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Date July 28 of 1988

DEVELOPMENT OF A MULTIVARIABLE STEADY-STATE CONTROLLER FOR THE BASIS WEIGHT PROFILE IN A PAPER MACHINE

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Pedro Luiz Bocchini

August 1988

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ABSTRACT

This thesis presents the development of an algorithm for the control of the cross machine basis weight of a typical Fourdrinier paper machine. The algorithm compensates for the complex multivariable interactions between the actuators and the basis weight profile and considers constraints on the individual actuators as well as the stress imposed on the slice bar by adjacent actuators. Presented in this thesis is also the development of a detailed dynamic model and simulation of the wet end section of a paper machine. The simulation is used in the testing of the control algorithm under a number of scenarios.

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CHAPTER 1

INTRODUCTION

Paper and paperboard are some of the most consumable products in the world today. Paper and paper products are all around in different forms and hundreds of applications such as: computer paper, tissue paper, wall paper, books, magazines, labels, boxes, printed advertizing, catalogs, photographs, etc. The total consumption of paper in the USA is approximately 650 lb per capita per year and it is estimated that it will reach 1000 lb per capita per year in the next generation, Saltman (1978).

To give an idea in terms of the size and potential of the entire paper industry, the annual production of paper, in 1986, in the USA was more than 70 millions short tons, produced in 652 paper mills spread all over the country (14 of them in Tennessee). In addition, in 1986 more than 20 millions short tons of paper were imported. The paper industry also includes the paper and paperboard converting industries, the forest industry and a big pulp production industry. More than 57 million short tons of wood pulp were produced in 388 pulp mills in USA, in 1986.

In the developing countries these number sound even more impressive. For example in Brazil, the pulp and paper industries are responsible for a big slice of the exportation income of the country and so, require a lot of care in terms of production effectiveness.

This work will address only those aspects of paper manufacturing related to profile control of paper webs; however, some general explanations about the difficulties of maintaining the quality of the paper being produced within the client's specification limits will be introduced.

Parameters like basis weight (weight of paper per unit of area), moisture content, thickness and others, directly the final products for which the paper will be used, such as: books, magazines, tissue, etc. Because of this, the converting industries require that the paper they buy arrive at their plants with the quality parameters within very narrow tolerance limits.

Achieving these limits is not an easy task for the paper maker. Paper is made in long, wide sheets and must be controlled considering the possibility of properties variations in the cross machine direction as well as in the machine direction. The central problem is multivariable and highly complex in terms of maintaining a tight control of the quality parameters in each spatial direction. It is a difficulty problem, especially considering that a paper machine can be more than 30 ft wide and operate at speeds higher than 3000 ft/min.

Dedicated computer control systems for on-line profile control in paper machines were developed and introduced in the market in the late 70's. Today they are largely used throughout the country and are very reliable. But, there are still some industries, especially the small ones, that cannot afford to put one of these expensive systems in their production lines. So, they have to rely on the skills and feelings of experienced process operators. This fact is especially true in the developing countries where the investments in terms of process control equipment are even more restricted.

This work will analyze some critical aspects of cross machine direction profile control (CD) of basis weight in paper machines. The focus will be on developing modern control strategies that could be implemented in small and relatively inexpensive computers.

CHAPTER 2

STATEMENT OF THE PROBLEM

2.1 Objective

The objective of this research work is to develop and implement in a digital computer a control algorithm to control the cross machine direction profile (CD) of basis weight in a paper machine. The algorithm is a general profile controller, and only slight modifications would be required to adapt it for the control of other properties like moisture and thickness.

Also, an important part of this work is the development of a dynamic simulation model of a Fourdrinier paper machine. This model is used to analyze the characteristics of the paper machine responses and also used as a benchmark for the tests of the control algorithm.

Another point that has to be mentioned is the fact that all efforts were made to keep the structure and size of the developed FORTRAN programs, suitable to be run in small personal computers. All of them were run and tested using an XT IBM PC with 640 Kb of memory.

2.2 Need for the Study

This work was formulated some years ago in Brazil, when the author, during his normal activities as a control systems design engineer for the pulp and paper industries began to survey the tools that were available to analyze and control effectively the performance of a paper machine with respect to production and quality. The conclusion from that survey was that there was very little available, at a reasonable cost, which could be used to improve the performance of paper machines. So, the author tried to identify the reasons for that situation and some general points were raised:

. personal computers were just arriving to the paper plants and design companies and they really could be used to improve the plant operation;
. there were almost no specific software available, at reasonable cost, that could simulate or evaluate the performance of the paper machines;
. there are approximate 160 paper mills in the country and less than 20 have machines with modern dedicated computerized control systems for basis weight, moisture and thickness;
. the available computerized control systems for basis weight, moisture and thickness had so many features that their costs were prohibitive to most of the Brazilian paper mills, that are normally small with low speed and not too wide machines;
. there were available in the market, independent suppliers of basis weight, moisture and thickness

sensors and actuators that could be integrated with some good control algorithm and be used to direct control of these properties in the paper machines.

So, in 1986 when the author decided to attend the University of Tennessee to take his Masters in Chemical Engineering, his goal was to develop some of the basic tolls required for the analysis and control of small paper machines, geared for the needs of small paper mills in Brazil and other developing countries.

2.3 Assumptions and Limitations

A general computerized system for profile control in a paper machine must contain at least the following basic features :

- algorithm to provide calibration and periodic standardization of the sensors ;
- filtering of the raw acquired data from the sensor to transform them into a form useful for operator guidance and automatic control ; for example, for basis weight control a filter is required to separate what is machine direction variation and cross machine direction variation to provide the operator and the control algorithm with the true cross machine direction profile ;
- provide the calculation and logical capacity

necessary for the control algorithm required by the profile control system ;

- provide the capacity for data manipulation and display, in order to provide the machine operator quality/production control engineer data to analyze machine performance and product quality.

In this work, only the aspects of the paper machine control relative to the algorithm for the cross machine direction profile control are analyzed. The profile example used in this work is basis weight.

CHAPTER 3

LITERATURE REVIEW

This chapter presents the basic problems related to the control of basis weight in a paper machine and also a general literature review of:

- paper machine simulation;
- basis weight definitions and control.

3.1 Paper Machine Simulation

Over the past twenty five years there has been a gradual trend in the pulp and paper industries to a more quantitative mathematical approach to the understanding of the operation and control of it's processes. Computers are increasingly used to simulate pulp and paper processes by numerically solving the complex equations which represent the operation of the equipment.

In general, the computer simulation methods have helped a lot in the development and better understanding of the complex processes involved in the pulp and paper mills. These methods can, generally, be divided into two classes:

- steady-state simulation;
- dynamic simulation.

3.1.1 Steady-State Simulation

Steady-state simulation is the most used simulation method in the pulp and paper industry. It basically consists of an organized and modular set of mathematical equations, that perform steady-state material and/or energy balances around a process, equipment or set of equipment.

Steady-state simulation models are used today in the pulp and paper industries especially for:

- design implementations;
- operational evaluation and analysis;
- mass and energy balances;
- energy and chemicals consumption analysis;
- definition of best process routes;
- economic evaluation of processes.

