_{4,5,6}$	$\mathcal{F}_1$	$\mathcal{F}_2$	$\mathcal{F}_3$	$\mathcal{F}_7$	$\mathcal{F}_8$	$\mathcal{F}_9$	$\mathcal{F}_{10}$	$\mathcal{F}_{y5}$
δ_1							X	X	X	
δ_2		X				X	X			
δ_3			X	X						X
δ_4		X			X	X		X		
δ_7			X		X					X
δ_9				X	X					X
δ_{10}			X	X	X					
δ_{11}		X			X				X	
δ_{12}		X	X						X	X
δ_{13}		X				X		X	X	

5.3.8 Testing the diagnostic system

This section will present the results from three different simulations. The first will be simulated with a clogging in pipe 4. The second will have a fault in sensor y_5. Finally, the third will have a fault in actuator u_6.

Clogging of pipe 4

The clogging of pipe 4 (f_4^a) belongs to fault mode $\mathcal{F}_{4,5,6}$. The fault will be introduced at time 1600 s and reach its maximum at time 2300 s. The clogging will reduce the flow through the pipe with approximately 15%. Figure 5.3 show the flow $4, 5, 6$ and 7 where the solid line is the flow calculated from the sensors and the dashed line is the true flow. The fault is the difference between these flows. Figure 5.4 shows all tests, the tests that exceed the thresholds are marked.. Figure 5.5 show the decision, in the figure, the fault modes are plotted against the time. At time 1900 s the fault is detected. At time 3000 s the fault is isolated. This example shows a successful detection and isolation. Note that the isolation is done after a considerable time lap.

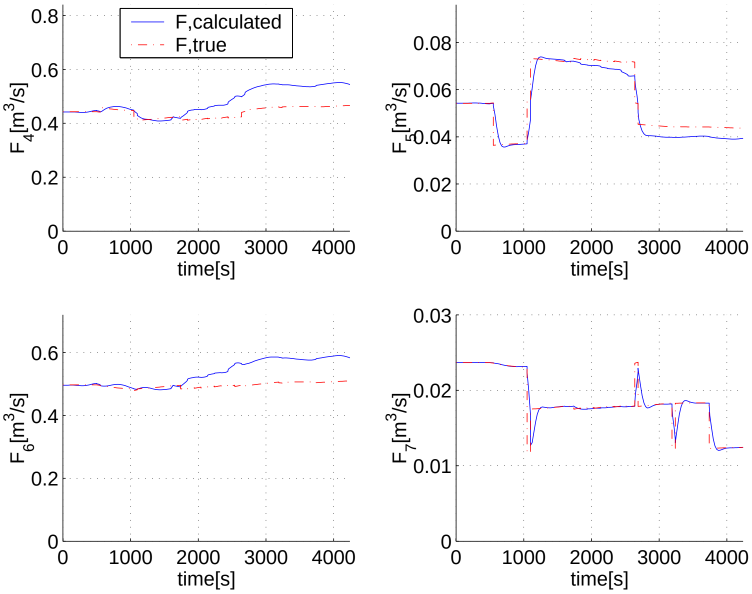

Figure 5.3: Flow in pipe $4, 5, 6$ and 7 for clogging in pipe 4. (Solid for calculated and dashed for true flow).

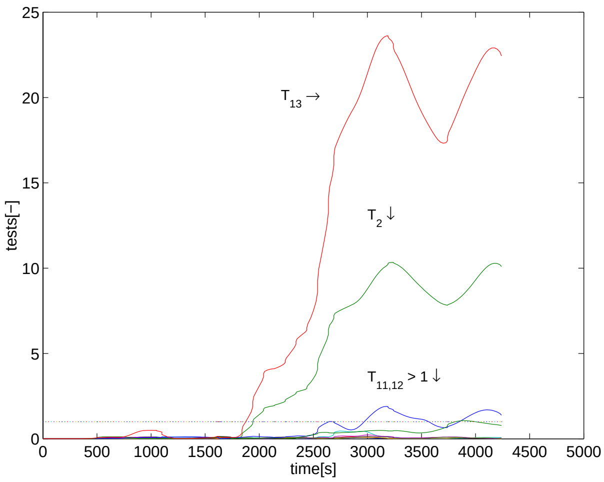

Figure 5.4: Tests for clogging in pipe 4.

