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System Identification and Control of a Thermo-Mechanical Pulping Refiner

by

Gary Chang. Bsc Mech. Eng.

A thesis submitted to
the Faculty of Graduate Studies and Research
in Partial fulfillment of
the requirements for the degree of

Masters of Science in Information and System Science

Department of System and Computer Engineering
Carleton University
Ottawa, Ontario, Canada
November 6th, 1995

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of a Thermo-Mechanical Pulping Refiner**

submitted by
Gary Chang, B. Sc. Mech. Eng.
in partial fulfilment of the requirements
for the degree of Masters of Science in
Information and System Science

Chair, Department of Systems and Computer Engineering

Professor H. M. Schwartz,
Thesis Supervisor

Carleton University
November 6th, 1995

Abstract

The research work involves the modelling, simulation, and control of a Thermo-mechanical pulping (TMP) process. The main component of this process is the TMP refiner. Experiments were run and data was collected from the refiner. The least squares identification technique and the Hooke and Jeeves algorithm were used to fit the process models to the collected data. One of the main relationships identified is the refiner's motor load relationship as a function of the production rate, the infeed dilution water flow rate, and the plate gap settings. This was then used to define the pulp properties, Canadian standard freeness (CSF), long fibre content (lfc), and shive content (shive) as functions of the input variables. Once the model was identified two control strategies are presented, one that uses the models to define control limits on the input variables so that it can be used as a prediction guide by the operators to do set point control. The other method is an adaptive control algorithm which will change the input variables automatically to compensate for the changing parameters in the model due to disturbances.

Acknowledgements

Completion of this study was only possible with the help of a number of individuals. The resources they provided, the guidance and support was priceless.

First of all I want to thank my supervisor, Professor H. M. Schwartz for guiding me throughout this project. His support and help is much appreciated.

I would like to thank Mr. Trung Phung, an engineer at the Avenor paper mill, for taking the time to collect data for me, and also for helping me understand the process. I also would like to thank the management of the Avenor Paper mill for allowing me to do this project on their refiner.

I am also thankful to Zaryab Hamavand, Kenny Sui, Reza Javanbakht, and Hamideh Mostafavi for their support and encouragement, that gave me motivation to complete this thesis.

Dedication

To my family, my mother Baby Chang, my two brothers, Byron Chang
and Tyrone Chang, and my sister Rosalie Chang, the people who
have the most faith in me and who stood by me always.

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Chapter 1

Introduction

1.1 Background

Woodpulp can be manufactured by a number of various methods, specifically chemical and mechanical methods. This work focuses on a specific method of chip mechanical pulping. Pollution problems, and the need to conserve natural resources, have been the main factors that have led manufacturers to eliminate chemical pulping from the production of newsprint pulp.

The main component in the thermo-mechanical pulping process is the refiner. The refiners are characterized as disc refiners which can either be single disc or double disc. The refiner plate can also be either conical or flat shaped. Figure 1.1 [13] shows a side view of a single disc conical shaped refiner which is similar to the refiners that this research was done on. Single disc refiners have one rotating disc and one stationary one and double disc refiners have two counter rotating discs. As the need for larger capacity machines developed, the diameters of the flat plate refiners kept increasing. There is a limit however to the diameters of the disc in flat plate refiners because of mechanical and stability restrictions. The conical plate refiners then emerged to eliminate this limitation. The outer refining zone of the refiner is turned through

Figure 1.1: Side view of refiner RGP-76 CD

an angle of 75 degrees in relation to the flat zone, thus forming an outer conical zone (Figure 1.2). This conical plate refiner will have an active refining surface area equivalent to a flat plate refiner of a much larger outer diameter, but it will operate at a much lower peripheral velocity.

1.2 Process description

The TMP process is best described with the help of the schematic diagram in Figure 1.3. The chips enter the metering screw which feeds the preheater plug screw feeder. The chips then fall into the pressurized preheater. At the bottom of the preheater there is discharge screw which is equipped with an agitator to ensure uniform filling of the screw. From the discharge screw the chips are then transferred by the plug screw feeder and the side screw feeder to the refiner inlet screw feeder. From the infeed screw the chips are fed between the primary refiner plates, where they are ground to a refined pulp. The pulp then enters the refiner housing where it is blown through the blow line into the cyclone. The primary refiner housing pressure is controlled by a ball valve on the cyclone steam discharge line. In the cyclone the pulp is separated

Figure 1.2: Conical shape of refiner plates

Figure 1.3: Schematic diagram of Pulp Milling System

from the steam and falls into the lower section of the cyclone.

From the primary cyclone discharge screw the pulp is continuously fed to the secondary refiner side feed screw. The pulp is then further refined between the secondary refiner's plate and then it is blown from the secondary refiner casing through the secondary refiner blow line to the secondary cyclone. The pulp is then diluted with large quantities of water prior to the latency removal in the latency chest. The secondary refiner casing pressure is controlled by a blow valve on the blow line. From the latency chest samples are directed to the pulp quality monitor (PQM) where pulp quality test are done.

1.3 Previous work

Thermo-mechanical pulping is a process by which wood chips are subjected to both mechanical and thermodynamic forces set up between the discs. Equations developed by Miles and May [1] describing the flow of pulp in the refining zone were developed from the perspective of analyzing the forces that impact on the pulp in the refining zone. Relationships for the pulp velocity, steam velocity, residence time, pressure gradients, and refining intensity were all developed. Also in their model they considered the chips to flow through the refiner as a continuous medium. The residence time (time chips spend in refining zone) of the chips then has a unique value for a given set of operating conditions. However from their work if the set points in the operating variables change, the residence time will change. These models could not be used for this work because the variables in the models were not available for measurement.

In this work the concepts put forward by Fan and Jeffrey [2] are used. They suggest that the chips do not form a continuous medium in the refiner. Instead they form discrete flocs. These flocs do not have a permanent identity, but rather they break up and re-form continuously.

1.4 System Identification Of a TMP refiner

The concept that the pulp forms flocs in the refining zone is considered. The flocs are then blown through the blow line from the refiner housing by the steam generated in the refiner. The steam velocity is assumed to be primarily a function of the refiner chamber pressure. Throughout the experimentation this pressure was maintained constant. With constant chamber pressure the steam velocity is a constant so the average velocity of the pulp through the refiner is a constant and thus the average residence time is also constant. It is then postulated that it is the number of wood fibers in the refining zone that affects the refiner's motor load. Also, regardless of the amount of time the chip spends in the refining zone, what is important is the amount of impact the chip makes with the plates in the refining zone. The main focus is then placed on the number of wood fibers in the refining zone and the ratio of the refining surface area to the volume of the refining zone. It is clear that the refining surface area is a constant for the particular refiner plate design.

The particular system for which this work was done is a two stage thermo-mechanical pulping process, which incorporates two conical plate refiners, primary and secondary. Keeping the above concepts in mind, the motor load for each refiner stage was modeled as a function of the production rate, the infeed dilution water flow rate and the refiner plate gaps, which are the inputs to that particular refiner. The relationship for the outlet consistency of each refining stage was obtained by performing a mass and energy balance across each refiner. Important output variables in the control problem are the Canadian Standard Freeness, the long fiber content, and the shive content and it has been shown [3][15][16] that these variables have good correlation with specific energy. Specific energy however, is a function of the motor load, thus the output variables can be found as functions of the operating variables, that is production rate, infeed dilution water flow rate, and plate gap.

1.5 About this Thesis

The objective of this research is to develop a model of the thermo-mechanical pulping process that would be suitable for closed loop control and as a guide for the plant operators. The goal is to relate the output pulp properties of CSF, shive content, and long fibre content to the control variables. The model parameters are to be identified from the available data as measured by the distributed control system and the pulp quality monitor (PQM).

The thesis has 7 chapters, with chapter 1 being the introduction. Chapter 2 looks at the system identification techniques used in the research work. Chapter 3 deals with the analytical models of the system. The refiner models for outlet consistency, motor load, and the relationship between the operating variables and the pulp property measures are all derived for both the secondary and primary refining stages. Greater detail on the derivation of these models will be looked at in this chapter. Chapter 4 deals with the collection of data and the experiments that were done in order to collect the data sets to model the system. Chapter 5 presents the fitting of the data to the defined models. The algorithms used to fit the data is given in brief and the statistical properties are examined. Chapter 6 deals with some preliminary results on controlling the refiners to achieve the desired output variables set point. An operator's guide is looked at and an adaptive control algorithm is also discussed whereby the operating variables are adjusted automatically in order to compensate for the time varying effect of plate wear on the motor load. The final chapter, chapter 7, is the conclusion.

Chapter 2

System Identification Algorithms

The problem of system identification is generally referred to as the determination of a mathematical model for a system or process by observing its output-input relationships [5]. The purpose of this chapter is then to present the basic theory of the system identification techniques used in this research. The identification problem can be represented as shown in Figure 2.1 in which the input-output data are measured and collected. A system identification technique is then applied to the data to yield the model of the system. The system identification problem can be classified into two categories, based on the degree of prior knowledge on the system:

1. Complete identification: this occurs when we know very little about the system to be identified. Basic properties such as whether the system is nonlinear or linear are unknown. This is obviously a very difficult problem to solve. Usually some assumptions are made before any kind of solution is obtained. This type of problem is referred to as a black box problem.
2. Partial identification: In this category some basic characteristics of the system are known. It is often possible to derive a mathematical model of the system where the only problem is to identify a set of parameters in the model equations.

Figure 2.1: Block Diagram Representation of the System Identification Problem

This type of identification is known as gray box identification. The modeling problem then is one of parameter identification.

There are a number of well known parameter identification techniques that have successfully been applied to the identification problem. They include maximum likelihood, least squares, cross-correlation, instrumental variable, and stochastic approximation. Other techniques include those for nonlinear optimization such as the Hooke and Jeeves algorithm. The least squares method and the Hooke and Jeeves algorithm are the two techniques used in this work.

2.1 The Least Squares Algorithm

The least squares technique [5][6] provides a mathematical procedure by which a model can achieve a best fit to experimental data in the sense of minimum squared error. Given a variable y which is related linearly to a set of m variables $x = (x_1, x_2, \dots, x_m)$, the following relationship holds

$$y = \theta_1 x_1 + \theta_2 x_2 + \dots + \theta_m x_m, \quad (2.1)$$

where $\Theta = (\theta_1, \theta_2, \dots, \theta_m)$ is a set of constant unknown parameters. Thus it is desired to estimate the values of Θ by observing the variables y and x at different times. The block diagram in Figure 2.2 best depicts the idea. A sequence of n observations are made on the variables y and x at various times $t_1, t_2, t_3, \dots, t_n$. The observation at any time i will be $y(i)$ and $x(i)$. The data can now be related by a set of n linear equations:

$$y(i) = \theta_1 x_1(i) + \theta_2 x_2(i) + \dots + \theta_m x_m(i) \quad (2.2)$$

where $i = 1, 2, \dots, n$. The equations above are generally known as regression functions and the parameters Θ are known as the regressors. The system of equations can be

Figure 2.2: An m -parameter linear system

represented in matrix form as:

$$Y = X\Theta \quad (2.3)$$

To estimate the m parameters of Θ it is necessary that $n \geq m$. If however $n = m$, then a unique solution can be found by:

$$\Theta = X^{-1}Y, \quad (2.4)$$

provided that the inverse of X exists. When $n > m$, it is generally not possible to determine a set Θ exactly satisfying all n equations because the data may be complicated by random measurement noise, error in the model, or a combination of both. The alternative then is to determine Θ on the basis of least squared errors. An error vector $\mathbf{e} = (e_1, e_2, e_3, \dots, e_n)^T$ is defined by

$$\mathbf{e} = Y - X\Theta. \quad (2.5)$$

One is to choose Θ in such a way that the criterion J

$$J = \sum_{i=1}^n e_i^2 = \mathbf{e}^T \mathbf{e} \quad (2.6)$$

is minimized. To carry out the minimization, express

$$J = (Y - X\Theta)^T(Y - X\Theta) \quad (2.7)$$

$$J = Y^T Y - \Theta^T X^T Y - Y^T X \Theta + \Theta^T X^T X \Theta \quad (2.8)$$

Differentiate J with respect to Θ and equate the result to zero to determine the condition on the estimate $\hat{\Theta}$ that minimizes J . Thus

$$\frac{\delta J}{\delta \Theta} \big|_{\Theta=\hat{\Theta}} = -2X^T Y + 2X^T X \hat{\Theta} = 0 \quad (2.9)$$

This then yields

$$X^T X \hat{\Theta} = X^T Y \quad (2.10)$$

from which $\hat{\Theta}$ can be solved as

$$\hat{\Theta} = (X^T X)^{-1} X^T Y \quad (2.11)$$

The result is called the least squares estimator of Θ . The bias of $\hat{\Theta}$ can be demonstrated by considering the following: Assuming that the expected value of the error e is 0 then the expected value of $\hat{\Theta}$ is given as:

$$E(\hat{\Theta}) = E[(X^T X)^{-1} X^T Y] \quad (2.12)$$

$$= E[(X^T X)^{-1} X^T (X\Theta + e)] \quad (2.13)$$

$$= E[(X^T X)^{-1} X^T X\Theta + (X^T X)^{-1} X^T e] \quad (2.14)$$

$$= \Theta \quad (2.15)$$

Since $(X^T X)^{-1} X^T X = I$ then $\hat{\Theta}$ is an unbiased estimator of Θ . The variances on the parameter estimates $\hat{\Theta}$ is expressed by the covariance matrix,

$$Cov(\hat{\Theta}) = E[(\hat{\Theta} - E(\hat{\Theta}))(\hat{\Theta} - E(\hat{\Theta}))^T] \quad (2.16)$$

$Cov(\hat{\Theta})$ is a $m \times m$ matrix with the j, j elements being the variance on the $\hat{\theta}_j$ parameters, and the (i, j) elements are the covariances between the $\hat{\theta}_i$ and $\hat{\theta}_j$ elements. The covariance matrix of $\hat{\Theta}$ then reduces to,

$$Cov(\hat{\Theta}) = \sigma^2 (X^T X)^{-1} \quad (2.17)$$

σ^2 is the variance on the error and is often estimated. Consider the sum of the squares of the residuals (error), SSe ,

$$SSe = \sum_{i=1}^n (y_i - \hat{y}_i)^2 \quad (2.18)$$

$$= \sum_{i=1}^n e_i^2 \quad (2.19)$$

$$= \mathbf{e}^T \mathbf{e} \quad (2.20)$$

Substituting $\mathbf{e} = Y - \hat{Y} = Y - X\hat{\Theta}$, SSe reduces to

$$SSe = Y^T Y - \hat{\Theta}^T X^T Y \quad (2.21)$$

The above equation is called the error sum of squares and has $n - m$ degrees of freedom. The mean square of the error, MSe , is

$$MSe = \frac{SSe}{n - m} \quad (2.22)$$

It can also be shown that the expected value of MSe is σ^2 , thus giving an unbiased estimator of σ^2 ,

$$\hat{\sigma}^2 = MSe \quad (2.23)$$

Therefore one can use 2.17 to determine the confidence intervals for the estimated parameters.