Many paper mills have their own in-house software development groups to implement the programs necessary for the good operation of the plant. Besides this, there are also available in the market, some commercial software packages, especially designed for the pulp and paper industry. The most well-known of these packages are:

GEMS - developed by the University of Idaho;
INDUNS - developed by the University of Lund;
MAPPS - developed by the Institute of Paper Chemistry - Wisconsin;

MASSBAL - developed by the University of Western Ontario;

MOPS - developed by the STFI - Sweden, based on the original GEMS routines.

3.1.2 Dynamic Simulation

The field of applications of dynamic simulation models for the pulp and paper industries is not as developed as the steady-state ones. Some reasons are: a consistent dynamic model for a process or equipment is much more difficult to obtain than the steady state equivalent.

The main objectives of a typical dynamic simulation model are:

- better understanding of the process, especially during transient conditions;
- analysis and evaluation of new control strategies;
- controller tuning;
- analysis of process perturbations propagation.

Specifically for the wet end of the paper machine, that is the part of the process modeled in this work, a dynamic model can be very useful for the analysis and study of:

- dynamic operation of the headbox, with the possibility of analysis of alternative control strategies;
- slice operation;

. wire section drainage;

. fines and fillers retention analysis;

. white water system evaluation;

. moisture and basis weight profile determination ;

. to establish the paper machine operating parameters like: positioning of vacuum devices in the forming wire, vacuum profile, wet line determination, etc.

In terms of specific commercial software packages for dynamic simulation of the pulp and paper processes, there are none available , and what is seen in the literature at present, are isolated efforts to generate proprietary models and software, and few details are disclosed. This, was one of the main reasons why it was decided to develop and implement a model for the wet end section of a paper machine to be used as a benchmark for the control objectives of this work.

3.1.3 Literature Review

The model for the wet end section of the paper machine is divided into three basic sections :

. pipe section;

. headbox;

. wire section.

a) Pipe Section

The pipe section is modeled as a constant volume tank.

b) Headbox

There are adequate models available in the literature for the headbox, like the ones developed by Talvio (1966), Mardon (1966) and others. The main particularities of the model presented in this work are concentrated in the slice section. In this case the slice was sub-divided into sections according to the number of slice actuators and for each of these sections a contraction coefficient was calculated. This fact leads to different emerging velocities for the stock.

c) Wire Section

The hydrodynamical processes involved at the wet end of the paper machine, mixing and water-fiber separation, are very complex and a detailed understanding and modelling of them are not completely available yet.

The separation of fibers and water on the wire was analyzed by Meyer (1962), Han (1964), Ingmanson (1964) and Nelson (1964). Meyer (1962) presented a distributed parameter model for the fiber concentration on the wire. Wahlstrom and O'Blenes (1962) presented an experimental study of the drainage under conditions similar to those found in a paper machine.

A very simple model was proposed by Beecher (1963), assuming that the retention constant in the wire section was constant. Ohlin and Rosemberg (1965) proposed a more elaborate lumped parameter model.

Alsholm, Schoeffler and Sullivan (1965) proposed a model suitable for on-line computer control. Sullivan and Schoeffler (1966) extended the same model for the study of grade change problems. Their work was based on the partial differential equations model obtained by Meyer (1962).

Smethurst (1966) modeled the paper machine, to study problems of grade changes.

Sastry and Vetter (1969) presented a model where the major concern was the stock flow and fiber concentration dynamics on basis weight.

Astrom and Haggman (1974) proposed a variation on the model developed by Beecher (1963). In their work they showed that the constant retention model proposed by Beecher (1963) was not totally correct and introduced another approach where the retention is a function of the variation of the basis weight on the wire. Using the results obtained by Astrom (1973) they concluded that a good approximation for the retention on the wire, obtained from static experiments, was the harmonic mean, or the average retention could be represented by:

$$RW(BW) = \frac{BW}{\displaystyle\int_0^W \frac{1}{1 - (1 - ALPHA)*EXP(-GAMA*BW)}\, d(BW)}$$

The same retention considerations proposed by Astrom and Haggman (1974) are used in this work plus the following assumptions :

- the wire was divided into a number of sections equal to the number of slice actuators;
- the average retention is calculated for each of the sections.

3.2 Basis Weight

Weight is the most common specification made on paper, because most papers are sold on a weight basis. The weight of paper is expressed per unit of area, rather than per unit of volume, as is the case of liquids, chemicals, etc. This is because paper is used in sheet or roll forms, where area is more important than volume.

3.2.1 Basis Weight Standards

The commercial standard for expression of basis weight in most English speaking countries has been the weight in pounds of a paper ream. Historically, in printing trades, it was measured in reams. Originally, a ream was 480 sheets, but it now signifies 500 sheets of a given size of paper.

In the USA, another way of expressing the substance of paper or paperboard is in pounds per 1000 square feet.

In most European and South American countries as well as more and more throughout the world, the metric system has been used. It reports basis weight in grams per square meter. This form of representation for the basis weight is also the one recommended in the TAPPI (Technical Association of Pulp and Paper Industries) standards, and is the one used in this work. TAPPI standard T-410 defines the procedure to determine basis weight of a paper.

Normally the basis weight is specified as a bone-dry basis or oven-dry basis, which means a compensation is made for the moisture content.

3.2.2 Basis Weight Variation Definition

Since the work of Burkhard and Wrist (1954), basis weight variation have been divided into three components :

- machine direction variations (MD)
- cross-machine direction variations (CD)
- residual or random variations (R)

So, a deviation in basis weight from the desired set point, may be characterized as a two dimensional function of the position on the sheet, and represented as:

$$BW = f(x,y)$$

where

BW = basis weight

x = machine direction coordinate (MD)

y = cross-machine direction coordinate (CD)

This function, due to the nature of paper processing, can be subdivided in three independent functions:

$$BW(x,y) = BW_{MD}(x) + BW_{CD}(y) + BW_{R}(x,y)$$

$BW_{MD}(x)$ = pure MD variation, usually due to process variations upstream from the headbox, although pulsations and vibrations in the headbox or wire section may contribute ;

$BW_{CD}(y)$ = pure CD variation, caused primarily by the distributor and slice operation ;

$BW_{R}(x,y)$ = residual or random component of variation that is not uniform in either direction , and primarily caused by hydraulic instability in the headbox or waves in the wire section.

This approach, leads to a big simplification in the analysis and control of basis weight in paper machines, because MD and CD control problems can be treated separately where MD variations are considered dynamic and CD static.

Another point that has to be mentioned is the fact that the magnitude of the three components are of the same order in an uncontrolled machine therefore so, the three of them are equally important in terms of process control.