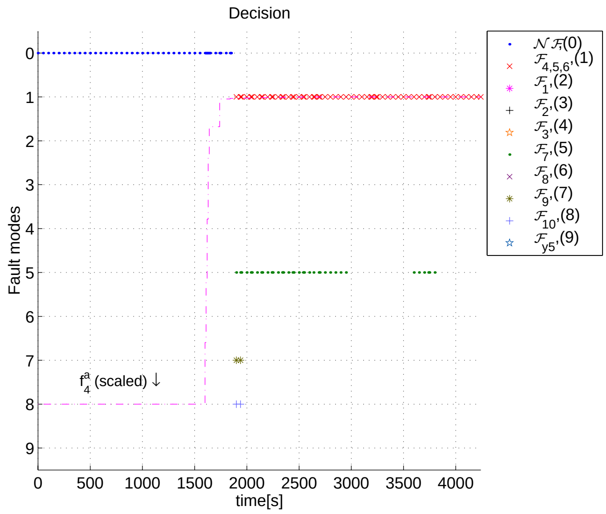

Figure 5.5: Decision for clogging in pipe 4.

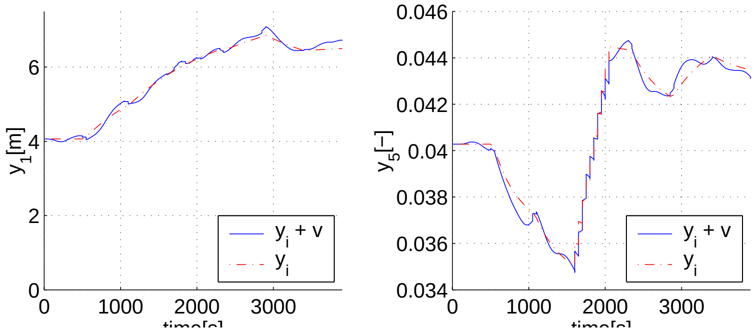

Figure 5.6: Sensor values for y_1 and y_5 for fault in sensor y_5.

Fault in sensor y_5

The fault in sensor y_5 (f_5^y) belongs to fault mode $\mathcal{F}_{y5}$. The fault is introduced at 1600 s and reaches maximum at 2050 s. The fault is 1% at its maximum. Figure 5.6 shows sensor y_1 and y_5. In the figure, dashed lines are the simulated value. The solid line is simulated value with band limited noise. The fault can bee seen in the figure as the fast increase of y_5 at time 1600 s. Figure 5.7 shows how the tests reacts to the fault. Figure 5.8 shows the diagnostic decision. At time 1800 s the fault is detected. At time 2025 s the fault is isolated. This example shows a successful detection and isolation.