2.2 Hooke and Jeeves Algorithm

The Hooke and Jeeves algorithm [7] is a direct search method that locates the minimum of a function of m variables. The direct search method is one that uses the function values only. Consider a function of two variables as in Figure 2.3 [7]. The minimum of the function is (x_1^*, x_2^*) . The search path is shown as the dotted lines that lead up to the best estimate of the minimum of the function. The Hooke and

Figure 2.3: General search pattern to the minimum of a function

Jeeves algorithm consists of a sequence of exploration steps which are small perturbations from a point. If an improvement in the objective occurs then a pattern move is carried out which is a longer step in the improving direction. The algorithm can be described as the following steps,

1. Choose an initial base point b_1 and a step length h_j for each variable x_j , $j = 1, 2, \dots, m$. A fixed step length for each variable can be assigned.
2. Carry out an exploration about b_1 . The purpose of this is to acquire knowledge of the local behavior of the function. This knowledge is used to find a likely direction for the pattern move by which it is hoped to obtain an even greater reduction in the value of the function. The exploration about b_1 proceeds as indicated.
 - (a) Evaluate $f(b_1)$
 - (b) Each variable is now changed in turn, by adding the step length. Thus we evaluate $f(b_1 + h_1 e_1)$ where e_1 is a unit vector in the direction of the x_1 axis. If this reduces the function, replace b_1 by $b_1 + h_1 e_1$. If not find $f(b_1 - h_1 e_1)$ and replace b_1 by $b_1 - h_1 e_1$ if the function is reduced. If neither step gives a reduction leave b_1 unchanged and consider changes in x_2 , i.e.

find $f(b_1 + h_2 e_2)$ etc. When all m variables are considered we will have a new base point b_2 .

- (c) If $b_2 = b_1$ i.e. no function reduction occurs, then the exploration is repeated about the same base point b_1 , but with a reduced step length. Reducing the step length to one tenth of its former value appears to be satisfactory in practice.
- (d) If $b_2 \neq b_1$ we make a pattern move.

3. Pattern moves utilize the information acquired by the exploration, and accomplish the function minimization by moving in the direction of the established pattern. The procedure is as follows.

- (a) It seems sensible to move further from the base point b_2 in the direction $b_2 - b_1$ since that move has already led to a reduction in the function value. So we evaluate the function at the next pattern point.

$$P_1 = b_1 + 2(b_2 - b_1). \quad (2.24)$$

In general

$$P_i = b_i + 2(b_{i+1} - b_i) \quad (2.25)$$

- (b) Then continue with the exploratory moves about P_1 or (P_i) .
 - (c) If the lowest value at step 3(b) is less than the value at the base point b_2 (b_{i+1} in general) then a new base point b_3 (b_{i+2}) has been reached. In this case repeat 3(a). Otherwise abandon the pattern move from b_2 (b_{i+1}) and continue with an exploration about b_2 (b_{i+1}).
4. Terminate the process when the step length(s) has been reduced to a predetermined small value (tolerance value). A flow chart of the algorithm is given in Figure 2.4 and 2.5 [7]

Figure 2.4: Flow chart of the Hooke and Jeeves Algorithm: Main program

Figure 2.5: Flow chart of the Hooke and Jeeves Algorithm: Exploration

The Hooke and Jeeves algorithm was chosen because it is easy to program and it give satisfactory results without the need for calculating derivatives but other algorithms such as the Newton Raphson algorithm could have also been used. However the Hooke and Jeeves algorithm can get stuck, that is, it may stop short of a local minimum unable to make further improvements in the objective function.

2.3 Recursive Least Squares Algorithm

The theory of the recursive least squares method [5][8] will be used later in chapter 6 when a preliminary adaptive controller will be constructed to control the TMP refiner. The recursive solution procedure can be referred to as sequential or on-line estimation. If we recall that in the least squares estimation the set of n equations can be represented as:

$$Y_n = X_n \Theta \quad (2.26)$$

furthermore $\hat{\Theta}$ can be denoted as $\hat{\Theta}(n)$

$$\hat{\Theta}(n) = (X_n^T X_n)^{-1} X_n^T Y_n \quad (2.27)$$

Suppose we obtain a new equation, the $(n+1)$ th equation, and represent the solution to this new system of $n+1$ equations as:

$$\hat{\Theta}(n+1) = (X_{n+1}^T X_{n+1})^{-1} X_{n+1}^T Y_{n+1} \quad (2.28)$$

where

$$X_{n+1} = \begin{bmatrix} X(n) \\ x^T(n+1) \end{bmatrix} \quad (2.29)$$

$$x^T(n+1) = [x_1(n+1) \dots x_m(n+1)] \quad (2.30)$$

It is apparent that to obtain $\hat{\Theta}(n+1)$ an $(n+1) * (n+1)$ matrix must be inverted. But $\hat{\Theta}(n+1)$ can be found by simply updating the previous estimate $\hat{\Theta}(n)$ without

matrix inversion. The following lemma [5] is used:

lemma. Let A , C , and $A + BCD$ be nonsingular square matrices, then the following relationship holds:

$$(A + BCD)^{-1} = A^{-1} - A^{-1}B(C^{-1} + DA^{-1}B)^{-1}DA^{-1} \quad (2.31)$$

Now define a new equation:

$$P(n) = (X_n^T X_n)^{-1} \quad (2.32)$$

therefore

$$P(n+1) = (X_{n+1}^T X_{n+1})^{-1} \quad (2.33)$$

now by substituting (2.29) into (2.33) $P(n+1)$ can be rewritten as

$$P(n+1) = (P(n)^{-1} + x(n+1)x^T(n+1))^{-1} \quad (2.34)$$

$$\begin{aligned} &= P(n) - P(n)x(n+1)(1 + x^T(n+1)P(n)x(n+1))^{-1} \\ &\quad x^T(n+1)P(n) \end{aligned} \quad (2.35)$$

also

$$\hat{\Theta}(n+1) = P(n+1)(X_n^T Y_n + x(n+1)y(n+1)) \quad (2.36)$$

$$= P(n)X_n^T Y_n - P(n)x(n+1)[1 + x^T(n+1)P(n)x(n+1)]^{-1} \quad (2.37)$$

$$\begin{aligned} &x^T(n+1)P(n)X_n^T Y_n + P(n)x(n+1)y(n+1) \\ &- P(n)x(n+1)[1 + x^T(n+1)P(n)x(n+1)]^{-1} \\ &x^T(n+1)P(n)x(n+1)y(n+1) \end{aligned} \quad (2.38)$$

The last two terms can be rearranged into the form

$$\begin{aligned} &P(n)x(n+1)(1 + x^T(n+1)P(n)x(n+1))^{-1} \\ &[1 + x^T(n+1)P(n)x(n+1) - x^T(n+1)P(n)x(n+1)]y(n+1) \\ &= P(n)x(n+1)(1 + x^T(n+1)P(n)x(n+1))^{-1}y(n+1) \end{aligned} \quad (2.39)$$

But from (2.27) and (2.32) we have that

$$\hat{\Theta}(n) = P(n)X_n^T Y_n \quad (2.40)$$

Thus $\hat{\Theta}(n+1)$ can be written as

$$\hat{\Theta}(n+1) = \hat{\Theta}(n) + P(n)x(n+1)[1 + x^T(n+1)P(n)x(n+1)]^{-1}[y(n+1) - x^T(n+1)\hat{\Theta}(n)] \quad (2.41)$$

The results clearly show that the new estimate is given by the old estimate plus a correction term. The matrix $P(n)$ in the correction term can be updated by the recursive formula in (2.34). It is clear that in (2.41) the need for matrix inversion is completely eliminated and thus the computational efficiency is greatly improved when updating $\hat{\Theta}$. From the equation it can be seen that the correction term is proportional to the quantity $[y(n+1) - x^T(n+1)\hat{\Theta}(n)]$, which represents the error of fitting the previous $\hat{\Theta}(n)$ to the new data $y(n+1)$ and $x^T(n+1)$. The vector $P(n)x(n+1)[1 + x^T(n+1)P(n)x(n+1)]^{-1}$ determines how the fitting error is weighted in the correction of $\hat{\Theta}(n)$. The recursive algorithm can then be summarized by the following.

$$\hat{\Theta}(n+1) = \hat{\Theta}(n) + \gamma(n+1)P(n)x(n+1)[y(n+1) - x^T(n+1)\hat{\Theta}(n)] \quad (2.42)$$

$$P(n+1) = P(n) - \gamma(n+1)P(n)x(n+1)x^T(n+1)P(n) \quad (2.43)$$

$$\gamma(n+1) = \frac{1}{[1 + x^T(n+1)P(n)x(n+1)]} \quad (2.44)$$

The algorithm above assumes that the estimated parameters are constant and therefore the measured signal $y(n)$ and the equation error $e(n)$ are all weighted equally over the measuring time $n = 0, 1, 2, \dots, N$. However if the parameters are slowly time varying, then the more recent measurements must be weighted more strongly than the old measurements. This has to be done for the algorithm to follow the time varying parameters. The estimation algorithm should therefore have a fading memory. This

can be incorporated into the recursive least squares algorithm by changing the 1 in the denominator of the (2.44) to λ . Also, (2.43) is multiplied by $\frac{1}{\lambda}$. The weighting factor λ is recommended to be between 0.90 and 0.995 [8]. Starting with an initial estimate $\hat{\Theta}(0)$ and the corresponding $P(0)$, we can sequentially update $\hat{\Theta}$ while the new observations are continually obtained. To start the recursive algorithm one must set

$$\hat{\Theta}(0) = \text{initial estimate}$$

$$P(0) = \alpha I$$

with α large. With recursive identification, a problem of no persistent excitation can occur. This occurs when variations of the process input and output signal become rather small. The process input is then not persistently exciting and problems may arise for continued parameter estimation, particularly if $\lambda < 1$. With the recursive least squares algorithm this circumstance is indicated by an increasing variance on the parameter estimates, which drift to incorrect values. This is known as bursting. One action to avoid this influence during simulation is to excite the input signal with random white noise.

2.4 Statistical Test for Identification

The statistical tests are used for giving some level of confidence as to which models support or best describe the data collected. The tests are used to validate linear relationships between the output and input variables or to discount them.

2.4.1 Test of significance of the multiple regression

The test of significance of multiple regression [6][9] is a test that is used to determine whether there is a linear relationship between a dependent variable y and the independent variables, $x(i)$, $i = 1, 2, \dots, n$. Two hypotheses are adopted and they are as

Source of variation	Sum of squares	Degrees of freedom	Mean square	F_o
Regression	SSr	m	MSr	MSr/MSe
Error or residual	SSe	$n - m - 1$	MSe	
Total	Syy	$n - 1$		

Table 2.1: Summary table for F test

follows:

$$H0: \theta_1 = \theta_2 = \dots = \theta_m = 0$$

$$H1: \theta_i \neq 0 \text{ for at least one } i$$

The rejection of the hypothesis $H0: \theta_i = 0$ implies that at least one of the independent variables contribute significantly to the model. The total sum of the squares, Syy is partitioned into a sum of squares due to regression, SSr and a sum of squares due to the error, SSe , so:

$$Syy = SSr + SSe \quad (2.45)$$

The test procedure for $H0: \theta_i = 0 \ i = 1, \dots, m$, is to compute

$$F_o = \frac{SSr/m}{SSe/(n - m - 1)} = \frac{MSr}{MSe} \quad (2.46)$$

$H0$ is rejected if $F_o > F_{\alpha, m, n-m-1}$ (α is the confidence required) [6][9]. The computational formulas for SSr and SSe are as follows

$$SSe = y^T y - \hat{\Theta} X^T y \quad (2.47)$$

and

$$SSr = \hat{\Theta}^T X^T y - \frac{(\sum_{i=1}^n y_i)^2}{n} \quad (2.48)$$

$$Syy = y^T y - \frac{(\sum_{i=1}^n y_i)^2}{n} \quad (2.49)$$

This procedure is summarized in the Table 2.1

2.4.2 Measure of the Model Adequacy

A number of techniques can be used to test or measure the model adequacy of multiple regression [6]. Model validation is an important part of the multiple regression model

building process. The coefficient of multiple determination R^2 is defined by

$$R^2 = \frac{SSr}{Syy} = 1 - \frac{SSe}{Syy} \quad (2.50)$$

R^2 is a measure of the amount of reduction in the variability of y obtained by using the regressor variables $x_1, x_2, \dots, x_m$. As in the simple case of linear regression, we must have $0 < R^2 < 1$. However, a large value of R^2 does not necessarily mean that the regression model is a good one but it is an indication that there is a strong correlation between at least one independent variable and the output variable.

The positive square root of R^2 is the multiple correlation coefficient between a dependent variable y and a set of variables $x_1, x_2, \dots, x_m$. R is therefore a measure of the linear relationship between y and $x_1, x_2, \dots, x_m$. If $m = 1$ then this is the simple correlation between y and x .

The simple correlation coefficient between x_j and y can be found by the following,

$$R_{jy} = \frac{S_{jy}}{(S_{jj}Syy)^{0.5}} \quad (2.51)$$

where R_{jy} is the simple correlation coefficient between the j th variable and the output variable y , Syy is the total corrected sum of the squares of y , and

$$S_{jj} = \sum_{i=1}^n (x_{ij} - \bar{x}_j)^2 \quad (2.52)$$

$$S_{jy} = \sum_{i=1}^n (x_{ij} - \bar{x}_j)(y_i - \bar{y}) \quad (2.53)$$

where $j = 1, 2, \dots, m$, $i = 1, 2, \dots, n$, $\bar{x}_j$ is the mean of the j th variable and $\bar{y}$ is the mean of the output variable. S_{jy} is called the corrected sum of cross products between x_j and y .

2.4.3 Confidence Intervals on Parameter Estimates

This section presents the theory used to develop confidence intervals on the parameter estimates [6]. The development of these confidence intervals is based on the

assumption that the errors are normally and independently distributed with a mean of zero and a variance of σ^2 . This assumption was made based on the Fast Fourier Transform (FFT) analysis of the data sets, which showed that the noise on the data sets was white noise. The least squares estimator $\hat{\Theta}$ is a linear combination of the observation so $\hat{\Theta}$ is normally distributed with a mean vector Θ and a covariance matrix $\sigma^2(X^T X)^{-1}$. Then

$$\frac{\hat{\theta}_j - \theta_j}{Stdev_j} \quad (2.54)$$

(where $j = 1, 2, \dots, m$) is distributed as a t distribution with $n - m$ degrees of freedom. Therefore to construct a $100(1 - \alpha)$ percent confidence interval for the regression coefficient θ_j the following is applied:

$$\hat{\theta}_j - t_{\alpha/2, n-m} Stdev_j \leq \theta_j \leq \hat{\theta}_j + t_{\alpha/2, n-m} Stdev_j \quad (2.55)$$

where $Stdev_j$ is the standard deviation of the j parameter. This is found from the square root of the parameter variances found from the diagonal elements of the covariance matrix.