3.2.2 Need for the Control of Basis Weight in Paper Machines

Normally, the paper or paperboard basis weight is fixed by the customer, within very narrow limits. These limits are established considering two different aspects:

- technical aspects: every paper property is proportional to basis weight. So, any variations in the basis weight cause variations in the optical and structural properties of the paper, as well as, moisture content and strength changes, and these directly affect the end uses of the paper. For example, an uneven basis weight profile can lead to uneven drying and caliper of the final products, various calender defects such as blackening and cuts, in addition to a major cause of the wet end breaks;

- economical aspects: the consumer, who buys paper in rolls or reams is concerned about the weight of this paper, because paper that is heavier than specified produces fewer sheets than paper with standard specifications. On the other hand, lighter paper produces a greater number of sheets but with less thickness, strength and opacity. A paper that is only slightly overweight can mean a substantial economic loss for the consumer.

The correction of a basis weight problem in a paper machine, usually, is labor and cost intensive and not straightforward but, a mill wide effort. This, as will be seen in the following chapters, is because there are many possible causes for basis weight variations, and for a good product to be obtained, all of them must be corrected.

The main causes for basis weight variations are:

- the stock that is been fed to the headbox is not homogeneous, mainly due to an inadequate blending operation or stock metering;
- variations in consistency or feed stock flow to the headbox, or simply problems with consistency or flow transmitters;
- pulsations or excessive turbulence, provoked by the approaching pipe to the headbox;
- mechanical deficiencies in the headbox that cause turbulence in the stock distribution to the wire;
- damages on the upper or lower "lips" of the headbox (part of the headbox where the stock distributed to former is modulated). These damages can be: deep corrosion spots, distortions, bends, etc.;
- the "lips" may be set to provide an even caliper and moisture profile rather than an even basis weight profile;
- waves on the wire, provoked by deficient distribution of stock emerging from the slice;
- slice actuators are not working properly or some of

them are out of service;

- wire speed fluctuations due to drive problems;
- irregularities in the forming wire that can lead to uneven drainage of paper;
- accumulation of fillers on the wire, that cause variations in the wire retention.

3.2.3 How Basis Weight is Measured and Controlled Today

The basis weight control of paper in many mills all over the world, is executed today by turnkey computerized control systems supplied by a unique vendor. These systems are composed of:

- field mounted sensors;
- control stations;
- final control elements (slice actuators).

The sensor, a beta gauge mounted on a scanner in the finishing section of the paper machine, sends a signal to the process control computer that is proportional to the basis weight of the material. This signal is filtered, decoupled from the material moisture content , compared with the desired profile and processed in an advanced control algorithm that generates a control signal to the slice actuators, in order to adjust the basis weight profile of the sheet.

a) Basis Weight Sensor

The sensor is composed of two independent parts. The bottom part, as can be seen in figure 3.2.1, holds the radioactive source or beta ray source that is, normally, of Kr-85 or Sr-90. The upper part of the sensor, is the ionization chamber that is a beta ray detector. The sheet which basis weight must be measured passes between these two sections.

As the sensor scans across the moving sheet, the source emits beta rays that pass through the sheet and the detector senses the part that is not absorbed by the paper and generates a signal that is proportional to the basis weight of the material.

Figure 3.2.2 shows an overall view of a typical basis weight scanner and the shape of its path on the sheet.

The path that is measured by the sensor depends on the sheet speed and scan speed. Figure 3.2.2 shows four different paths for a constant sheet speed and different scan speeds. Path 'A' is an ideal scan path which is not practical to be achieved by a scanner. This path would yield ideal CD and MD information. Path 'B' is a fast scan speed path that yields good CD and MD informations. Path 'C' is a slow scan speed path which yields poor information of the sheet. Path 'D' is a single point measurement, which yields useless CD information and poor MD information. Therefore, as the scan time gets longer, the extracted CD and MD

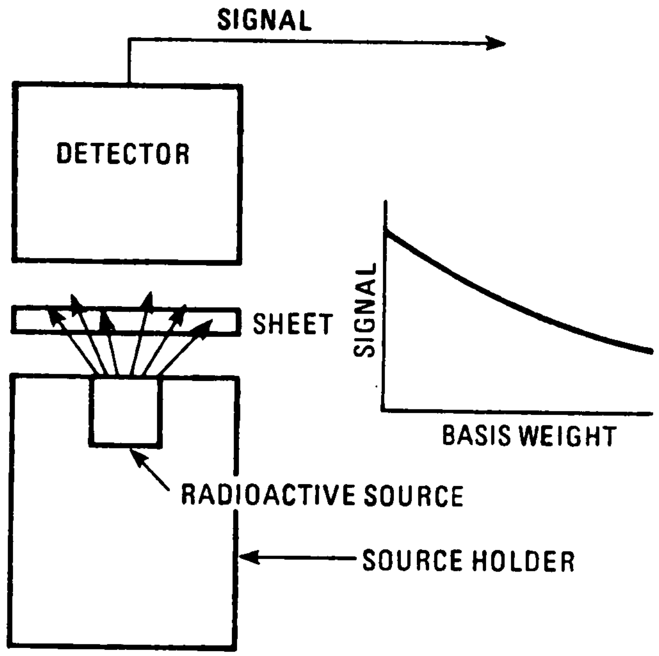


FIGURE 3.2.1 - View of a Typical Basis Weight Sensor.
(Source - Measurex (1977))

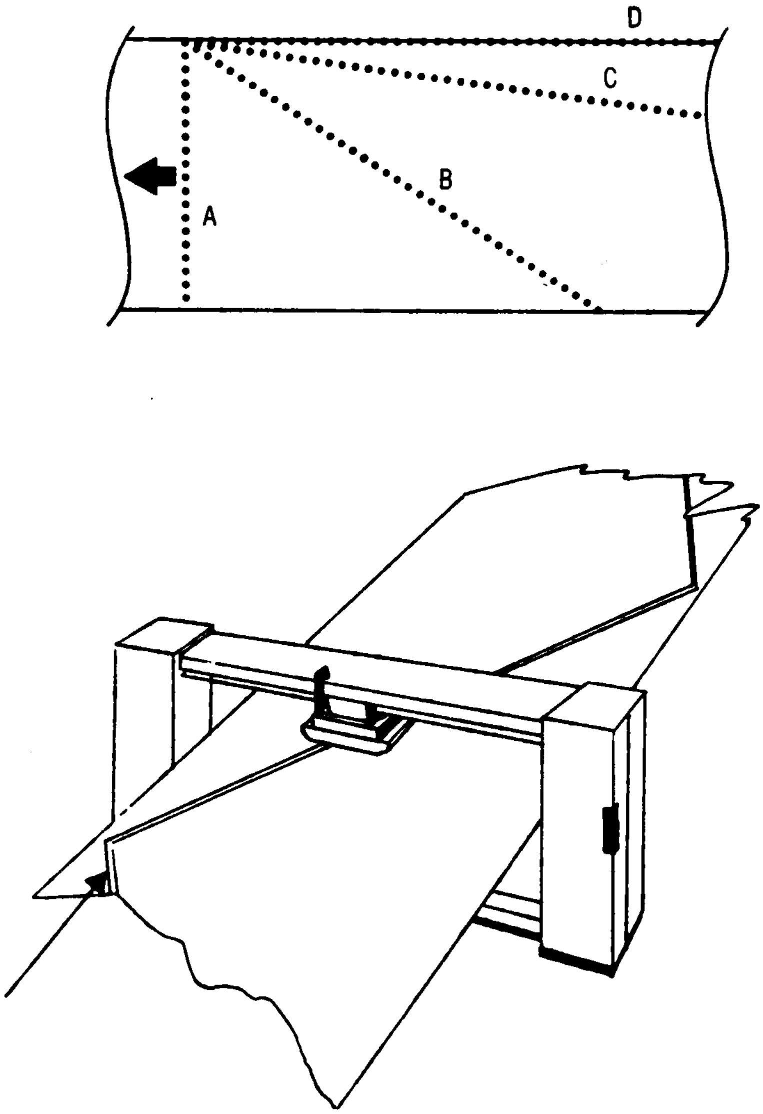


FIGURE 3.2.2 - Various Paths of a Basis Weight Scanner.
(Source - Measurex (1978))

information gets less and less valuable.