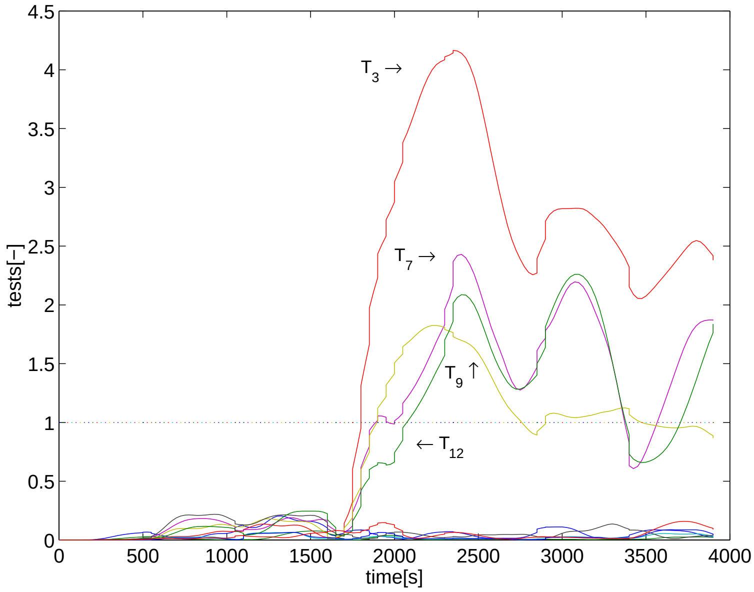

Figure 5.7: Tests for fault in sensor y_5.

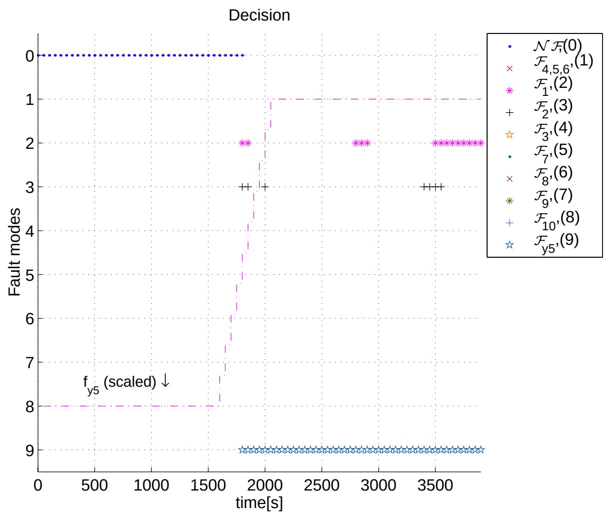

Figure 5.8: Decision for fault in sensor y_5.

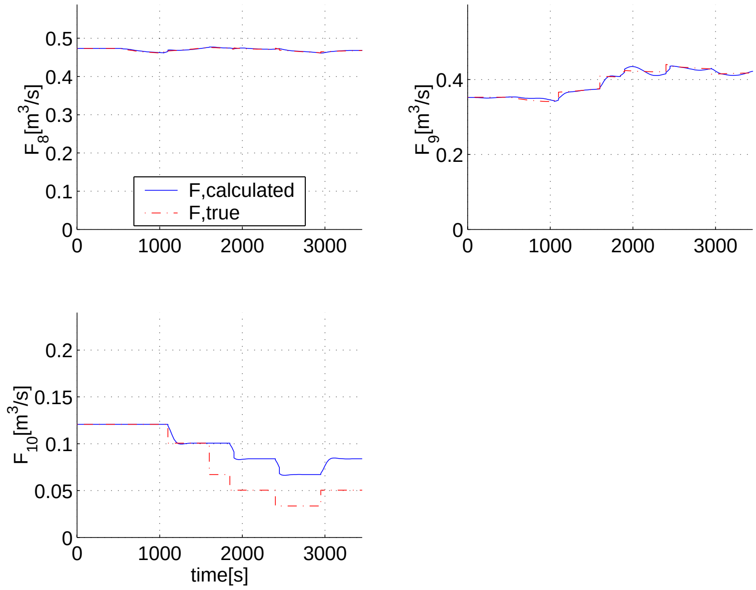

Figure 5.9: Flow in pipe 8,9 and 10 for fault in actuator u_6. (Solid for calculated and dashed for true flow).

Fault in actuator u_6

The fault in actuator u_6 (f_6^u) belongs to fault mode $\mathcal{F}_{10}$. The fault is introduced at time 1600 s with a value of -0.1 decreasing the actuator with 1/3. The result is a decrease of approximate 1/3 of the flow through the valve. Figure 5.9 shows F_8, F_9 and F_{10} where the solid line is the flow calculated from the sensors and the dashed line is the true flow through the pipe. The fault is the difference between the flows. Figure 5.10 shows all tests and figure 5.11 shows the decision. At time 1750 s the fault is detected and is isolated to fault mode $\mathcal{F}_{10}$ or $\mathcal{F}_{y5}$. This example shows a successful detection but an unsuccessful isolation.