Chapter 3

Analytical models of the thermo-mechanical refiner

The TMP refining process can be controlled by three main control variables, the production rate, the infeed dilution water flow rate, and the plate gap setting of the refiner, both flat zone and conical zone plate gap. These variables control the refiner's motor load, outlet consistency of the pulp from the refiner, and the specific energy of the refiner. The refiner's specific energy is a function of both the refiner's motor load and the production rate, it is defined as the energy used to refine a unit volume of wood chips. The pulp properties CSF, long fiber content, and shive content, can be modeled as a function of the specific energy. Since specific energy is a function of the motor load and the production rate the pulp properties can then be modeled as a function of the input control variables.

3.1 Outlet Consistency

The outlet consistency relationship was found primarily by performing a mass and energy balance across the refiner. Outlet consistency of the refiner is the ratio of the dry mass of pulp to the total mass of pulp and water mixture, at the exit of the

Figure 3.1: Block Diagram Of Refiner system

refiner. This relationship depends on the motor load and the dilution water content in the pulp. The block diagram in Figure 3.1 shows the refiner with all of the inputs and outputs. The outlet consistency is dependent on the production rate, the dilution water flow rate and the motor load. If one assumes steady state conditions, and that the fluid in the refiner has very little variation in thermodynamic properties from that of water, then the energy balance across the refiner is given as:

$$w = e_w + e_s \quad (3.1)$$

Where w is the work done on system, e_w is the energy that goes into the water and e_s is the energy that goes into the making of steam. Considering the system in more detail the following derivation is obtained. The total amount of water into the system, M_{wi} , is given as the sum of the dilution water input, M_d , and the initial water content in the chip as it enters the refiner, M_{ci} .

$$M_{wi} = M_{ci} + M_d \quad (3.2)$$

The initial water content in the chip is found from the inlet consistency of the chip to the refiner.

$$C_i = \frac{R}{(R + M_{ci})} \quad (3.3)$$

therefore

$$M_{ci} = \frac{R(1 - C_i)}{C_i} \quad (3.4)$$

Where R is the oven dry mass flow rate of chip flowing through the refiner, and C_i is the inlet consistency of the chip. The mass flow rate of water at the outlet of the system is given as the total mass flow rate of water entering the refining zone minus the mass flow rate of steam generated in the refiner.

$$M_{co} = M_{wi} - M_s \quad (3.5)$$

where M_{co} is the mass flow rate of the water in the chip at the outlet of the refiner and M_s is the mass flow rate of the steam generated in the refining zone. Therefore the energy absorbed by the water, e_w , at the outlet is,

$$e_w = M_{co} C_{pw} (T_{in} - T_{out}) \quad (3.6)$$

where C_{pw} is the specific heat capacity of water at constant pressure, T_{in} is the temperature of the water at inlet to the refiner, and T_{out} is the temperature of the water at outlet of the refiner. However, because all of the inlet water to the refiner is at different temperatures, then,

$$e_w = (M_d - M_s) C_{pw} (T_2 - T_3) + M_{ci} C_{pw} (T_1 - T_3) \quad (3.7)$$

where T_1 , T_2 , and T_3 are the temperatures of the water at the points indicated in Figure 3.1. Assuming that the steam generated in the refiner is at constant pressure and temperature and that it is superheated, and that the steam generated comes mainly from the dilution water input, then the energy used to generate steam is given as:

$$e_s = M_s (h_3 - h_2) \quad (3.8)$$

where h_3 and h_2 are the enthalpies of steam at the exit and water at entrance to the refiner. Assuming minimal losses in the refiner then the complete energy balance equation is given as:

$$E_f(ML) = (M_d - M_s)C_{pw}(T_2 - T_3) + M_{ci}C_{pw}(T_1 - T_3) + M_s(h_3 - h_2) \quad (3.9)$$

The only unknown variables in the above relationship are the amount of steam generated, M_s , and the percentage of motor load energy, E_f , that is transferred to the water, the pulp and to the making of steam. The amount of steam generated can then be found by rearranging the formula to give

$$M_s = \frac{E_f(ML) - M_d C_{pw}(T_3 - T_2) - M_{ci} C_{pw}(T_3 - T_1)}{(h_3 - h_2) - C_{pw}(T_3 - T_1)} \quad (3.10)$$

The outlet consistency is then given as :

$$C_o = \frac{R}{(R + M_{co})} \quad (3.11)$$

where:

$$M_{co} = M_{ci} + M_d - M_s \quad (3.12)$$

The above derivation holds for both the secondary and primary refiners with the only difference being that of the constant terms. The following constant values were used in the derivation as obtained from the data and set as assumed values. The temperature of the infeed dilution water, T_2 is assumed to be $70^\circ C$. The temperature of the chip water mixture, T_1 entering the refiner is assumed to be $100^\circ C$. The inlet consistency, C_i , to the primary refiner is assumed to be constant and is given to be 47 percent. The inlet consistency to the secondary refiner is taken to be equal to the outlet consistency of the primary refiner. The steam temperature in the refining zone T_3 is measured by the DCS and is approximately $170^\circ C$. The chamber pressure P_3 at the output of the primary refiner is kept constant at $370 kpa$ and the output pressure, P_3 of the secondary refiner is kept constant at $335 kpa$. Dilution water enters

the primary and secondary refiners at an assumed value equal to that of atmospheric pressure. The specific heat capacity, C_{pw} of the water is taken to be 4.2kJ/kgK . The production rate R is directly related to the speed of the metering screw feeder ($smsf$) which is measured by the Distributed Control System.

3.2 Motor load relationship

Two attempts were made at modeling the motor load relationship of the TMP refiners, with the first model being discarded for reasons which will be shown later in the text. The first attempt at modeling the refiner was to use a model that represented the motor load as a linear function of the input controlled variables, that is production rate, infeed dilution water flow rate and the refiner plate gap. The following relationship was used to model motor load.

$$ML = a(ifd) + b(fzg) + c(czg) + d(smsf) + e \quad (3.13)$$

where ML is the motor load, ifd is the infeed dilution water flow rate to the refiner, $smsf$ is the speed of the metering screw feeder to the refiner (this defines the production rate), fzg is the flat zone plate gap setting, and czg is the conical zone gap setting, and a , b , c , d , and e are parameters to be identified. In this model the motor load has a linear relationship with the dilution water, the production rate, the flat zone gap and the conical zone gap and also a constant factor is included. The idea to model the motor load this way came from the paper by Tessier and Kian [3]. In their paper they model the motor load as a linear function of the infeed dilution water flow rate and the closing pressure on the hydraulic system that controls the plate gap. This model however did not accurately represent the normal operation of the refiner.

The second attempt to model the motor load relationship is somewhat more intuitive. The load on the refiner motor is mainly attributed to the shearing of the wood

fibres between the refiner plates. This energy is therefore a function of the number of wood chips per unit volume of material in the refining zone and also the refining surface area to volume of refining zone ratio. The refining surface area of any given refiner is a constant but what changes is the refining zone volume which comes about by a change in the refiner's plate gap. For a given set point in the production rate and the dilution water flow rate, an increase in the plate gap will increase the refining zone volume thus allowing wood fibres to move more freely in the refining zone and impact less with the refiner's plates. This then results in less shearing of the chips and ultimately a reduced motor load. Miles and May [4] also showed that a linear relationship exists between the motor load and the inverse of the plate gap which is in agreement with this hypothesis.

The number of wood chips in the refining zone at any instant of time then becomes a function of the amount of dilution water that is put into the system and also the production rate. Assuming constant residence time, the material in the metering screw feeder to the refiner is viewed as a continuous mass of dry wood chips and water as it enters the refiner. If the speed of the screw is increased (that is increased production rate) then a larger number of wood fibres would enter the refining zone per unit volume of material entering the refining zone. Alternatively, if the infeed dilution water flow rate is increased then there would be more water and less fibres per unit volume of material entering the refiner.

Therefore an increase in dilution water will cause the motor load to drop while the production rate and plate gap are kept constant because there is less shearing due to less fibres in the refining zone. A decrease in the production rate will also cause the motor load to drop while the dilution water flow rate and the plate gap is kept constant. Also while the production rate and dilution water flow rate are kept constant, an increase in plate gap will cause the load on the motor to drop. Based on the assumptions and the analysis of the refining mechanics the following relationships

for the refiner motor load were developed. If one assumes that the volume of the dry wood fibres is small compared to the volume of water in the mixture then the number of wood fibers that enter the refiner per unit volume can be modeled as,

$$N_{wood} = \frac{a(R)}{ifd} \quad (3.14)$$

where a is a constant parameter, R is the dry mass of chip production rate, N_{wood} is the number of wood fibres per unit volume of mixture, and ifd is the dilution water volume flow rate.

The other factor affecting the motor load is the refining surface area to volume of refining zone ratio, Q , which is given by:

$$Q = \frac{b(A)}{(fzg)} + \frac{c(A)}{(czg)} \quad (3.15)$$

where b and c are constants, A is the refining surface area which is a constant, fzg is the flat zone gap, czg is the conical zone gap. The ratio is split into two parts so as to account for both flat zone, and conical zone regions. The model for the motor load relationship reduces to the following:

$$ML = (N_{wood})(Q) \quad (3.16)$$

by substituting (3.14) and (3.15) into (3.16) we get

$$ML = \frac{a(R)b(A)}{(ifd)(fzg)} + \frac{a(R)c(A)}{(ifd)(czg)} \quad (3.17)$$

Since A , a , b , and c are all constants the model reduces to

$$ML = \frac{k_1(R)}{(ifd)(fzg)} + \frac{k_2(R)}{(ifd)(czg)} \quad (3.18)$$

where k_1 , and k_2 are constant parameters to be identified. The production rate is a function of the metering screw feeder speed, $smsf$, so R in the above equation can be replaced by $smsf$. In the above relationship for motor load it is assumed that all other effects that contribute to the motor load will be included in the parameters to be identified.

3.3 Pulp Quality Measures

CSF gives a relative value which can be used to indicate the action of the pulp on the paper machine. The term is used to designate the rate at which water drains through and from a suspension of pulp and water when a wire or perforated plate is used as a strainer. It is used to measure the draining of water from the mixture of pulp and water as it would actually take place on the paper machine. The long fiber content is a measure of the percentage of long fibers in the pulp. This classification gives an indication of how strong the finished product (paper) will be. Shive is an impurity that is present in the refined pulp. The Canadian standard freeness (CSF), the long fiber content (LFC), and the shive content (Shive) were all found, based on experimental results to have good linear correlation with specific energy [3][14][15]. The pulp quality measures were therefore modeled as a function of the specific energy. The model used is a linear function. Specific energy is defined as the energy expended in refining unit mass of pulp and is a function of the refiner's motor load and the production rate, and is given as,

$$E = \frac{ML}{R} \quad (3.19)$$

Where E is the specific energy, ML is the refiner's motor load, and R is the production rate. This equation can be written as

$$E = \frac{24000ML}{4.39smsf} \quad (3.20)$$

Where the specific energy is in Kwh , the refiner's motor load is in MW , and $smsf$ is the speed of the metering screw feeder and is given in rpm ($4.39smsf$ gives the production rate in $tons/day$). The model used for determining the CSF is,

$$CSF = k_3(E) + k_4 \quad (3.21)$$

where k_3 and k_4 are constant parameters to be determined. The model used for determining the long fiber content is,

$$LFC = k_5(E) + k_6 \quad (3.22)$$

where LFC is the Long Fiber Content, k_5 and k_6 are constant parameters to be determined. The model used for determining the shive content is,

$$SHIVE = k_7(E) + k_8 \quad (3.23)$$

where $SHIVE$ is the Shive Content, k_7 and k_8 are constant parameters to be determined.

Chapter 4

Experiments and data collection

The experiments were done on a Sunds Defibrator RGP-76 Conical disc refiner, for both primary and secondary refining stages. A block diagram of the refining process was shown in Figure 1.3 in Chapter 1. Experiments were performed on the refiners in order to collect suitable data for analysis. The experiment had to be performed within certain constraints in that they had to be run without affecting the normal operation of the plant. The first experiment involved the changing of the set points in the primary refiner's operating variables while that on the secondary refiner were kept constant. That is, the infeed dilution water flow rate, the production rate, and the flat and conical zone plate gaps were all varied on the primary refiner. The second set of experiments involved keeping the operating variables on the primary constant and vary the operating variables for the secondary refiner. Data was collected by the DCS computer. The data collected was the speed of the metering screw feeder which determines the production rate, the infeed dilution water flow rate to each refiner, the flat zone gap, and the conical zone gap settings, the motor load, the outlet consistency, the chamber pressure, the steam temperature, and the specific energy for each refiner. The data collected from the two experiments described above were used to identify the motor load relationship for each refiner. Other experiments were conducted to

identify the relationship for the pulp quality measures.

The results from the Pulp Quality Monitor gives the Canadian standard freeness, the shive content, and the long fiber content. As shown in Figure 1.3 in Chapter 1, the PQM is situated upstream of the two refining stages and also the refined pulp is only tested at approximately 30 minute intervals. Due to the location of the PQM, a set point change on the primary refiner will produce an effect in the PQM results approximately 45 minutes after they are made and a set point change in the secondary refiner will produce an effect approximately 30 minutes after they are made.

For the primary refiner the experiment was performed and the data collected. The input variables to the primary refiner, speed of the metering screw feeder (smsf), the infeed dilution water flow rate (infd), the flat zone gap (fzg) and the conical zone gap (czg) were all varied as shown in Figure 4.1. The corresponding data for the motor load and the outlet consistency were also collected and these plots are shown in Figure 4.2. On the secondary refiner the experiments proceeded much the same way as that of the primary refiner. That is set points on the primary refiner were maintained constant and changes in the secondary refiner infeed dilution flow rate, the flat zone plate gap and the conical zone plate gap were made. The data plot for the secondary refiner input variables are shown in Figure 4.3. The motor load and outlet consistency data for the secondary refiner is also given in Figure 4.4.

For the pulp properties, CSF, long fiber content, and shive content, data was collected from the refiners continuously for a certain period of time and at the same time, data from the PQM was collected. In order to match the values of the input variables to the results given by the PQM, when considering the primary refiner, a time lag of approximately 45 minutes was subtracted from the PQM times and at this new time the corresponding data for the input variables was read off the refiner data sets. Figure 4.5(a), (b), and (c) shows the PQM data set for the Canadian standard Freeness, the long fiber content, and the shive content when the input variables to

Figure 4.1: Data Plots of the input variables to the Primary Refiner

Figure 4.2: Data plot for the Primary refiner Motor Load and Outlet Consistency

Figure 4.3: Data Plots of the input variables to the secondary Refiner

Figure 4.4: Data plot for the Secondary refiner Motor Load and Outlet Consistency

the primary refiner were varied. Figure 4.6 shows the input variables to the primary refiner. Similarly, the data for the secondary refiner pulp properties was collected. The time lag for the secondary refiner was 30 minutes. Figure 4.7 shows the pulp properties, and Figure 4.8 shows the input variables.