b) Control Station

The control station is a special developed panel, suitable to be mounted in the machine site. This panel includes:

- . video-display;
- . operator stations;
- . pushbuttons and switches;
- . mini-computers and peripherals;
- . accessories.

Through the control station, the machine operators have full access to the information necessary to control the paper basis weight. Usually, the system can present the following information for the machine operator:

- . video-displays of basis weight profile deviations and set points, flow and consistency informations, wire speed, calculated values of jet to wire speed ratio and others;
- . reel, grade, shift, daily, profile reports ;
- . quality control reports;
- . alarm informations;
- . process status messages.

c) Basis Weight Actuators

The actuators for basis weight control, also called slice actuators, are specially designed devices to adjust the profile of the slice bar or upper "lip" of the paper machine. These actuators, according to their operating principle, can be grouped into three categories:

- thermal-expansion actuators;
- thermal-hydraulic actuators;
- motorized actuators.

The thermal-expansion actuators utilize hollow SS rods that are engineered to replace existing slice rods. When a high-speed duty cycle current is passed through a low voltage heating element inserted in the rod, the rod heats and expands.

The thermal-hydraulic actuators use the thermal expansion of a fluid to translate power input into linear movement of the spindle rods.

The motorized actuators use an electric motor to transmit power to the screw actuators.

3.2.5 Literature Review

This review will cover only aspects related to the control of the cross machine direction profile of basis weight in paper machines. The subject MD control has been extensively covered in the literature and so, it is not objective of this work.

Some survey papers have to be mentioned in this review because they are very helpful in terms of grouping the references related to computer control and advanced control algorithms applied to the pulp and paper industries. Brewster and Bjerring (1970) gave an overall idea of the field in the period of 1961-1969. Church (1976) reviewed the major problems that are normally found in the pulp and paper industries in the application of process control.
Keyes (1977) reviewed the computer installations in the industry. Battershill and Rogers (1980) presented a survey of the on-line computers installations in the pulp and paper industry. Dumont (1986) reviewed the application of advanced control strategies in the pulp and industries and concluded that very few industrial control schemes use advanced control methods. On the other hand, he mentioned some encouraging applications of adaptive control and signs of fruitful cooperation between academia, industry and suppliers.

The first tentative to control the basis weight CD profile in a paper machine is reported to St.Regis Paper Co. in the mid-60's in a machine with a 92 in. wide wire and 16 slice actuators. The results obtained at that time were 60 % less variation in the basis weight profile. The mathematical considerations applied in the control model were presented by Beecher and Bareiss (1970). This work stands out as the most complete early treatment of CD profile control and the linear dependence between the basis weight and slice opening are still used today in all advanced control algorithms for CD profile control.

Boyle (1977) introduced the concepts of non-linear programming in the solution of CD profile control. In his studies he used another way to set the slice actuators, using a linear incremental steady-state process model and a quadratic objective function. He used quadratic programming to determine the optimum actuator settings. He also touched the problem of required computer size and time when using optimal control algorithms and introduced the concept of quasi-optimal solutions or penalty functions.

Boyle (1978) extended his conclusions and proposed a new set of equations and constraints to describe the basis weight profile control in a paper machine. In this approach he merged the MD profile control with CD profile control in order to guarantee the maximum performance of the latter.

Karlson (1982) discussed the impact of dry weight responses for different machines and their impact on the controllability of CD profiles. He stressed the importance of the slice profile. The conclusion of his studies is that it is necessary to optimize both the slice profile and the dry weight profile, and in some cases it is necessary to balance this control between several profiles.

Wilhelm Jr. and Fjeld (1983) made a review of the state of the art of CD profile control algorithms in general.

Wilhelm Jr. (1984) pointed out that the spatially distributed nature of CD variations implies that a spatial as well as a temporal response is involved in the process behavior, and that both spatial and temporal variations in the sheet affected its controllability.

Balakrishnan and McFarlin (1985) presented the theory and results of a strategy for the control of basis weight profile on paper machines, based on a model of the slice lip as an elastic beam subjected to loads by elastic actuators. They also discussed how the high degree of cross coupling and asymmetries observed in the profile response to actuator moves, can be explained in large part by the elastic nature of the slice lip.

Nuyan (1986) also discussed the influence of the slice characteristics in the controllability of basis weight CD profile control.

Chen and Wilhelm Jr. (1986) presented a more rigorous mathematical treatment for the quadratic programming and penalty functions approach proposed by Boyle (1977).

Chen, Snyder and Wilhelm Jr. (1986) presented an adaptive control algorithm to control the basis weight CD profile on paper machines. The designed controller minimizes a quadratic cost function based on a process response model and the necessary actuator constraints. The process model is identified on-line using a modified generalized least-squares algorithm.

Other references about CD profile control are presented in the bibliography of this work.

CHAPTER 4

MATHEMATICAL MODEL OF THE PAPER MACHINE

One major focus of this work is in the development of a dynamic model for a paper machine. The model is used to develop and test a computer based strategy for controlling the basis weight. Only the wet end of the machine is considered here, because once the sheet is formed at the wet end section, the dry basis weight does not vary significantly through the presses and dryers sections.

This chapter is basically divided into two parts:

- general description of the process for paper production and the paper machine;
- simulation model and assumptions made for each section of the wet end of the paper machine:
    - pipe section;
    - headbox;
    - wire section.

4.1 General Process Description

The objective of a paper mill is to provide the transformation of the cellulose pulp produced in the pulp mill into a final useful product that is the paper.

The produced paper may have different characteristics and specifications according to its final application. So, the paper mills are designed and operated in different ways in order to meet the product and production requirements. But, in general they can be divided in three sections that are common to all of them. These sections are:

- stock preparation plant
- paper machine

  wet end
  dry end
  finishing

- converting plant

Figure 4.1.1 presents a general view of a typical paper mill using a Fourdrinier type paper machine.

4.1.1 Stock Preparation Plant

The pulp, as it is produced in the pulp mill is not normally suitable for the manufacture of most paper grades. A sheet made with only this pulp would have low strength, high bulk, irregular texture, uneven formation and would not be resistant to water. Therefore, in order to make the pulp suitable for the paper manufacture, various characteristics must be imparted to the fibers. This is accomplished by blending different types of fibers, adding chemical additives and fillers and mechanically treating the fibers.