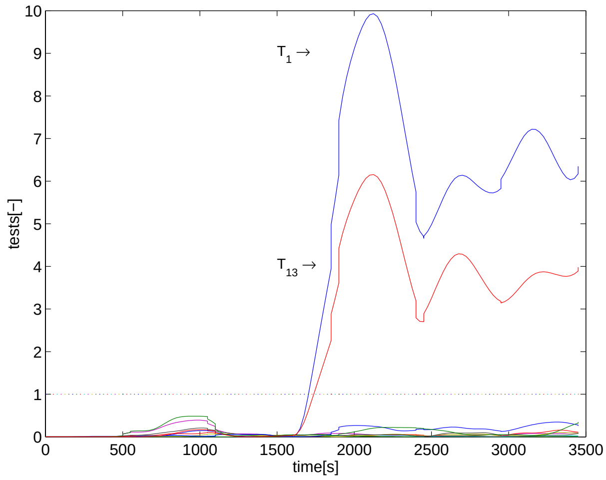

Figure 5.10: Tests for fault in actuator u_6.

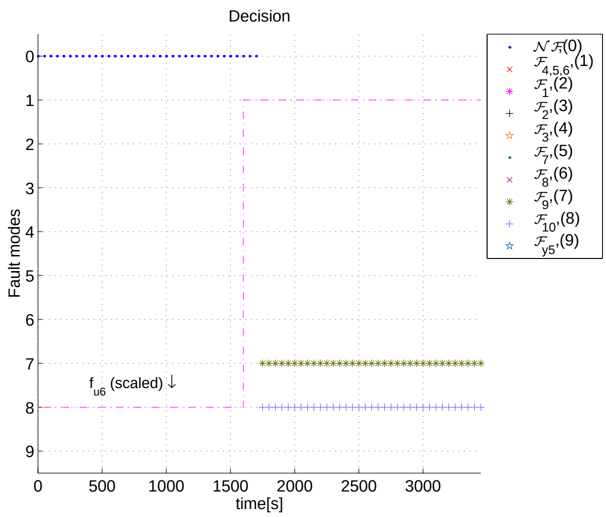

Figure 5.11: Decision for fault in actuator u_6.

Chapter 6

Conclusions and topics for further studies

6.1 Conclusions

General models for fluid systems have been presented. The models simulate slow dynamics based on object-oriented sub-models. The sub-models consists of tanks, pipes, control valves, pumps, mixers and dividers.

The diagnostic systems are based on hypothesis tests and decision structures. The hypothesis tests are formed as tests with thresholds. The tests are constructed as normalized residuals. Consistency relations are used to construct the residuals.

To find the consistency relations, two different methods are presented. The first directly eliminates the unknown variables through calculations of Gröbner bases. The negative aspect with this method is that it is extremely computer intense and can not be used for large systems. The positive aspect is that it might be possible to isolate all fault modes. The second method avoids this problem by reducing the number of fault modes. First, the flows are calculated, then the remaining equations are used to construct consistency relations. Multiple Gröbner bases are calculated where the flows are eliminated in order to gain a good decision. The negative aspect with this method is the reduced possibility to isolate faults. The positive aspect is that it can be used for large systems.

The methods presented are used to construct diagnostic systems for a part of a paper mill, a stock preparation and broke treatment system. The direct method fails to extract consistency relations, because of the complexity of the system. The flow method successfully constructs a diagnostic system. Three different simulations including three different faults corresponding to three different fault modes are presented. The diagnostic system constructed with the flow method successfully detects the three faults. One of the simulations achieves a partial isolation. In the two other simulations isolation of the fault mode are achieved.