Figure 4.5: Data plot for the Primary refiner Pulp Properties

Figure 4.6: Data plot for the Primary refiner input variables for the pulp properties

Figure 4.7: Data plot for the Secondary refiner Pulp Properties

Figure 4.8: Data plot for the Secondary refiner input variables for the pulp properties

Chapter 5

Fitting models to data

The two identification techniques described, were used to fit the experimental data to the mathematical models identified in Chapter 3. The Hooke and Jeeves algorithm was used to find the single parameter, E_f , (3.10) in the outlet consistency model that minimized the error between the experimental data and the mathematical model. The unknown parameters in the motor load relationship, the CSF, the shive content, and the long fiber content relationships were all identified using the least squares method.

5.1 Outlet Consistency

The mathematical model of outlet consistency for the primary refiner is given by (3.10) to (3.12) in Chapter 3, with the parameter E_f to be identified, which is a measure of the efficiency of the motor or how much of the motor load energy goes into the refiner. The data set for outlet consistency as shown in Figure 4.2(b) was fitted to this model and the results are depicted in Figure 5.1. Figure 5.1(a) shows the data plot for the primary refiner outlet consistency, Figure 5.1(b) shows the model plot of the relationship and Figure 5.1(c) shows the error between the data plot and

Figure 5.1: Comparison of primary refiner's Outlet Consistency data and model plots: (a) Data plot of outlet consistency, (b) Plot of estimated relationship, (c) Error between the data and estimated relationship

the model plot. The Estimated parameter E_f was found to be 0.99. The procedure for the identification of the secondary refiner outlet consistency is the same as that for the primary refiner. The data set in Figure 4.4(b) was fitted to the model thus giving the estimate of the parameter E_f to be 0.96. The results of the estimate is given in Figure 5.2, with the data plot in part (a), the model plot in part (b), and the error plot in part (c).

5.2 Motor Load

Two models of the motor load relationship were presented in Chapter 3: equation 3.13 for model one and equation 3.18 for model two.

5.2.1 Model One

In using the data sets from Chapter 4, equation 3.13 for the primary refiner was fitted to the data from Figure 4.2(a) for the motor load and Figure 4.1 for the input variables. Using the least squares method to fit the data to the model the following parameters were obtained:

$$ML = a(ifd) + b(fzg) + c(czg) + d(smsf) + \epsilon \quad (5.1)$$

where $a = -0.1939$, $b = 4.2430$, $c = -2.1092$, $d = -0.0936$, and $\epsilon = 59.3358$. The diagonal elements of the covariance matrix of the regression give the variances of the parameter estimates as shown in Table 5.1. The mean of the error was found to be 0 and the RMS value of the error is 0.6536. The variance on the error is 0.4272. The estimated model of the primary refiner's motor load was then simulated using the data for the input variables. The simulated results are shown in Figure 5.3 where the motor load relationship is compared to the data. The three dimensional plot of the relation (equation 5.1) shown in Figure 5.4, best depicts how the motor

Figure 5.2: Comparison of secondary refiner's Outlet Consistency data and model plots : (a) Data plot of outlet consistency, (b) Plot of estimated relationship, (c) Error between the data and estimated relationship

parameter	variance
a	0.0001
b	0.2524
c	0.0951
d	0.0016
e	10.9544

Table 5.1: Variances of parameter estimates for model 1

Variable	Correlation Coefficients
ifd	-0.7426
fzg	-0.5268
czg	0.4705
smsf	-0.1226

Table 5.2: Correlation coefficients of input variables for model 1

load changes with the input variables. From equation 5.1 the motor load increases with decreasing dilution water and increases with increasing flat zone plate gap and decreases with increasing production rate. Some of the effects brought about by the changes in the input variables are consistent with the general operation of the plant but the modeled effects of flat zone gap and production rate are inconsistent with the normal operation of the plant. This then suggests that something is wrong with the model. The model was then examined by using the statistical techniques described in Chapter 2. On applying these tests the test of significance produced a F_o value of 283.8 and the multiple correlation coefficient was $R = 0.78$. The statistical test results shows that with a 95 percent confidence F_o is greater than the F so one should reject the hypothesis H_o . This indicates that some of the input variables contribute significantly to the motor load. To check the contribution of each independent variable the correlation coefficient between each variable and the output variable was calculated. Table 5.2 shows the correlation coefficients. The infeed dilution water flow rate and the flat zone plate gap contributes the most to the motor load. These two variables are both negatively correlated with the motor which is consistent with the plant operation, but the conical zone gap is positively correlated and the speed of the metering screw feeder is negatively correlated. This is not consistent with the operation of the plant. The correlation coefficients for *smsf* and *czg* are low which indicates that their contributions to the motor load are small. The low correlation coefficients and the inconsistency with the normal operation of the plant do not support the linear model, so this model was discarded.

Figure 5.3: Model 1 of motor load relationship for primary refiner

Figure 5.4: Model 1 of motor load relationship for primary refiner with the conical zone gap kept constant.

Parameter	Variance
$k_1 = 27.1699$	1.8575
$k_2 = 0.5322$	0.5959
$K = 11.4128$	0.4137

Table 5.3: Parameters and variances for equation 5.2 (primary refiner)

5.2.2 Model Two

The next model was then developed as described in Chapter 3. Equation 3.18 in Chapter 3 is the motor load relationship that models the motor load as a function of the infeed dilution water flow rate, the production rate, the flat zone gap, and the conical zone gap. In this function only two constant parameters need to be identified. The least squares estimation method was then used to identify these two constant parameters. Given the data set in Figure 4.1 and Figure 4.2(a) and equation 3.18, the model for the primary refiner was found with the estimated constant parameters $k_1 = 48.8206$ and $k_2 = 12.58$. The RMS of the error between the data and the model is 0.9458 and the variance on the error is 0.8955. The variances on the parameter estimates are 0.4973 for k_1 and 0.1816 for k_2 . On applying the F test and the test for model adequacy it was found that H_0 was rejected and the multiple correlation coefficient R is 0.4201. The simple correlation coefficients of term 1 ($\frac{(smsf)}{(ifd)(fzg)}$) with motor load is 0.625 and of term 2 ($\frac{(smsf)}{(ifd)(czg)}$) is -0.321. These values indicate that the majority of the motor load is accounted for by term 1. A further test was done whereby a constant parameter was added to the model, the following relationship was then formed

$$ML = \frac{k_1(smsf)}{(ifd)(fzg)} + \frac{k_2(smsf)}{(ifd)(czg)} + K \quad (5.2)$$

The parameters and their variances are as shown in Table 5.3. The high variance and the low negative correlation coefficient on term 2 further suggest that this term contributes very little to the motor load which is an indication that there is not enough information in the data to identify this term. Removing term 2 the model for

the primary refiner motor load is then reduced to,

$$ML = \frac{k_1(smsf)}{(ifd)(fzg)} + K \quad (5.3)$$

The estimated parameters are $k_1 = 26.6259$ and $K = 11.8030$ with the respective variances of 1.2341 and 0.0934. The RMS of the error is 0.8139 with a variance of 0.8144. These values are lower than the value for the model in equation 3.18. With

95 percent confidence the upper and lower limit on k_1 is 28.8034 and 24.4485 and the upper and lower limit on K is 12.4019 and 11.2042. These limits are well within the range of the estimated values thus supporting the low variances on the estimated parameters. The identified relationship (equation 5.3) was then simulated and the results are shown in Figure 5.5, with the data and model plots depicted in part (a) and part (b). A three dimensional plot of the estimated relationship (equation 5.3) is also given in Figure 5.6. The primary refiner motor load is varied with the infeed dilution water and flat zone gap and the speed of the metering screw feeder. From Figure 5.6 it can be seen that as the flat zone plate gap and the infeed dilution water flow rate increases the motor load decreases and as the production rate increases the motor load increases. These observations follow the experience of the plant operators and the theoretical analysis.

Similarly the motor load relationship for the secondary refiner is found. On applying the least squares method to fit the data from Figure 4.4(a) to the model in equation 3.18, the estimated constant parameters are $k_1 = 4.0429$ and $k_2 = 0.0243$ with variances on the estimate being 0.007 and 0.0048 respectively. The RMS value of the error between the estimated plot and the data is 0.5301. Using the F test the results were $F_o = 470$ so H_0 is rejected thus indicating that the independent variables contribute to the motor load. R was found to be 0.678 which is an indication that there is some linear relation between the independent variables (terms 1 and 2) and the output variable. The simple correlation coefficient for terms 1 and 2 are 0.67 and

Figure 5.5: Primary Refiner Motor Load Plots : (a) Data Plot , (b) Model Plot, (c) Error plot ($ML(\text{Data}) - ML(\text{Model})$)

Figure 5.6: Effect of Dilution water flow rate, flat zone gap, and speed of metering screw feeder (circles represent the data points).

0.51 respectively. The low correlation coefficient of term 2 and the high variance on parameter k_2 gives an indication that term 2 does not contribute much to the output variable. The model was then reduced to that of equation 5.3. The parameters are $k_1 = 4.068$ and $K = 0.011$. The variances are 0.0176 and 0.1204 respectively. The low value of the constant parameter K and the high variance suggest that this constant parameter is insignificant and one can reduce the model to,

$$ML = \frac{k_1(smsf)}{(ifd)(fzg)} \quad (5.4)$$

For the secondary refiner this model was fitted to the data in Figure 4.4. The parameter k_1 was estimated to be 4.0723 with a variance of 0.00000374. The RMS of the error is 0.5301 and the variance on the error is 0.2813. Using a 95 percent confidence the upper and lower limits on k_1 are 4.0842 and 4.0603. The simulated results are shown in Figure 5.7 with the data, the estimate and the error plots. Figure 5.8 shows a three dimensional plot (equation 5.4) depicting the effect on motor load when changing flat zone gap, infeed dilution water flow rate and production rate. The secondary refiner motor load is affected in the same way as that of the primary refiner but with a few differences. The infeed dilution water flow rate to the secondary refiner is much less than that for the primary refiner as indicated by Figure 5.8.

5.3 Pulp Properties

The three important pulp property measures, CSF, Shive content, and Long fiber content are all modeled as functions that are linearly related to the specific energy. The effects of the primary and secondary refiner on these properties are examined independently. The effect of each refiner on the pulp properties was modeled independently because the experiments to collect the data was done in such a manner. Data for the combined effect of both refiners on the pulp properties was not available.

Figure 5.7: Secondary Refiner Motor Load Plots : (a) Data Plot , (b) Model Plot, (c) Error plot ($ML(Data) - ML(Model)$)

Figure 5.8: Effect of Dilution water flow rate, flat zone gap, and speed of metering screw feeder on the Secondary Refiner's Motor Load (circles represent the data points).

Pulp Property	parameter	parameter	variance	variance
CSF	$k_3 = -0.2011$	$k_4 = 511.4582$	0.00111	2537.4
LFC	$k_5 = -0.0421$	$k_6 = 91.7192$	0.000031	70.543
SHIVE	$k_7 = -2.20$	$k_8 = 4414.4$	0.2158	492990.0

Table 5.4: Parameters and variances for the pulp properties identification based on the primary refiner

For the primary refiner the data from Figures 4.5 and 4.6 were fitted to the models in equations 3.20 to 3.23. The identified relationships are plotted in Figure 5.9. Figure 5.9 (a), (b) and (c), shows the comparison of the data plot to the estimated plot for the primary refiner CSF, shive content, and long fiber content respectively. The estimated parameters for these relationships with the variances are shown in Table 5.4.

The hypothesis H_0 was rejected for all three relationships and the correlation coefficients between specific energy and the pulp properties, CSF, long fiber content and shive content are -0.7349, -0.8056 and -0.6428 respectively. The scatter diagrams are shown in Figure 5.10. The correlation coefficients and the linear trend of the scatter diagrams support the identified relationships for the pulp properties. The models of the pulp properties based on the primary refiner are functions of the primary refiner specific energy, and specific energy is a function of motor load and production rate, the pulp properties can then be plotted as functions of the input variables, dilution water flow rate, flat zone gap, and production rate. These three dimensional plots are based on equations 3.20 to 3.23 and 5.3 and are plotted in Figures 5.11, 5.12 and 5.13.

The material from the primary refiner is sent to the secondary refiner and the model for the pulp properties are the same as that for the primary refiner. Using equations 3.20 to 3.23 and 5.4 and the data from Figures 4.7 and 4.8, the least squares method was applied and the parameter estimates are given in Table 5.5. The hypothesis H_0 was rejected and the correlation coefficients between specific energy and the pulp properties, CSF, long fiber content and shive content are -0.7737, -0.6392

Figure 5.9: **Primary Refiner Pulp properties relationships** :(a) Canadian Standard Freeness, (b) Long Fiber Content, (c) Shive Content .

Pulp Property	parameter	parameter	variance	variance
CSF	$k_3 = -0.1788$	$k_4 = 334.7022$	0.00102	770.6014
LFC	$k_5 = -0.0148$	$k_6 = 38.9671$	0.000015	11.3546
SHIVE	$k_7 = -3.301$	$k_8 = 4008.2$	0.1991	150310

Table 5.5: Parameters and variances for the pulp properties identification based on the secondary refiner

Figure 5.10: Scatter diagram of Primary Refiner Pulp properties: (a) Canadian Standard Freeness, (b) Long Fiber Content, (c) Shive Content .

Figure 5.11: Primary Refiner Canadian Standard Freeness (circles represent the data points).

Figure 5.12: Primary Refiner Long Fiber Content (circles represent the data points).

Figure 5.13: Primary Refiner Shive Content (circles represent the data points).

and -0.8500 respectively. The scatter diagrams between the pulp properties and the secondary refiner specific energy are shown in Figure 5.14. The linear trend seen in the scatter diagrams and the reasonable values on the correlation coefficients give a good indication that the pulp properties data is closely modeled by this linear relation. Figure 5.15 shows the comparison of the data plots to the estimated relationship. Figures 5.16, 5.17 and 5.18 show the pulp properties versus the dilution water flow rate, flat zone gap and production rate.

The effect of the production rate to the secondary refiner on the pulp properties is small as shown by the simulated results, but on the primary refiner the production rate has a measurable effect on the pulp properties. The results also show that the operating range of the infeed dilution water flow rate to the primary refiner is larger than that for the secondary refiner. As shown in Figures 5.11 to 5.13, a change in the dilution water flow rate over this range produces a greater change in the pulp properties than a change in the flat zone plate gap over its operating range. On the secondary refiner the infeed dilution water flow rate operating range is smaller and thus as shown in Figures 5.16 to 5.18, changing the flat zone plate gap has a significant effect on the secondary refiner.