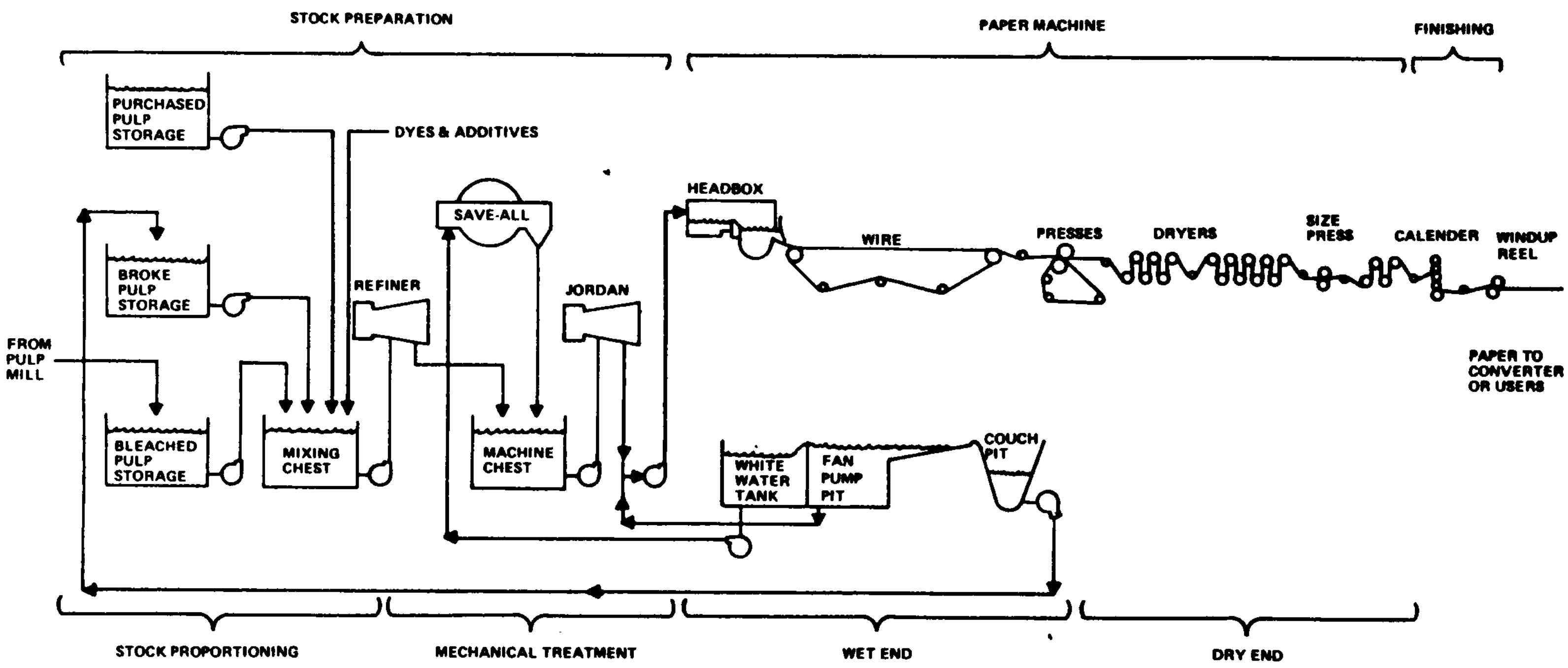


FIGURE 4.1.1 - Simplified Flow Diagram of a Typical Paper Mill.
(Source - Lavigne (1979))

a) Blending of Fibers

Normally a paper is not made of only one type of fiber because the blending of different fibers in specific proportions, give the final product special characteristics, for example: softwood fibers give strength to the sheet while hardwood fibers give fine quality.

b) Mechanical Treatment of the Fibers

In order to prepare the fibrous slurry for a better sheet formation in the paper machine, the pulp flux passes through a series of refiners and screens.

The fibers are actually hollow and stiff, so they are put through a series of serrated metal disks in the refiners which then rough them up, fray them and cause the fibers to collapse. This gives the mixture better bonding quality, allowing the fibers to adhere to each other more perfectly at the wet end of the machine.

c) Additives and Fillers

The chemical additives and fillers are added to the pulp in the stock preparation plant in order to provide the the final paper some properties like : ink holdout, tear strength, printability, pick resistance, water resistance, bulk and color.

If a closer look is taken to a sheet of paper made only of pulp and no additives or fillers, it will be observed a lot of hills and valleys that must be evened out in order that the paper meets the necessities of the printing industry. These hills and valleys are evened out by the addition of fillers like calcium carbonate,that also adds brightness to the paper. Another group of additives that can be added to the pulp are the ones that improve the paper paper resistance to the penetration of water or water solutions. These additives are called sizing additives.

Titanium dioxide, dyes, etc. can also be added to improve the paper quality.

Figure 4.1.2 shows a general view of a typical stock preparation plant and its basic controls.

4.1.2 Paper Machine

After the stock is suitably prepared in the stock preparation plant, it is furnished to the paper machine where the final formation and drying of the paper or paperboard sheet is accomplished.

There is a number of different types of paper machines used to manufacture the many and varied required grades. However, the general method used to make them is essentially the same and can be summarized as:

. the web formation takes place in a section called the WET END;