Fulfilled objectives

The objectives for the diagnostic method was that it should be *easy to adapt for a specific system*. Partially the flow method fulfills this objective. The objectives for the diagnostic system was that it should be able to *detect all faults*, *isolate all faults* and *be robust*. The first objective is fulfilled. The second objective is fulfilled partially. It is only possible to isolate the fault to a limited area. The system is robust against disturbances, which means that the third objective is fulfilled.

6.2 Further studies

Identification: In this report it has been assumed that the model has been identified. To be able to test the diagnostic system in a real system the identification has to be done.

Thresholds: In the report the thresholds was decided through simulations. In a real system, the thresholds have to be calculated based on disturbances and model faults. If it is possible to find approximate values for the disturbances and model faults, it might be possible to decide the thresholds. It might even be possible to decide optimal thresholds, based on the probability for false alarm and missed detection.

Isolation: High thresholds will reduce the probability to detect and isolate faults. It is however not clear when the isolation will be reduced.

Sub-problem: Since the problem with the direct method to extract consistency relations are the complex equations, it would be interesting to see if it would be possible to divide the problem into sub-problems that can be solved. A trivial example of this is a model consisting of several sub-models not connected to each other. However, even if the sub-models are connected it might be possible to divide them into distinct parts.

Gröbner bases: Gröbner bases are used to achieve a decision structure that might isolate all fault modes. However, it is not shown in the report that this is necessary for a general model. It might exist much simpler methods to achieve a good decision structure from the basic consistency relations.

Extra tests: Expansion of the diagnostic system can easily be achieved. E.g. the diagnostic system can be expanded with more tests and fault modes, e.g. observers for sensors.

Concentration sensor y_6: It is in the report said that it is very difficult to diagnosis concentration sensor y_6. However, it is not shown how difficult it is. It might still be possible to diagnosis the sensor, e.g. an observer that gives an approximation of the concentration in pipe 6.

Flow derivatives: In section 5.1.1 it is said that a consistency relation including concentration sensor y_6 can be found. The problem was that this consistency relation would include flow derivatives. By expanding the methods to include the flow derivatives, more faults can be detected and isolated.

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Notation

Symbols used in the report.

Variables and parameters

L	Fluid level in tank
$\chi^{in/out}$	Concentration of paper fiber *in* or *out* of the part
$p^{up/down}$	Pressure *up* or *down* stream of the part
Δp	Pressure difference between p^{down} and p^{up}
A	Tank cross-section area
a	Pipe friction
b	Valve parameter
d_1	Maximal pump pressure increase
d_2	Maximal pump flow
F_i	Flow through pipe i
y	Sensor output from system
u	Actuator input to system
v	Unknown disturbances
w	Known disturbances
g	Gravitational constant
p^{atm}	Atmospheric normal pressure
ρ	Density

Fault and fault mode

f^a	Friction fault in pipe
f^d	Fault in pump
f^u	Actuator fault
f^y	Sensor fault
$\mathcal{F}_x$	Fault mode

Symbols

r_i	Residual i
T_i	Test i
δ_i	Hypothesis test i
S_i	Sub-decision i
S	Decision

Operators

$\alpha \succ \beta$	α has higher priority than β
$A \subseteq B$	set A is a subset or equal to set B
$\lvert A\rvert$	Number of elements of the set A
$dim(a)$	Dimension of list a

Appendix A

Semi-automatic construction of diagnostic systems

This chapter will describe the semi-automatic construction of diagnostic systems from the methods presented chapter 4. It is the *flow method* that will be implemented. The reason for this is that only this method has been possible to implement.

To be able to use the algorithm the following assumptions are made:

- All physical parameters are known including the parameters connecting the system to the environment. This is a reasonable but not an easy fulfilled demand;
- There are level sensors in all tanks;
- Concentration sensors are only placed in tanks (or in the pipes leading from the tanks);
- There are no sensors measuring the flows.