Figure 5.14: Scatter diagram of Secondary Refiner Pulp properties: (a) Canadian Standard Freeness, (b) Long Fiber Content, (c) Shive Content .

Figure 5.15: Secondary Refiner Pulp properties relationships : (a) Canadian Standard Freeness, (b) Long Fiber Content, (c) Shive Content.

Figure 5.16: Secondary Refiner Canadian Standard Freeness (circles represent the data points).

Figure 5.17: Secondary Refiner Long Fiber Content (circles represent the data points).

Figure 5.18: **Secondary Refiner Shive Content** (circles represent the data points).

Chapter 6

Preliminary results on control

Controlling the TMP refiners and subsequently the pulp properties can take several directions. One can implement consistency control as suggested by Corte and Barrette [11]. They suggest that if consistency is controlled by itself it is the most simple form of closed loop control that could be implemented. It has been shown that such control can reduce variations in the refiner operation and also variations in the pulp quality. However with consistency control, special equipment such as a near infra-red sensor is required to measure on-line the moisture content of the pulp. Also Strand [16] showed that with aggressive consistency control increased variations in the CSF can occur. In this case a more direct method is proposed when the identified relationships are used.

As seen in Chapter 3, the specific energy, or energy per mass unit of wood fibers, is the major factor that controls the pulp quality measures. The specific energy is a function of the motor load and the production rate, so controlling the specific energy means controlling the motor load and the production rate. But as seen in Chapter 5 the production rate had an effect on the pulp properties based on the primary refiner model but had little effect based on the secondary refiner model. The production rate also has considerable effect on the motor load of both refiners. However, the plant

	Accepted Range
CSF	140ml to 200ml
LFC	24 to 32 percent
SHIVE	less than 1500 no/g

Table 6.1: Prescribed limits on pulp properties set by plant operators

operates at near constant production rate so the performance of the refiner is therefore governed by how well the refiner's motor load is controlled, when impacted by disturbances such as variations in chip quality and refiner plate condition. Presently the operators use a set point control strategy whereby the production rate, the plate gap, and the infeed dilution water flow rate to both primary and secondary refiners are set at a certain level so as to achieve a desired motor load and thus the desired pulp quality measures. The plant operators try to control the refiners such that they achieve the pulp properties within the limits shown in Table 6.1.

6.1 Control Using Limits

In using set point control, the major problem that the plant operators face is that when they make a set point change in one of the input variables to any one of the refiners, they have no immediate result as to how the set point change affected the pulp properties. The PQM result is only available approximately 30 to 45 minutes after the change in the set point was made. By using the prescribed limits on the pulp properties and the identified equations describing the system, control limits on the input variables to the primary and secondary refiners can be obtained. From Figures 5.10 to 5.12, one can see that with constant production rate, varying the primary refiner's infeed dilution water flow rate over its operating range gives a greater change in the pulp properties than changing the flat zone gap over its range. Also from Figures 5.14 to 5.16 for the secondary refiner, the dynamic range of the infeed

dilution water flow rate is smaller than that of the primary refiner but a change in the plate gap resulted in a significant effect on the pulp properties. From these results it is therefore proposed that the two significant operating variables are the infeed dilution water flow rate on the primary refiner and the flat zone plate gap on the secondary refiner. This however is based on the assumption that all other variables (production rate, etc.) are set at certain set points and do not change during the steady state operation of the plant. So by using the identified relationships for the primary and secondary refiner motor load, the CSF and the long fiber content from Chapters 3 and 5 as shown below,

$$ML_p = \frac{k_1(smsf)}{(ifd)(fzg)} + K \quad (6.1)$$

$$ML_s = \frac{k_1(smsf)}{(ifd)(fzg)} \quad (6.2)$$

$$E = \frac{24000(ML_{p,s})}{4.39smsf} \quad (6.3)$$

$$CSF = k_3(E) + k_4 \quad (6.4)$$

$$LFC = k_5(E) + k_6 \quad (6.5)$$

(where ML_p is the primary refiner motor load and ML_s is the secondary refiner motor load) and the prescribed limits on the pulp properties in Table 6.1, the limits for infeed dilution water flow rate on the primary refiner and flat zone gap on the secondary refiner can be obtained. With these limits on the input variables, the operator now has a control window in that they can predict the output variables from the changes in the set points of the input variables. The limits on the input variables for the primary refiner's infeed dilution water flow rate and the secondary refiner's plate gap is given below.

Primary refiner

$$ifd_{upper} = \frac{24000(k_1)(k_3)(smsf)}{fzg[4.39smsf(cs f_{upper} - k_4) - K(k_3)24000]} \quad (6.6)$$

$$ifd_{lower} = \frac{24000(k_1)(k_5)(smf)}{fzg[4.39smf(lf_{clower} - k_6) - K(k_5)24000]} \quad (6.7)$$

Secondary refiner

$$fzg_{upper} = \frac{k_1 k_3 24000}{4.39(ifd)(csf_{upper} - k_4)} \quad (6.8)$$

$$fzg_{lower} = \frac{k_1 k_5 24000}{4.39(ifd)(lf_{clower} - k_6)} \quad (6.9)$$

The limits for each pulp property will produce different limits for the operating variables but it was found that the upper limit on the CSF and the lower limit on the long fiber content produced the upper and lower limits for the input variables that would maintain all three pulp properties, CSF, long fiber content and shive content within their prescribed limits. Figure 6.1 depicts the operating window for the pulp quality measures when the limits on the input variables, infeed dilution water on the primary refiner, and flat zone gap on the secondary refiner are maintained.

6.2 Adaptive Control

The type of control that was just described involved the manual set point control of the input variables to control the pulp properties due to refiner variations. This is based on the operators predicting the pulp properties in advance using the guidelines previously stated. It is however natural to use the models of the refiner operation to develop a control algorithm that will automatically update the plant input variables to compensate for the disturbances that affect the pulp properties.

An adaptive control algorithm is therefore proposed. This algorithm will adjust the input variables to the primary and secondary refiners while maintaining the pulp

Figure 6.1: The operating window for the Pulp Properties when the limits on the input variables are maintained.

quality measures within the prescribed limits. The adjustment of these variables becomes necessary because of the disturbances and the time varying effect of plate wear on the system that may cause the pulp quality measures to go out of the prescribed limits. It was shown by Guy Dumont [12] that the refiner's motor load decreases as the refiner plates wear. This then suggests that in order to model the effect of the plate wear, the parameters in the motor load relationship must also be time varying. No evidence or data was available to model the plate wear to motor load relationship, nonetheless an experimentally decreasing function was chosen to model the time varying effect of the motor load with plate wear. This was an arbitrary selection purely to motivate the adaptive algorithm. The function used was an exponential function in time for the parameter $a(t)$.

$$a(t) = e^{-\frac{t}{T}} \quad (6.10)$$

T is the time constant for the time varying parameter a .

This is a preliminary attempt at constructing an adaptive controller for the control of the paper mill refining process. To control the pulp properties one has to control the motor load on each refiner and it has been shown previously that the defining input variables to each refiner is the infeed dilution water flow rate to the primary refiner and the flat zone plate gap to the secondary refiner. However, to demonstrate the ideas being proposed for the adaptive controller a simple case was considered whereby only the primary refiner motor load was controlled. The only controlled variable is the infeed dilution water flow rate to the primary refiner. The production rate, the flat zone and conical zone plate gaps are assumed to be constant while the plant is under steady state operation. The set points of the input variables to the secondary refiner are assumed to be fixed at some level, so that the secondary refiner has little or no effect on changes to the pulp properties.

The general structure of the adaptive control algorithm is shown in Figure 6.2.

The parameter identification technique used is the recursive least squares algorithm. The estimation model is then given as,

$$ML(t) = a(t) \left[\frac{k_1(smsf)}{(ifd(t))(fzg)} + K \right] \quad (6.11)$$

This can be written in the form:

$$y(t) = \theta(t)\psi(t) \quad (6.12)$$

where $y(t) = ML(t)$, $\theta(t) = a(t)$, and $\psi(t) = \left[\frac{k_1(smsf)}{(ifd(t))(fzg)} + K \right]$.

The least squares estimator of $\theta(t+1)$ then becomes:

$$\hat{\theta}(t+1) = \hat{\theta}(t) + \gamma(t+1)P(t+1)\psi(t+1)[y(t+1) - \psi^T(t+1)\hat{\theta}(t+1)] \quad (6.13)$$

$$P(t+1) = \frac{P(t) - \gamma(t+1)P(t)\psi(t+1)\psi^T(t+1)P(t)}{\lambda} \quad (6.14)$$

$$\gamma(t+1) = \frac{1}{\lambda + \psi^T(t+1)P(t)\psi(t+1)} \quad (6.15)$$

A forgetting factor of $\lambda = 0.99$ was used. Using equations 6.10, 6.3 and 6.4 the adjustment of the infeed dilution water to the primary refiner is done based on the following criteria. The estimate of the motor load at time $(t+1)$ is evaluated, that is $ML(t+1)$, then the specific energy $E(t+1)$, and the Canadian standard freeness $csf(t+1)$. The infeed dilution water is then updated according to the criteria:

$$if \quad csf > csf_{upper} \quad (6.16)$$

$$ifd(t+1) = \frac{a(t+1)24000(k_1)(k_3)(smsf)}{fzg[4.39smsf(cs f_{upper} - k_4) - K(k_3)24000a(t+1)]} \quad (6.17)$$

$$elseif \quad !fc < lfc_{lower} \quad (6.18)$$

$$ifd(t+1) = \frac{a(t+1)24000(k_1)(k_3)(smsf)}{fzg[4.39smsf(lfc_{lower} - k_6) - K(k_3)24000a(t+1)]} \quad (6.19)$$

$$else \quad (6.20)$$

$$ifd(t+1) = ifd(t) \quad (6.21)$$

Figure 6.2: Block diagram of the Adaptive Control Algorithm

Simulations of the algorithm were done, where the flat zone gap, the conical zone gap, and the production rate were all set at constant steady state values. A suitable value of the time constant $T = 17520 \text{ hrs}$ (2 years) and the forgetting factor $\lambda = 0.99$, was assigned. The simulations were done for over a period of 100 days which works out to be 2400 hours. The results of the simulations are shown in Figure 6.3 and 6.4. Figure 6.3(a) shows the values of the infeed dilution water flow rate as it was adjusted to maintain the motor load, the CSF, the long fiber content, and the shive content within their desired limits. These are all depicted in Figure 6.3 (b), (c), (d), and Figure 6.4 (a) respectively. Figure 6.4 (b) and (c) show the true values of the parameters over the simulation period and also the estimated values. As shown the estimation algorithm tracked the true parameter values very closely as they changed over time. The decreasing exponential function was used to simulate plate wear on the refiner, which will cause the refiner's motor load to drop over a period of time. With the dropping motor load the pulp properties will be affected and probably move out of the desired limits. The preliminary results of the adaptive algorithm shows

that the Canadian standard freeness, the long fiber content, and the shive content were all maintained within the desired limits as the plate condition decreased, by adjusting the set point value of the infeed dilution water flow rate to the primary refiner.

Figure 6.3: (a) Dilution water flow rate: (b) Motor load, estimate and actual: (c) Canadian Standard Freeness: (d) Shive content

Figure 6.4: (a) Long fiber content: (b) Parameter 1 ($a(t)$), estimate and actual: (c) Motor load error, Actual - Estimate

Chapter 7

Conclusion

System identification of a two stage thermo-mechanical pulping process was done by using DCS data collected from the primary and secondary conical plate refiners at the Gatineau, Quebec refinery. One of the main relationships identified was the relationship between the refiners motor load and the input variables to that refiner. In identifying this relationship, two models were looked at, a linear model similar to that put forward by Tessier and Kian [3], and a model that views the pulp flow in a unique way. The residence time is assumed to be constant because the chamber pressure is a constant throughout the experimentation. This pressure is believed to have the most significant effect on the steam velocity [4] which is the main factor affecting the residence time [4]. The latter model showed better results. This model of the refiner's motor load was then used to develop the relationships for the pulp properties. The mathematical models of the motor load and the pulp properties are linear equations whereby system identification techniques such as the least squares method could be used to fit the data to the models. The results of the identification showed that changes in the dilution water flow rate to the primary refiner over its operating range produced a greater change in the pulp properties than changes in

the plate gap over its operating range. The infeed dilution water flow rate to the secondary refiner operates on a smaller range than the primary refiner but changes in the flat zone plate gap had a significant effect on the pulp properties. With these observations the control of the system can be reduced to controlling two variables, the infeed dilution water flow rate on the primary refiner and the flat zone gap on the secondary refiner, while all other variables are maintained at a constant level.

With the identification of the refining system, the plant operators now have guidelines as to what adjustments to make in order to achieve their objectives when they try to compensate for disturbances. The models therefore can define an operating window for the operators. This window will indicate the maximum and minimum set points for the input controlled variables such that the pulp properties remain within their limits. Preliminary results on an adaptive controller design were also presented. The control algorithm will track the changes in the model parameters thus updating the input variables so that the pulp properties are within limits.

One weakness of the research is that the combined effect of the two stages of refining, primary and secondary, on the pulp quality measures, was not looked at. This was a restriction because of the data sets collected. Another weakness of the identification was in the data sets collected. This weakness resulted in the inability to sufficiently model the effect of the conical zone plate gap on the refiners motor load due to insufficient information in the data. However for future research, better experimentation methods should be implemented. Also modeling the combined effect of the primary refiner and the secondary refiner on the pulp properties will be very useful in developing better control strategies for the pulping process. Other work would be to model paper quality indexes such as tear index, burst index, and tensile index as functions of the input variables, infeed dilution water flow rate, production rate, and plate gap settings.

The contributions of this thesis are that a new conceptualization of the 'thermo-

2 OF 2

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mechanical pulping process was used to define a model structure whose parameters can be identified from available DCS and PQM data and also an operating window was defined whereby the maximum and minimum settings on the control variables can be obtained. These settings are then used to keep the pulp properties within their specified bounds. This operating window could either be used as an operator's guide or as a controller which maintains the input setpoints at the window center.