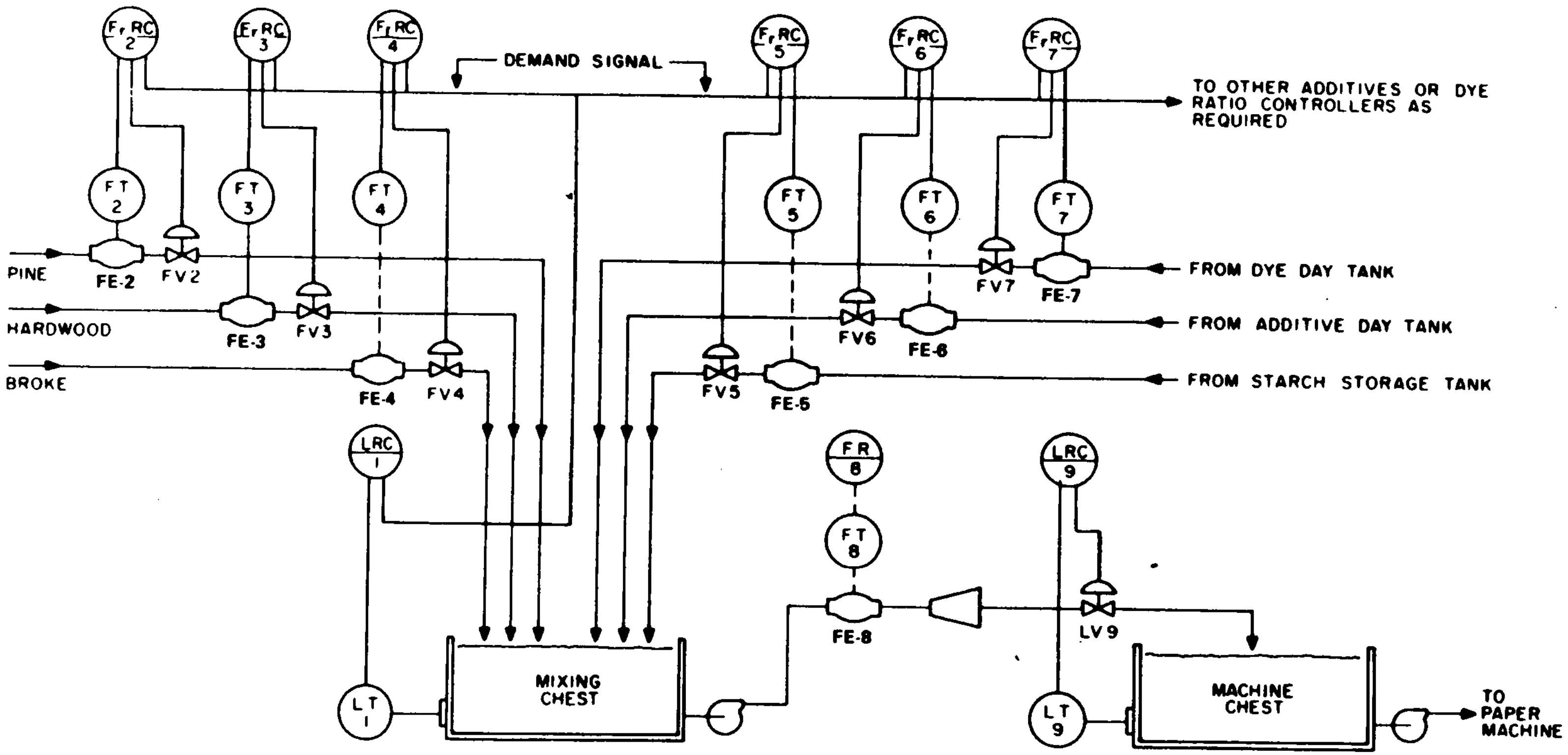


FIGURE 4.1.2 - Typical Stock Preparation Plant.
(Source - Lavigne (1979))

- after most of the water contained in the feed stock is retained in the wet end section, the web goes to the DRY END SECTION where it is conveniently dried to the final specifications;
- FINISHING;

a) Paper Machine - Wet End

The wet end section of the paper machine is where 99% of the water contained in the feed stock is retained and the formation of the sheet occurs.

The most common types of paper machines wet ends are:

- Fourdrinier type
- Cylinder type
- Sheet Formers.

The Fourdrinier type is far the most extensively used, and is the one considered throughout this work.

The principal components of a typical Fourdrinier type machine are : machine chest, refiner, stuff box, fan pump, cleaners, screens, headbox, wire screen, white water tank, wire pit, couch pit, presses, save all, broke pulper, etc. In sections 4.2, 4.3, 4.4 more details are given for the operation of most of the listed items.

A special consideration is given in this section to the PRESSES, because of their many functions in the paper machine operation.

The importance of the press section can be characterized by:

- increase the consistency of the sheet by removal of at least 2% of the water that still remains in the sheet after its formation;
- convey the paper from the forming unit to the drying section, without disrupting or disturbing the structure of the sheet;
- alter the surface properties of the paper;
- reduce the bulk of the paper.

Figure 4.1.3 shows a general view of a typical Fourdrinier type wet end of a paper machine, its basic equipment and controls.

b) Paper Machine - Dry End

Paper leaves the presses with approximate 40% of solids. It is conveyed to the dry end section of the paper machine, where heat is applied to drive off water by evaporation, and bring the sheet to the desired moisture content specification.

The dry end of a conventional Fourdrinier machine consists of from 40 to 70 paper drying cylinders, divided into from two to five top and bottom sections. Each section has its own drier felt. Sectionalization is adopted in order to allow a degree of shrinkage control and to reduce the

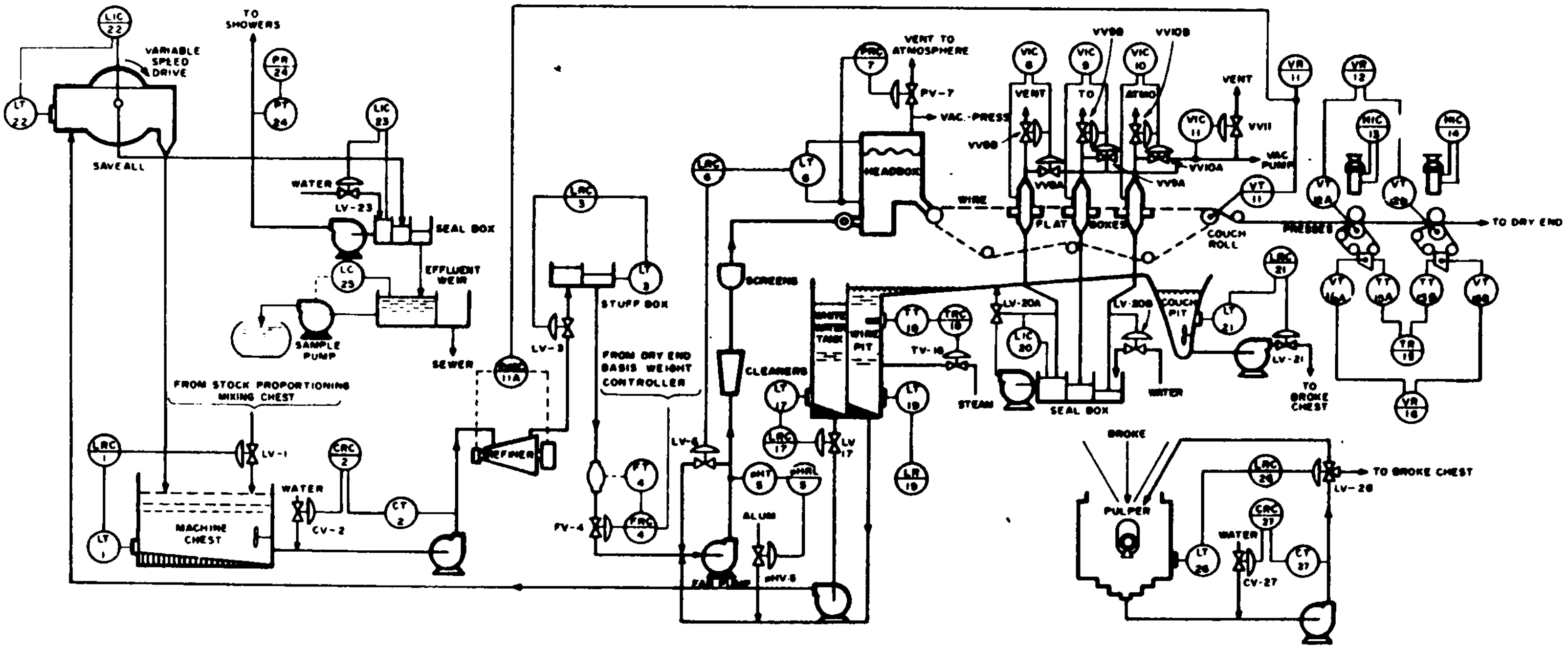


FIGURE 4.1.3 - Wet End Section of a Fourdrinier Paper Machine.
(Source - Lavigne (1979))

possibility of sheet creasing and breaking.