The algorithm is as follows:

1. The user writes the characteristics for the system to a file. This file shall include information about pipes, tanks, connections and sensors.
2. From the user supplied information, model equations are calculated. The model equations include pressure-loops for all pipes, flow equilibrium in mixers and dividers, volume changes and concentration changes in tanks.

3. All sensors are introduced to the model.
4. Find, if possible, analytic expressions for all flows, with the help of the corresponding equations. This will be possible for all pipes where the start and end pressure is known through sensors.
5. If there are flows that are unknown because there are unknown pressure variables, prompt the user to supply an algorithm that finds expressions for the unknown flows. This can be done through analytic or numeric algorithms.
6. From the model the algorithm will now have found basic consistency relations that can be used to calculate the Gröbner bases. Gröbner bases are calculated where the flows are eliminated in order, to find a good influence structure and thereby a good decision structure.
7. Construct residuals as floating mean square values of consistency relations.
8. The tests are constructed as normalized residuals.
9. Find the decision structure and present the diagnostic system to the user.
10. The user evaluates the system.

The algorithm will use maple to find the Gröbner bases and matlab for the remaining algorithm.

Appendix B

Comparison, complete and simplified model

This chapter gives a short comparison between the model developed by ABB and the simplified model that are used to construct diagnostic systems in this report. The major difference between the models is that in the simplified model, it is assumed that density, enthalpy and molar mass is constant.

Figure B.1 shows a comparison between the complex model, lined, and the simplified model, dashed, for the stock preparation and broke treatment system in chapter 5. As is seen in the figure the deviation of the simplified system is very small.

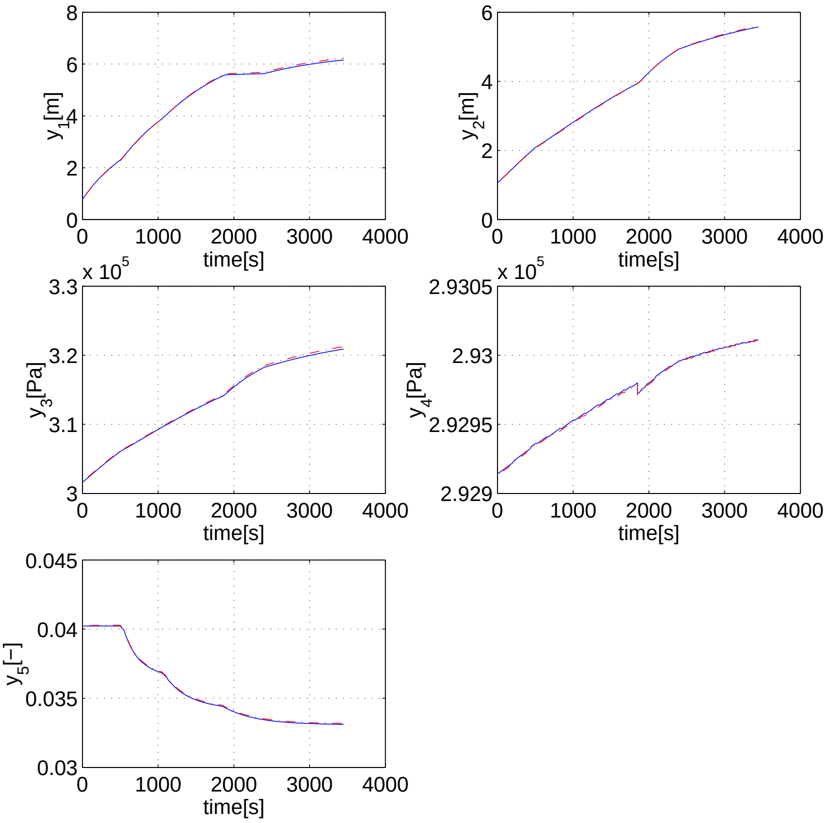

Figure B.1: Plots for sensor values for the stock preparation and broke treatment system. Dashed line simplified model.