Bibliography

1. K.B. Miles and W.D. May, "The flow of pulp in chip refiners," *J. Pulp and Paper Science*, 16(2): J63-J72, (1982).
2. K. Fan and D.J. Jeffery, "Stochastic model for the motion of pulp in a single disc chip refiner," *81st Annual Meeting, Technical Section, CPPA*, (1995).
3. P. Tessier and X. Quian, "Modeling and Simulation of a CTMP process," *80th Annual Meeting, Technical Section, CPPA*, A143-A149 (1993).
4. K.B. Miles and W.D. May, "Predicting the Performance of a Chip Refiner: a Constitutive Approach," *J. Pulp and Paper Science*, 19(6): J268-J274, (1993).
5. T. C. Hsia, "System Identification," Lexington Books, (1977).
6. William W. Hines and Douglas C. Montgomery, "Probability and Statistics in Engineering and Management Science," Wiley, (1990).
7. Brian D. Bunday, "Basic Optimization Methods," Arnold, London (1984).
8. Rolf Isermann, Karl-Heinz Lachmann, and Drago Matko, "Adaptive Control Systems," Prentice Hall, (1992).
9. Richard J. Larsen and Morris L. Marx, "An Introduction to Mathematical Statistics and its Applications," Prentice Hall, (1981).
10. R.E. Jones and A. Pila, "Process control for Thermomechanical pulping," *IFAC Instrumentation and Automation in the Paper, Rubber, Plastics and Polymerisation industries, Antwerp, Belgium*, 191-198 (1983).
11. Corte, B.J. and Barrette, M.M., "Installation of Blowline Consistency Control Improves Mill Operation," *81st Annual Meeting, Technical Section, CPPA*, B281-B287 (1994).

12. Guy A. Dumont and Ye Fu, "Non-Linear adaptive control via Laguerre expansion of Volterra Kernels," *International Journal of Adaptive Control and Signal Processing*, vol. 7, 367-382 (1993).
13. Ronald G. Macdonald and John N. Franklin, "Pulp and Paper Manufacture: The Pulping Of Wood," vol. 1, McGraw-Hill, (1969).
14. W. G. Mihelich, D. J. Wild, S. B. Beaulieu and L. R. Beath, "Single-Stage Chip Refining-Some Major Operating Parameters and their effects on Pulp Quality," *7th International Mechanical Pulping Conference, Technical Section, CPPA*, 78-82 (1971).
15. B. C. Strand and N. Hartler, "Modelling and Optimization of Full Scale Chip Refining," *Proceedings, Intl. Mechanical Pulping Conference, Stockholm*, 46-54 (1985).
16. B. C. Strand, "The Effect of Refiner Variation on Pulp Quality," *Proceedings, Intl. Mechanical Pulping Conference, Ottawa, Canada*, (1995).
17. B. J. Allison, A. J. Isaksson and A. Karlstrom, "Grey Box Identification of a TMP Refiner," *Proceedings, Intl. Mechanical Pulping Conference, Ottawa, Canada*, (1995).

Appendix A

Identification Algorithms

This appendix contains the programs for the least squares algorithm and the Hooke and Jeeves algorithm. The programs are written in Matlab code.

A.1 Least Squares Algorithm

Program: least.m

```
*****
This is the main Program for the Least squares algorithm. This program calculates
the parameter estimates for the estimated relationship.
*****

Y = B;
X = A;
XX=X'*X;
C = inv(XX);
theta = C * X' * Y;
SSe = Y' * Y - theta' * X' * Y;
s = 0;
sm = zeros(size(Y));
for j = 1 : n
    sm(j) = Y(j) + s;
    s = sm(j);
end

SSr = theta' * X' * Y - (sm(n).^2)./n;
Syy = SSe + SSr;
m = max(size(theta));
MSe = SSe./(n - m);
MSr = SSr./m;
Cov = MSe * C;
parvar = zeros(size(theta));
```



```

for  $I = 1 : m$ 
    for  $J = 1 : m$ 
        if  $I == J$ 
             $parvar(I) = Cov(I, J);$ 
        else
            end
        end
    end
end

```

```

 $Fo = MSr./MSe;$ 

```

```

 $F = 4.61;$ 

```

```

if  $Fo > F$ 

```

```

     $Ho = 0;$ 

```

```

else

```

```

     $Ho = 1;$ 

```

```

end

```

```

***** Multiple correlation Coefficient *****

```

```

 $R = sqrt(SSr./Syy);$ 

```

```

***** Simple Correlation Coefficients*****

```

```

 $Ybar = sum(Y)./n;$ 

```

```

 $Xbar = [];$ 

```

```

for  $j = 1 : m$ 

```

```

     $Xbar(j) = sum(X(:, j))./n;$ 

```

```

end

```

```

for  $j = 1 : m$ 

```

```

    for  $i = 1 : n$ 

```

```

     $XXbar(i,j) = X(i,j) - Xbar(j);$ 
     $YYbar(i) = Y(i) - Ybar;$ 
     $XY(i,j) = XXbar(i,j) * YYbar(i);$ 
     $XXS(i,j) = XXbar(i,j)^2;$ 
end
 $SJJ(j) = sum(XXS(:,j));$ 
 $SJY(j) = sum(XXbar(:,j) * YYbar);$ 
 $RS(j) = SJY(j) ./ ((SJJ(j) * Syy)^{0.5});$ 
end

```

```

t = 1.96;
stddev = zeros(size(theta));
lower = zeros(size(theta));
upper = zeros(size(theta));

```

```

for k = 1 : m
    stddev(k) = sqrt(parvar(k));
    lower(k) = theta(k) - t * stddev(k);
    upper(k) = theta(k) + t * stddev(k);
end

```

A.2 Hooke and Jeeves Algorithm

Program: Hooke.m

This is the main Program for the Hooke and Jeeves algorithm. This program uses the function files *norma.m* that defines the function to be minimized and the m-file *explore.m* that does the exploration search.

```

maya;
may7a;
jun15;
junf16;
global smsf ml oc ifd fzd czd x n
smsf = [A(:,2); D(:,2); G(:,2); K(:,2)];
ml = [A(:,4); D(:,4); G(:,4); K(:,4)];
oc = [C(:,5); F(:,5); J(:,5); M(:,5)];
ifd = [B(:,3); E(:,3); H(:,3); L(:,3)];
fzd = [B(:,4); E(:,4); H(:,4); L(:,4)];
czd = [B(:,5); E(:,5); H(:,5); L(:,5)];
cong = [A(:,7); D(:,7); G(:,7); K(:,7)];
x = input('initial_point')
H = input('step_length')
tol = input('tolerance')
k = H;
n = max(size(x));

for i = 1 : n
    y(i) = x(i);
    b(i) = x(i);
    p(i) = x(i);

```

end

$q = \text{norma}(x);$

$FI = q;$

$PS = 0;$

$BS = 1;$

$FB = FI;$

while $k \geq \text{tol}$

 explore ;

 if $FI < (FB - \text{tol})$

 for $i = 1 : n$

$p(i) = 2 * y(i) - b(i);$

$b(i) = y(i);$

$x(i) = p(i);$

$y(i) = x(i);$

 end

$q = \text{norma}(x);$

$FB = FI;$

$PS = 1;$

$BS = 0;$

$FI = q;$

 elseif $PS == 1$ and $BS == 0$

 for $i = 1 : n$

$p(i) = b(i);$

$y(i) = b(i);$

$x(i) = b(i);$

 end

$q = \text{norma}(x);$

$BS = 1;$

$PS = 0;$

$FI = q;$

$FB = q;$

```

        else
             $k = k./10$ 
        end
    end

     $Q = q$ 
     $X = x$ 

```

A.3 Primary Refiner Outlet Consistency Function Definition

Program: norma.m

This a function file that defines the function to be minimized by the Hooke and Jeeves algorithm. The function is the mean square of the error between the outlet consistency data and estimate.

```
function q = norma(x)
global smsf ml oc ifd fzd czd bld czg fzg POC err ms md
cpw = 4200;
t1 = 100;
t2 = 30;
t3 = 170;
h2 = 125900;
h3 = 2800000;
a = cpw * (t3 - t2);
b = cpw * (t3 - t1);
c = h3 - h2;
fc = 4.39. * 0.6944. * smsf;
mci = ((1 - 0.47). * fc)./(0.47);
md = ifd + fzd + czd;
ms = (x(1). * 60000000. * ml - a. * md - b. * mci)./(c - a);
(***** (60,000,000 is to convert MJ/s to KJ/min)*****)
mco = mci + md - ms;
OC = (fc./(fc + mco)). * 100;
err = (oc - OC);
q = sqrt(err' * err)./nn;
```

A.4 Secondary Refiner Outlet Consistency Function Definition

Program: snorma.m

*****; *****

This is a function file that defines the function to be minimized by the Hooke and Jeeves algorithm. The function is the mean square of the error between the outlet consistency data and estimate.

```
function q = norma(x)
global smsf ml oc ifd fzd czd bld czg fzg POC err ms md
nn = max(size(smsf));
cpw = 4200;
t4 = 164;
t5 = 30;
t6 = 170;
h2 = 125900;
h3 = 2800000;
aa = cpw * (t6 - t5);
bb = cpw * (t6 - t4);
cc = h3 - h2;
fc = 4.39. * 0.6944. * smsf;
mco = ((1 - 0.65). * fc)./(0.65);
md = ifd(1 : nn) + fzd(1 : nn) + czd(1 : nn) + bld(1 : nn);
ms = (x(1). * 600000000. * ml(1 : nn) - aa. * md - bb. * mco)./(cc - aa);
mcos = mco + md - ms;
POC = (fc./(fc + mcos)). * 100;
err = (oc(1 : nn) - POC);
q = sqrt(err' * err)./nn;
```

A.5 Hooke and Jeeves Algorithm Exploration

Program: explore.m

This is the m-file that does the exploration search for the Hooke and Jeeves
algorithm

$j = 1;$

while $j \leq n$

$x(j) = y(j) + k;$

$q = \text{norma}(x);$

 if $q < FI$

$y(j) = x(j);$

$q = \text{norma}(x);$

$FI = q;$

 else

$x(j) = y(j) - k;$

$q = \text{norma}(x) ;$

 if $q < FI$

$y(j) = x(j);$

$FI = q;$

 else

$x(j) = y(j);$

$q = \text{norma}(x)$

$FI = q;$

 end

end

$j = j + 1;$

end

Appendix B

Primary Refiner Identification

Programs for the identification and simulation of the primary refiner motor load, CSF, long fiber content, and shive content relationships are found in this appendix. (Programs are written in Matlab codes).

B.1 Primary Refiner Motor load Identification and Simulation

Program: primml.m

This program uses the data stored in files Maya.m, may7a.m, jun15.m, jun16.m, jun152b.m, jun162b.m to identify the motor load relationship for model 2. This program also uses the m-file least.m to do the least squares parameter identification.

maya;

jun15.m, jun16.m may7a;

jun15;

junf16;

jun152b;

junf162b;

*The variables ml, spe, smsf, ifd, czg, fzg, and oc are defined from the data files **

$ml = [D(:, 4); G(:, 4); KA(:, 4)];$

$spe = [D(:, 5); G(:, 5); KA(:, 5)];$

$smsf = [D(:, 2); G(:, 2); KA(:, 2)];$

$ifd = [E(:, 3); H(:, 3); LA(:, 3)];$

$czg = [D(:, 7); G(:, 7); KA(:, 7)];$

$fzg = [D(:, 6); G(:, 6); KA(:, 6)];$

$oc = [F(:, 5); J(:, 5); MA(:, 5)];$

$n = \max(\text{size}(ml));$

$chip = (smsf) ./ ifd(1 : n);$

$fv = 1 ./ (fzg);$

```

cv = 1./czg;
fun = fv.*chip;
cun = cv.*chip;
A = [fun(1:n)ones(size(ml))];
B = [ml(1:n)];
least

for i = 1:n
    Mle(i)=theta(1)*fun(i) + theta(2);
end

t = [0:1:n-1];

```

Simulation of the estimated Motor Load relationship for Primary Refiner

```

figure(1)
subplot(3,1,1)
plot(t,ml)
grid
ylabel('MLe (MW):data')
title('(a)')
subplot(3,1,2)
plot(t,ML)
grid
ylabel('ML (MW):estimate')
title('(b)')
subplot(3,1,3)
plot(t,mlerror)
ylabel('ML error')
xlabel('time (x10 sec)')
grid

```

```
title('(c)')
figure(2)
subplot(2,1,1)
plot(t,ml)
grid
ylabel('ML (MW): Data')
title('(a)')
subplot(2,1,2)
plot(t,oc)
grid
ylabel('OC (xlabel('time (x10 sec)'))
title('(b)')
figure(3)
subplot(3,1,1)
plot(t,smsf)
grid
ylabel('smsf (rpm)')
title('(a)')
subplot(3,1,2)
plot(t,ifd(1:n))
grid
ylabel('infd (lpm)')
title('(b)')
subplot(3,1,3)
plot(t,czg,t,fzg)
grid
xlabel('time (x10 sec)')
ylabel('plate gaps')
gtext('flat zone')
gtext('conical zone')
title('(c)')
```

Three dimensional simulation of the primary refiner motor load relationship.

```

infd = 180 : 1 : 205;
flatzg = 1.2 : 0.028 : 1.9;
[IFD, FLATZG] = meshgrid(infd, flatzg);
chip1 = (72)./(IFD);
fv1 = 1./(FLATZG);
fun1 = chip1. * fv1;
mlmp1 = theta(1). * fun1 + theta(2);
chip2 = (77)./(IFD);
fv2 = 1./(FLATZG);
fun2 = chip2. * fv2;
mlmp2 = X(1). * fun2 + X(2);
figure(4)
meshz(infd,flatzg,mlmp1)
view(-217.5,30)
hidden off
hold
mesh(infd,flatzg,mlmp2)
hidden off
hold off
hold
plot3(ifd(1:n),fzg,ml,'o')
hold off
axis([180 205 1.2 1.9 14 25])
grid
xlabel('infeed dilution water (lpm)')
ylabel('flat zone plate gap (mm)')
zlabel('Motor load (Mw)')

```

```
title('Primary Refiner Motor load relationship')
text(187,1.9,16,' $smsf = 72rpm$ ')
text(180,1.4,23,' $smsf = 77rpm$ ')

```

B.2 Primary Refiner CSF Identification and Simulation

Program: primcsf.m

This program uses the data stored in the file primprop.m to identify the Canadian Standard Freeness relationship for the primary refiner. This program also uses the m-file least.m to do the least squares parameter identification.

```
primprop;
n = max(size(csf)); A = [SPE(1 : n)ones(size(csf(1 : n)))];
B = [csf(1 : n)];

for i = 1 : n
    CSF(i) = x(1) * SPE(i) + x(2);
end

t = [1 : 1 : n];
e = csf(1 : n) - CSF(1 : n)';
```