Figure 4.1.4 shows a general view of a typical drying section of a paper machine and its basic controls.

c) Finishing

In a paper machine, the finishing operation can be can be divided in calendering the produced paper and winding it up to the required paper roll diameter.

In the paper making process the calenders produce the the desired finish and caliper (paper thickness) to the paper being produced. Finish is varied to the desired degree by increasing or decreasing the number of rolls in the calender, by loading or relieving the weight of the roll system to create higher or lower nip pressures, and by heating or cooling the rolls.

Caliper is controlled by adjusting the nip load. Light loads or fewer rolls, result in less reduction of caliper; heavy loads, or more rolls, result in great reduction.

One of the secondary functions of the calender is to correct certain variations existing in the sheet prior to entering the calender, for example heavy centers or edges. Another secondary function can be the application of sizing solution, color or coatings.

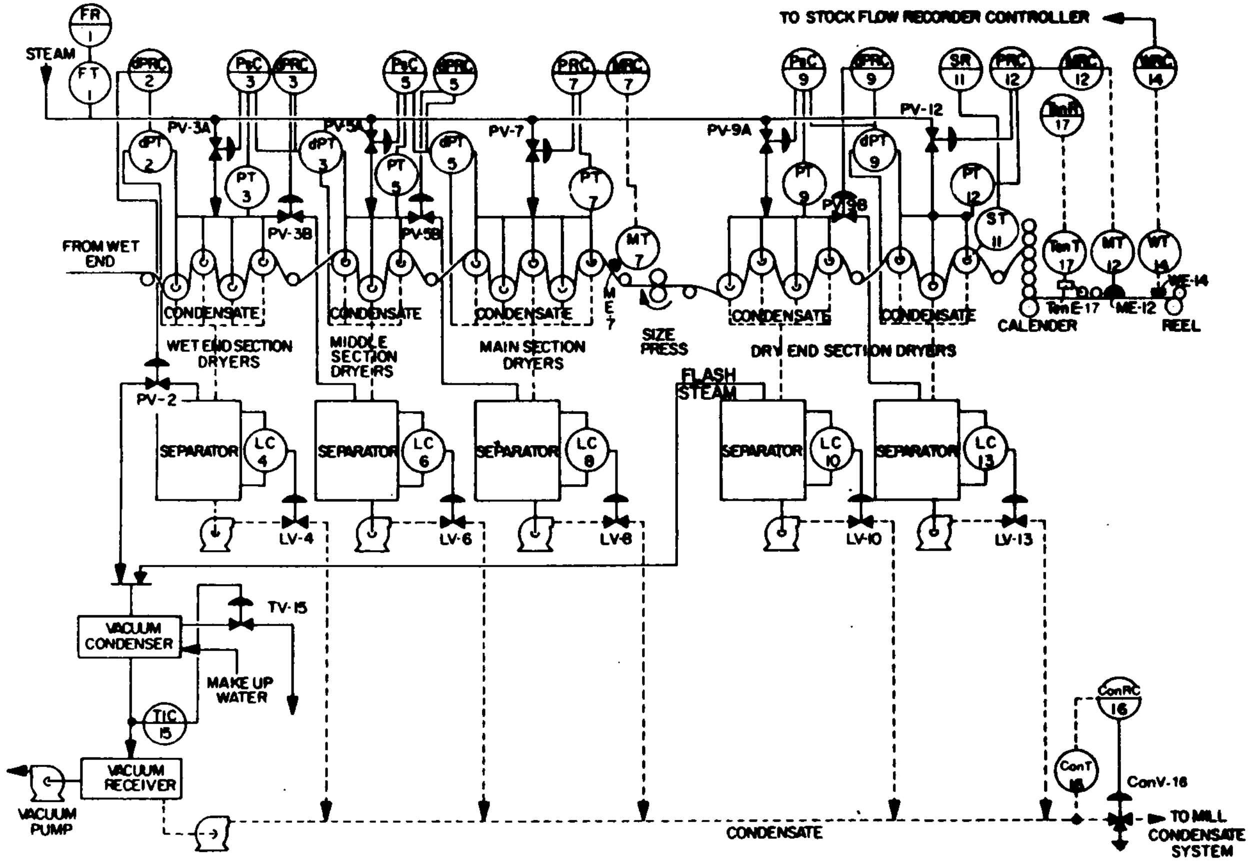


FIGURE 4.1.4 - Dry End Section of a Typical Paper Machine.
(Source - Lavigne (1979))

4.1.3 Converting Plant

The paper roll obtained in the paper machine is sent directly to the converting plant, where it is transformed in rolls with smaller diameters and widths to fit final clients requirements, or it is transformed in smaller rolls and later in sheets in a sheeter. Also in this section of the mill, the paper rolls or sheet stacks are packed and delivered to the final users.

Once given an overall view of the paper making process, the discussions can, now, be more specific and analyze the features of the developed dynamic model for the wet end section of the paper machine.

4.2 Pipe Section

The PIPE SECTION of a paper machine consists of all equipments and pipes leading the paper stock to the headbox. More precisely it consists of the following items:

- pipe from stuff-box up to the fan pump;
- fan pump;
- pipe between fan pump and cleaners;
- cleaners;
- pipe between cleaners and screen;
- screen;
- pipe between screen and headbox;
- pipe between wire pit and suction of fan pump.

4.2.1 Process Variables

The process variables involved in the operation of the pipe section are summarized in figure 4.2.1, and their descriptions can be found in appendix A (Nomenclature).

4.2.2 Mathematical Development

The pipe section is modeled as a constant volume tank. The volume of this tank varies from system to system and has to be specified for each machine. The volume of the tank is equal to the sum of the volumes of each individual pipe and equipment contained in the pipe section.