Simulation of the estimated Canadian Standard Freenes relationship

```
figure(1)
subplot(2,1,1)
plot(t,csf,t,CSF,'-')
grid
xlabel('time')
ylabel('Canadian standard freeness (ml)')
```

```
title('Canadian standard freeness VS time')
subplot(2,1,2)
plot(t,e)
xlabel('time')
ylabel('error = csf(data) - csf(estimate)')
grid
figure(2)
subplot(2,2,1)
plot(t,fzg)
grid
xlabel('time')
ylabel('flat zone gap(mm)')
title('Flat zone gap VS time')
subplot(2,2,2)
plot(t,ifd)
grid
xlabel('time')
ylabel('infeed dilution water(lpm)')
title('Infeed dilution VS time')
subplot(2,2,3)
plot(t,spe,t,SPE,'-')
grid
ylabel('specific energy (kwh)')
xlabel('time ')
subplot(2,2,4)
plot(t,czg)
grid
xlabel('time')
ylabel('conical zone gap(mm)')
title('conical zone gap VS time')
figure(3)
```



```

plot(t,smsf(1:n))
grid
xlabel('time')
ylabel('smsf (rpm)')
title('Smsf VS time')

```

```

*****

```

Three dimensional simulation of the primary refiner Canadian Standard Freeness
relationship.

```

*****

```

```

X = [48.2344; 12.7108];
infd = 155 : 1.8 : 200;
flatzg = 1.6 : 0.008 : 1.8;
[IFD, FLATZG] = meshgrid(infd, flatzg);
chip1 = (72)./IFD;
fv1 = 1./(FLATZG);
fun1 = chip1.*fv1;
mlmp1 = X(1). * fun1 + X(2);
chip2 = (77)./IFD;
fv2 = 1./(FLATZG);
fun2 = chip2.*fv2;
mlmp2 = X(1). * fun2 + X(2);
specen1 = (mlmp1 * 24000)./(4.39 * 72);
specen2 = (mlmp2 * 24000)./(4.39 * 77);
CSFR1 = (theta(1) * specen1 + theta(2));
CSFR2 = (theta(1) * specen2 + theta(2));
figure(4)
meshz(infd,flatzg,CSFR1)
hidden off
hold
mesh(infd,flatzg,CSFR2)

```

hidden off

hold off

hold

axis([155 200 1.6 1.8 180 280])

plot3(ifd,fzg,csf,'o')

hold off

grid

xlabel('infeed dilution water (lpm)')

ylabel('flat zone gap (mm)')

zlabel('Canadian standard freeness (ml)')

title('Canadian standard freeness relationship')

B.3 Primary Refiner LFC Identification and Simulation

Program: primlfc.m

This program uses the data stored in the file primprop.m to identify the Long Fiber Content relationship for the primary refiner. This program also uses the m-file least.m to do the least squares parameter identification.

```
primprop;
n = max(size(lfc)); A = [SPE(1 : n)ones(size(lfc(1 : n)))];
B = [lfc(1 : n)];
least;

for i = 1 : n
    LFC(i) = theta(1) * SPE(i) + theta(2);
end

t = [1 : 1 : n];
e = lfc(1 : n) - LFC(1 : n)';
```

Simulation of the estimated Long Fiber Content relationship

```
figure(1)
subplot(2,1,1)
plot(t,lfc,t,LFC,'-')
grid
xlabel('time')
ylabel('Long fibre content title('Long fibre content VS time'))
```

```

subplot(2,1,2)
plot(t,e)
xlabel('time')
ylabel('error = lfc(data) - lfc(estimate)')
grid
figure(2)
subplot(2,2,1)
plot(t,fzg)
grid
xlabel('time')
ylabel('flat zone gap(mm)')
title('Flat zone gap VS time')
subplot(2,2,2)
plot(t,ifd)
grid
xlabel('time')
ylabel('infeed dilution water(lpm)')
title('Infeed dilution VS time')
subplot(2,2,3)
plot(t,spe,t,SPE,'-')
grid
ylabel('specific energy (kwh)')
xlabel('time ')

```

Three dimensional simulation of the primary refiner Long Fiber Content
relationship .

```

X = [48.2344; 12.7108];
infd = 160 : 1.8 : 205;
flatzg = 1.6 : 0.008 : 1.8;

```

```

[IFD, FLATZG] = meshgrid(infd, flatzg);
chip1 = (72)./IFD;
fv1 = 1./(FLATZG);
fun1 = chip1.*fv1;
mlmp1 = X(1). * fun1 + X(2);
chip2 = (77)./IFD;
fv2 = 1./(FLATZG);
fun2 = chip2.*fv2;
mlmp2 = X(1). * fun2 + X(2);
specen1 = (mlmp1 * 24000)./(4.39 * 72);
specen2 = (mlmp2 * 24000)./(4.39 * 77);
LFCR1 = (theta(1) * specen1 + theta(2));
LFCR2 = (theta(1) * specen2 + theta(2));
figure(3)
meshz(infd,flatzg,LFCR1)
hidden off
hold
mesh(infd,flatzg,LFCR2)
hidden off
hold off
hold
axis([160 205 1.6 1.8 26 33])
plot3(ifd,fzg,lfc,'o')
hold off
grid
xlabel('infeed dilution water (lpm)')
ylabel('flat zone gap (mm)')
zlabel('Long fibre content title('Long fibre content relationship')

```

B.4 Primary Refiner Shive Identification and Simulation

Program: primshiv.m

```

*****

This program uses the data stored in the file primprop.m to identify the Shive
Content relationshi for the primary refiner. This program also uses the m-file
least.m to do the least squares parameter identification.

*****

primprop;
n = max(size(shive)); A = [SPE(1 : n)ones(size(shive(1 : n)))];
B = [shive(1 : n)];
least;

for i = 1 : n
    SHIVE(i) = theta(1) * SPE(i) + theta(2);
end

t = [1 : 1 : n];
e = shive(1 : n) - SHIVE(1 : n)';

*****

Simulation of the estimated Shive Content relationship

*****

figure(1)
subplot(2,1,1)
plot(t,shive,t,SHIVE,'-')
grid
xlabel('time')
ylabel('Shive content (no/g)')

```

```

title('Shive content VS time')
subplot(2,1,2)
plot(t,e)
xlabel('time')
ylabel('error = shive(data) - shive(estimate)')
grid
figure(2)
subplot(2,2,1)
plot(t,fzg)
grid
xlabel('time')
ylabel('flat zone gap(mm)')
title('Flat zone gap VS time')
subplot(2,2,2)
plot(t,ifd)
grid
xlabel('time')
ylabel('infeed dilution water(lpm)')
title('Infeed dilution VS time')
subplot(2,2,3)
plot(t,spe,t,SPE,'-')
grid
ylabel('specific energy (kwh)')
xlabel('time ')

```

Three dimensional simulation of the primary refiner Shive Content relationship.

```

X = [48.2344; 12.7108];
infd = 160 : 1.8 : 205;
flatzg = 1.6 : 0.008 : 1.8;

```

```

[IFD, FLATZG] = meshgrid(infd, flatzg);
chip1 = (72)./IFD;
fv1 = 1./(FLATZG);
fun1 = chip1.*fv1;
mlmp1 = X(1).*fun1 + X(2);
chip2 = (77)./IFD;
fv2 = 1./(FLATZG);
fun2 = chip2.*fv2;
mlmp2 = X(1).*fun2 + X(2);
specen1 = (mlmp1 * 24000)./(4.39 * 72);
specen2 = (mlmp2 * 24000)./(4.39 * 77);
SHIVER1 = (theta(1) * specen1 + theta(2));
SHIVER2 = (theta(1) * specen2 + theta(2));
figure(3)
meshz(infd,flatzg,SHIVER1)
hidden off
hold
mesh(infd,flatzg,SHIVER2)
hidden off
hold off
hold
axis([160 205 1.6 1.8 800 1600])
plot3(ifd,fzg,shive,'o')
hold off
grid
xlabel('infeed dilution water (ipm)')
ylabel('flat zone gap (mm)')
zlabel('Shive content (no/g)')
title('Shive content relationship')

```


Appendix C

Secondary Refiner Identification

Programs for the identification and simulation of the secondary refiner motor load, CSF, long fiber content, and shive content relationships are found in this appendix. (Programs are written in Matlab codes).

C.1 Secondary Refiner Motor load Identification

Program: seconml.m

This program uses the data stored in files s2decd,s2jana,s2janb, s2janc, p2deca, p2decbb, p2decc, p2decc, p2jana, p2janb, and p2janc, to identify the motor load relationship for the secondary refiner. This program also uses the m-file least.m to do the least squares parameter identification.

```
s2deca;
s2decbb;
s2decc;
s2decd;
s2jana;
s2janb;
s2janc;
p2deca;
p2decbb;
p2decc;
p2decd;
p2jana;
p2janb;
p2janc;
ml = [a(:,1); g(:,1); k(:,1); s(100 : 300,1)];
spe = [a(:,2); g(:,2); k(:,2); s(100 : 300,2)];
smsf = [N(:,2); T(:,2); W(:,2); CC(100 : 300,2)];
```

```

ifd = [a(:, 7); g(:, 7); k(:, 7); s(100 : 300, 7)];
fzd = [b(:, 1); h(:, 1); m(:, 1); t(100 : 300, 1)];
czd = [b(:, 2); h(:, 2); m(:, 2); t(100 : 300, 2)];
czg = [a(:, 4); g(:, 4); k(:, 4); s(100 : 300, 4)];
fzg = [a(:, 3); g(:, 3); k(:, 3); s(100 : 300, 3)];
oc = [c(:, 1); j(:, 1); nnn(:, 1); u(100 : 300, 1)];
n=max(size(smsf))
chip=(smsf)./ifd(1:n);
fv=1./(fzg);
cv=1./czg;
fun=fv(1:n).*chip;
cun=cv(1:n).*chip;
A=[fun(1:n)];
B=[ml(1:n)];
least

for i = 1 : n
    ML(i)=theta(1)*fun(i);
end

e = (ml(1 : n) - ML');
t = 1 : 1 : n;

```

```

*****

```

Simulation of the estimated secondary refiner motor load relationship

```

*****

```

```

figure(1)
subplot(3,1,1)
plot(ml(1:n))
axis([0,n,8,16])
grid
ylabel('ML (MW)- data')

```

```
title('(a)')
subplot(3,1,2)
plot(ML)
axis([0,n,8,16])
grid
ylabel('ML (MW)- estimate')
title('(b)')
subplot(3,1,3)
plot(e)
axis([0,n,-2,2])
grid
ylabel('ML error')
xlabel('time (x10 sec)')
title('(c)')
figure(2)
subplot(2,1,1)
plot(ml(1:n))
axis([0,n,8,16])
grid
ylabel('ML (MW) - data')
title('(a)')
subplot(2,1,2)
plot(oc(1:n))
grid
ylabel('OC (xlabel('time (x10 sec)'))
title('(b)')
figure(3)
subplot(3,1,1)
plot(ifd)
grid
ylabel('ifd (lpm)')
```

```

title('(a)')
subplot(3,1,2)
plot(t,fzg(1:n),t,czg(1:n))
grid
ylabel('plate gaps')
gtext('fzg')
gtext('czg')
title('(b)')
subplot(3,1,3)
plot(smsf)
grid
ylabel('smsf (rpm)')
xlabel('time (x10 sec)')
title('(c)')
figure(4)
subplot(2,1,1)
plot(fzd)
grid
ylabel('fzd')
subplot(2,1,2)
plot(czd)
grid
ylabel('czd')

```

Three dimensional simulation of the primary refiner motor load relationship.

```

infd = 19 : 0.2 : 24;
flatzg = 0.9 : 0.024 : 1.5;
[IFD, FLATZG] = meshgrid(infd, flatzg);
chip1 = (72)./(IFD);

```

```

fv1 = 1./(FLATZG);
fun1 = chip1. * fv1;
mlmp1 = X(1). * fun1;
chip2 = (77)./(I`D);
fv2 = 1./(FLATZG);
fun2 = chip2. * fv2;
mlmp2 = theta(1). * fun2;
figure(5)
meshz(infd,flatzg,mlmp1)
hidden off
view(-217.5,30)
hold
mesh(infd,flatzg,mlmp2)
hidden off
hold off
hold
plot3(ifd,fzg,ml,'o')
hold off
axis([19 24 0.9 1.5 8 19])
grid
xlabel('infeed dilution water (lpm)')
ylabel('flat zone plate gap (mm)')
zlabel('Motor load (Mw)')
title('Motor load relationship')
text(19,1.2,14,'smsf = 77rpm')
text(21,1.5,9,'smsf = 72rpm')

```

C.2 Secondary Refiner CSF Identification

Program: seccsrf.m

This program uses the data stored in the file secprop.m to identify the Canadian Standard Freeness relationship for the secondary refiner. This program also uses the m-file least.m to do the least squares parameter identification.

secprop;

$n = \max(\text{size}(\text{csf})); A = [SPE(1:n)' \text{ones}(\text{size}(\text{csf}(1:n)))];$

$B = [\text{csf}(1:n)];$

least;

for $i = 1 : n$

$CSF(i) = \text{theta}(1) * SPE(i) + \text{theta}(2);$

end

$t = [1 : 1 : n];$

$e = \text{csf}(1:n) - CSF(1:n)';$

Simulation of the estimated Canadian Standard Freeness relationship

figure(1)

subplot(2,1,1)

plot(t,csf,t,CSF,'-')

grid

xlabel('time (x 45 min)')

ylabel('Canadian standard freeness (ml)')

```
title('(a)')
gtext('data')
gtext('estimate')
subplot(2,1,2)
plot(t,e)
xlabel('time')
ylabel('error = csf(data) - csf(estimate)')
xlabel('time (x 45 min)')
grid
figure(2)
subplot(2,2,1)
plot(t,ifd)
grid
xlabel('time')
ylabel('infeed dilution water(lpm)')
title('(a)')
subplot(2,2,2)
plot(t,fzg,t,czg)
grid
xlabel('time')
ylabel('plate gaps (mm)')
title('(b)')
subplot(2,2,3)
plot(t,spe,t,SPE)
grid
ylabel('specific energy (kwh)')
xlabel('time ')
subplot(2,2,4)
plot(t,smsf)
grid
ylabel('smsf')
```


xlabel('time ')

Three dimensional simulation of the secondary refiner Canadian Standard Freeness
relationship.

```

X = [4.0429;0.0243];
infd = 20 : 1 : 40;
flatzg = 0.7 : 0.05 : 1.7;
[IFD, FLATZG] = meshgrid(infd, flatzg);
chip1 = (72)./IFD;
fv1 = 1./(FLATZG);
fun1 = chip1.*fv1;
mlmp1 = X(1).*fun1;
chip2 = (77)./IFD;
fv2 = 1./(FLATZG);
fun2 = chip2.*fv2;
mlmp2 = X(1).*fun2;
specen1 = (mlmp1 * 24000)./(4.39 * 72);
specen2 = (mlmp2 * 24000)./(4.39 * 77);
CSFR1 = (theta(1) * specen1 + theta(2));
CSFR2 = (theta(1) * specen2 + theta(2));
figure(3)
meshz(infd,flatzg,CSFR1)
hidden off
hold
mesh(infd,flatzg,CSFR2)
hidden off
hold off
hold
axis([20 40 0.7 1.7 140 220])

```

```
plot3(ifd,fzg,csf,'o')  
hold off  
grid  
xlabel('infeed dilution water (lpm)')  
ylabel('flat zone gap (mm)')  
zlabel('Canadian standard freeness (ml)')  
title('Canadian standard freeness relationship')
```

C.3 Secondary Refiner LFC Identification

Program: seclfc.m

This program uses the data stored in the file secprop.m to identify the Long fiber Content relationship for the secondary refiner. This program also uses the m-file least.m to do the least squares parameter identification.

secprop;

$n = \max(\text{size}(lfc)); A = [SPE(1 : n)'ones(\text{size}(lfc(1 : n)))];$

$B = [lfc(1 : n)];$

least; $n = \max(\text{size}(lfc));$

for $i = 1 : n$

$LFC(i) = \theta(1) * SPE(i) + \theta(2);$

end

$t = [1 : 1 : n];$

$e = lfc(1 : n) - LFC(1 : n)';$

Simulation of the estimated Long Fiber Content relationship

figure(1)

subplot(2,1,1)

plot(t,lfc,t,LFC,'-')

grid

xlabel('time')

ylabel('Long Fibre Content (title('Long Fibre content VS time'))

```
subplot(2,1,2)
plot(t,e)
xlabel('time')
ylabel('error = lfc(data) - lfc(estimate)')
grid
figure(2)
subplot(2,2,1)
plot(t,fzg)
grid
xlabel('time')
ylabel('flat zone gap(mm)')
title('Flat zone gap VS time')
subplot(2,2,2)
plot(t,ifd)
grid
xlabel('time')
ylabel('infeed dilution water(lpm)')
title('Infeed dilution VS time')
subplot(2,2,3)
plot(t,spe,t,SPE)
grid
ylabel('specific energy (kwh)')
xlabel('time ')
subplot(2,2,4)
plot(t,smsf)
grid
ylabel('smsf')
xlabel('time ')
```

Three dimensional simulation of the secondary refiner Long Fiber Content
relationship.

```

X = [4.0429;0.0243];
infd = 20 : 1 : 40;
flatzg = 0.7 : 0.05 : 1.7;
[IFD, FLATZG] = meshgrid(infd, flatzg);
chip1 = (72)./IFD;
fv1 = 1./(FLATZG);
fun1 = chip1.*fv1;
mlmp1 = X(1).*fun1;
chip2 = (77)./IFD;
fv2 = 1./(FLATZG);
fun2 = chip2.*fv2;
mlmp2 = X(1).*fun2;
specen1 = (mlmp1 * 24000)./(4.39 * 72);
specen2 = (mlmp2 * 24000)./(4.39 * 77);
LFCR1 = (theta(1)*specen1 + theta(2));
LFCR2 = (theta(1)*specen2 + theta(2));
figure(3)
meshz(infd,flatzg,LFCR1)
hidden off
hold
mesh(infd,flatzg,LFCR2)
hidden off
hold off
hold
axis([20 40 0.7 1.7 22 30])
plot3(infd,flatzg,LFCR1,'o')

```

hold off

grid

xlabel('infeed dilution water (lpm)')

ylabel('flat zone gap (mm)')

zlabel('Long fibre content (title('Long Fibre Content relationship'))

C.4 Secondary Refiner Shive Identification

Program: secshiv.m

This program uses the data stored in the file secprop.m to identify the Shive Content relationship for the secondary refiner. This program also uses the m-file least.m to do the least squares parameter identification.

secprop;

$n = \max(\text{size}(\text{shive})); A = [SPE(1 : n)' \text{ones}(\text{size}(\text{shive}(1 : n)))];$

$B = [\text{shive}(1 : n)];$

least; $n = \max(\text{size}(\text{shive}));$

for $i = 1 : n$

$SHIVE(i) = \text{theta}(1) * SPE(i) + \text{theta}(2);$

end

$t = [1 : 1 : n]; e = \text{shive}(1 : n) - SHIVE(1 : n)';$

Simulation of the estimated Shive Content relationship

figure(1)

subplot(2,1,1)

plot(t,shive,t,SHIVE,'-')

grid

xlabel('time')

ylabel('Shive Content (no/g)')

title('Shive content VS time')

```
subplot(2,1,2)
plot(t,e)
xlabel('time')
ylabel('error = shive(data) - shive(estimate)')
grid
figure(2)
subplot(2,2,1)
plot(t,fzg)
grid
xlabel('time')
ylabel('flat zone gap(mm)')
title('Flat zone gap VS time')
subplot(2,2,2)
plot(t,ifd)
grid
xlabel('time')
ylabel('infeed dilution water(lpm)')
title('Infeed dilution VS time')
subplot(2,2,3)
plot(t,spe,t,SPE)
grid
ylabel('specific energy (kwh)')
xlabel('time ')
subplot(2,2,4)
plot(t,smsf)
grid
ylabel('smsf')
xlabel('time ')
```

Three dimensional simulation of the primary refiner Shive Content relationship

```

X = [4.0429; 0.0243];
infd = 20 : 1 : 40;
flatzg = 0.7 : 0.05 : 1.7;
[IFD, FLATZG] = meshgrid(infd, flatzg);
chip1 = (72)./IFD;
fv1 = 1./(FLATZG);
fun1 = chip1.*fv1;
mlmp1 = X(1). * fun1;
chip2 = (77)./IFD;
fv2 = 1./(FLATZG);
fun2 = chip2.*fv2;
mlmp2 = X(1). * fun2;
specen1 = (mlmp1 * 24000)./(4.39 * 72);
specen2 = (mlmp2 * 24000)./(4.39 * 77);
SHIVER1 = (theta(1) * specen1 + theta(2));
SHIVER2 = (theta(1) * specen2 + theta(2));
figure(3)
meshz(infd,flatzg,SHIVER1)
hidden off
hold
mesh(infd,flatzg,SHIVER2)
hidden off
hold off
hold
axis([20 40 0.7 1.7 300 2000])
plot3(ifd,fzg,shive,'o')
hold off

```

grid

xlabel('infeed dilution water (lpm)')

ylabel('flat zone gap (mm)')

zlabel('Shive content (no/g)')

title('Shive Content relationship')

Appendix D

Identification Of Model 1 Motor Load

The program for the identification and simulation of the first motor load relationship (model 1) is found in this appendix.

D.1 Motor load model 1 Identification and Simulation

Program: motor1.m

This program uses the data stored in files Maya.m, may7a.m, jun15.m, jun16.m, jun152b.m, jun162b.m to identify the motor load relationship for model 1. This program also uses the m-file least.m to do the least squares parameter identification.

```

maya;
may7a;
jun15;
junf16;
jun152b;
junf162b;
ml = [D(:, 4); G(:, 4); K A(:, 4)];
spe = [D(:, 5); G(:, 5); K A(:, 5)];
smsf = [D(:, 2); G(:, 2); K A(:, 2)];
ifd = [E(:, 3); H(:, 3); L A(:, 3)];
czg = [D(:, 7); G(:, 7); K A(:, 7)];
fzg = [D(:, 6); G(:, 6); K A(:, 6)];
oc = [F(:, 5); J(:, 5); M A(:, 5)];
n = max(size(ml))
A = [ifd(1 : n)fzg(1 : n)czg(1 : n)smsf(1 : n)ones(size(ml(1 : n)))];
B = [ml(1 : n)];
least
t = [0 : 1 : n - 1];

```

```

for i = 1 : n
     $ML(i) = \theta(1) * ifd(i) + \theta(2) * fzg(i) + \theta(3) * czg(i) + \theta(4) * smsf(i) + \theta(5);$ 
end

mlerror = ml - ML';

```

Simulation of the estimated Motor Load relationship

```

figure(1)
subplot(2,1,1)
plot(t,ml,'r',t,ML,'m')
grid
xlabel('time(sec)')
ylabel('motor load (MW)')
title('Comparison of actual motor load data to the estimated relationship')
subplot(2,1,2)
plot(t,mlerror)
ylabel('mlerror = ml(data) - ML(estimate)')
xlabel('time (sec)')
grid

```

Three dimensional simulation of the primary refiner motor load relationship with the conical zone gap kept constant

```

infd = 180 : 1 : 205;
flatzg = 1.2 : 0.028 : 1.9;
[IFD, FLATZG] = meshgrid(infd, flatzg);

```

```
mlmp1 = theta(1) * IFD + theta(2) * (FLATZG) + theta(3) * 0.8 + theta(4) * 72 +
theta(5);
```

```
mlmp2 = theta(1) * IFD + theta(2) * (FLATZG) + theta(3) * 0.8 + theta(4) * 77 +
theta(5);
```

```
figure(2)
```

```
meshz(infd,flatzg,mlmp1)
```

```
view(-217.5,30)
```

```
hidden off
```

```
hold
```

```
mesh(infd,flatzg,mlmp2)
```

```
hold off
```

```
hold
```

```
plot3(ifd,fzg,ml,'o')
```

```
hold off
```

```
axis([180 205 1.2 1.9 15 27])
```

```
grid
```

```
xlabel('infeed dilution water (lpm)')
```

```
ylabel('flat zone plate gap (mm)')
```

```
zlabel('Motor load (Mw)')
```

```
title('Motor load relationship')
```

```
text(200,1.85,18,'smsf = 72rpm')
```

```
text(180,1.4,24,'smsf = 77.25rpm')
```

```
*****
```

Three dimensional simulation of the primary refiner motor load relationship
with the flat zone gap kept constant

```
*****
```

```
infd = 180 : 1 : 205;
```

```
conzg = 0.6 : 0.024 : 1.2;
```

```
[IFD,CONZG] = meshgrid(infd,flatzg);
```

```
mlmp3 = theta(1) * IFD + theta(2) * (1.2) + theta(3) * (CONZG) + theta(4) * 72 +
theta(5);
```

```
mlmp4 = theta(1) * IFD + theta(2) * (1.2) + theta(3) * (CONZG) + theta(4) * 77 +
theta(5);
```

```
figure(3)
meshz(infd,conzg,mlmp3)
view(-217.5,30)
hidden off
hold
mesh(infd,conzg,mlmp4)
hold off
hold
plot3(ifd,czg,ml, 'o')
hold off
axis([180 205 0.6 1.2 13 23])
grid
xlabel('infeed dilution water (lpm)')
ylabel('conical zone plate gap (mm)')
zlabel('Motor load (Mw)')
title(' Primary Refiner Motor load relationship')
text(195,1.2,14,'smsf = 72rpm')
text(180,1,22,'smsf = 77rpm')

```

Appendix E

Adaptive Control Algorithm

The program for the adaptive control algorithm is found in this appendix.

E.1 Adaptive Control Algorithm

Program: adapt.m

This program uses the data stored in files Maya.m, may7a.m, jun15.m, jun16.m,
jun152b.m, jun162b.m, to simulate the adaptive control Algorithm.

```

maya;
may7a;
jun15;
junf16;
jun152b;
junf162b;
ml = [D(:, 4); G(:, 4); KA(:, 4)];
spe = [D(:, 5); G(:, 5); KA(:, 5)];
smsf = [D(:, 2); G(:, 2); KA(:, 2)];
ifd = [E(:, 3); H(:, 3); LA(:, 3)];
czg = [D(:, 7); G(:, 7); KA(:, 7)];
fzg = [D(:, 6); G(:, 6); KA(:, 6)];
lamda = 0.99;
p(1) = 100000000000000;
w(:, 1) = [26.6259 * (smsf(n))/(ifd(n) * fzg(n)) + 11.803];
theta(1) = [1];
SMSF = smsf(2);
ML(1) = 18.5;
MLE(1) = 18.5;
csf(1) = 180;
lfc(1) = 27;

```

```

shive(1) = 1300;
IFD(1) = ifd(n - 1);
IFD(2) = ifd(n);
par1(1) = 1;

for i = 2 : 2400
    par1(i) = 1 * exp(-0.0000345 * i);
    IFD(i) = IFD(i) + (1 * randn);
    ML(i) = par1(i) * ((26.6259 * smsf(2))/(IFD(i) * fzg(2))) + 11.803;
    IFDI(i) = (26.6259 * smsf(2))./(IFD(i) * fzg(2));
    w(:, i) = [IFDI(i) + 11.803];
    p(i) = (p(1) - (p(1) * w(:, i) * w(:, i)' * p(1))./(lamda + w(:, i)' * p(1) * w(:, i)))./(lamda);
    r(:, i) = p(i - 1) * w(:, i)./(lamda + w(:, i)' * p(i - 1) * w(:, i));
    theta(:, i) = theta(:, 1) + r(:, i) * (ML(i) - theta(1)' * w(:, i));
    p(1) = p(i - 1);
    theta(1) = theta(i);
    eta = theta(1);
    MLE(i) = eta(1) * ((26.6259 * (smsf(2))/(IFD(i) * fzg(2))) + 11.803);
    SE(i) = (MLE(i) * 24000)./(4.39 * SMSF);
    csf(i) = (-0.2011 * SE(i) + 511.4582);
    lfc(i) = (-0.0421 * SE(i) + 91.7192);
    shive(i) = (-2.2 * SE(i) + 4414.4);
    if MLE(i) < 0.2833 * SMSF
        EE = (0.2833 * SMSF)/(eta(1));
        IFD(i + 1) = (26.6259 * SMSF)/(fzg(2) * (EE - 11.803));
    elseif MLE(i) > 0.3379 * SMSF
        EEE = (0.3379 * SMSF)/(eta(1));
        IFD(i + 1) = (26.6259 * SMSF)/(fzg(2) * (EEE - 11.803));
    else
        IFD(i + 1) = IFD(i);
    end
end
end

```

```

e = ML' - MLE';
t = 1 : 1 : 2400;

```

```

*****

```

· Simulation of the Adaptive Control Algorithm

```

*****

```

```

figure(1)
subplot(2,2,1)
plot(t,IFD(1:2400))
grid
ylabel('infeed dilution(lpm)')
title('(a)')
subplot(2,2,2)
plot(t,ML,t,MLE,'-')
grid
ylabel('motorload (MW)')
gtext('— actual')
gtext('— estimate')
title('(b)')
subplot(2,2,3)
plot(t,csf)
grid
ylabel('CSF (ml)')
xlabel('time (hrs)')
title('(c)')
subplot(2,2,4)
plot(t,shive)
grid
ylabel('Shive (no/g)')
xlabel('time (hrs)')

```

```
title('(d)')
figure(2)
subplot(3,1,1)
plot(t,lfc)
grid
ylabel('long fibre content(title('(a)'))
subplot(3,1,2)
plot(t,theta,t,par1,'-')
ylabel('parameter 1')
grid
title('(b)')
gtext('rule[-0.1in]0.25in0.01in estimate')
gtext('— actual value')
subplot(3,1,3)
plot(t,e)
grid
ylabel('error')
xlabel('time (hrs)')
title('(c)')
```

END

0 5 - 0 6 - 9 | 6

FIN