The STEADY-STATE MATERIAL BALANCE in stock, in the pipe section is :

$$Q_{TKS}(0)*C_{TKS}(0) + Q_{WW}(0)*C_{WW}(0) = Q_{TNS}(0)*C_{TNS}(0) + + Q_{R}(0)*C_{TNS}(0) \qquad \text{eq. 4.2.1}$$

Considering that the solids concentration in each flux is very small, they can be neglected, and so thin stock flow to the headbox can be written as :

$$Q_{TNS}(0) = Q_{TKS}(0) + Q_{WW}(0) - Q_{R}(0) \qquad \text{eq. 4.2.2}$$

The initial consistency of the material being sent to the headbox is :

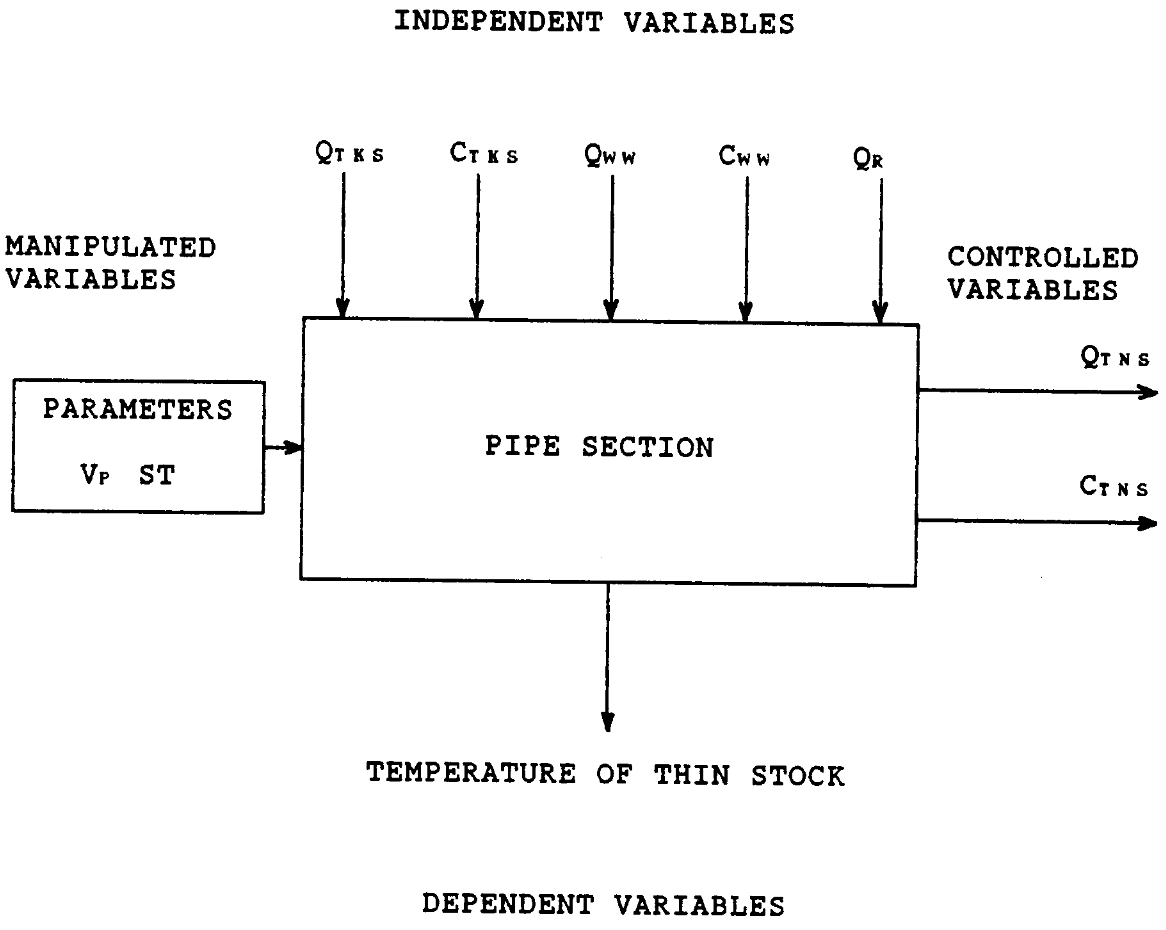


FIGURE 4.2.1 - Block Diagram of the Pipe Section

$$C_{TNS}(0) = \frac{Q_{TKS}(0) * C_{TKS}(0) + Q_{WW}(0) * C_{WW}(0)}{Q_{TKS}(0) + Q_{WW}(0)} \qquad \text{eq. 4.3.3}$$

The consistency of the thin stock going to the headbox (C_{TNS}), varies according to the consistencies and flow rates of the in and outflows to the pipe section. The dynamics of its variation can be described by :

$$\frac{d\,C_{TNS}}{dT} = \frac{1}{V_P} * (Q_{TKS}(T) * C_{TKS}(T) + Q_{WW}(T) * C_{WW}(T) -$$

$$- Q_{TNS}(T) * C_{TNS}(T) - Q_R(T) * C_{TNS}(T)) \qquad \text{eq.4.3.4}$$

If the system sampling time ST is much smaller than the time constant of the process, equation 4.3.4 can be discretized in terms of time quantizer K. The result of this quantization is shown in equation 4.3.5.

$$C_{TNS}(K+1) = C_{TNS}(K) + \frac{ST}{V_P} * (Q_{TKS}(K) * C_{TKS}(K) +$$

$$+ Q_{WW}(K) * C_{WW}(K) - Q_{TNS}(K) * C_{TNS}(K) -$$

$$- Q_R(K) * C_{TNS}(K)) \qquad \text{eq. 4.3.5}$$

where K varies from 0 to the value of the simulation time divided by ST.

4.3.3 Major Assumptions Used in the Model

a) The pipe section is modeled as a constant volume tank.

b) The mixing between the thick stock flow and recirculated white water is instantaneous and the resulting thin stock is homogeneous.

c) The temperature of the thick stock and white water are constant.

d) All fibers that compose the thick stock have the same characteristic.

e) The wire pit is considered a well mixed tank.

f) The fillers contained in the thick stock flow to the headbox are not explicitly considered.

g) The sampling time ST is much smaller than the time constant of the process.

4.3 Headbox

The HEADBOX is one of the most significant sections of the paper producing process. It has a very important effect on the formation of the sheet and its basis weight. These two factors along with the fibers characteristics make a dominant share of the quality factors of the produced paper.

The headbox is a flow chamber that receives the diluted pulp slurry and discharges it uniformly onto the wire of the Fourdrinier Machine (wire section).

The quality of the paper being produced is governed by the even dispersion of fibers and fillers in the forming mat.

The headbox is designed to distributing the paper stock evenly and uniformly across the machine width. It levels out machine direction velocity gradients and cross - direction profile variations, and helps eliminate fiber floccing through controlled turbulence and matching the slurry discharge velocity with the forming section velocity (jet to wire speed ratio).

The "key" operation variables of the headbox are:

- stock consistency
- stock temperature
- jet to wire speed ratio

The stock consistency and temperature are inter-related variables. The headbox consistency can be controlled by direct actuation of the slice actuators.

The design of the paper machine headbox varies from supplier to supplier, so this particular study will consider the analysis of the variables involved in the operation of a general headbox, without any supplier particularization.

The general case considered in this study is a closed type headbox. Although some low speed machines use open headboxes, where the pressure over the liquid phase is the atmospheric pressure. Such cases will be considered a particular solution of the general model.

Figure 4.3.1 shows an overall view of a paper machine headbox.

4.3.1 Process Variables

The process variables involved in the operation of the headbox of a paper machine are summarized in figure 4.3.2, and their descriptions can be found in appendix A called Nomenclature.

4.3.2 Mathematical Development

The most significant aspect of the analysis of the headbox of a paper machine is the hydraulic behavior of the process and in particular the fiber flow itself.

The fiber flow is dependent on the liquid flow, and so, the knowledge of the hydraulic process inside the headbox is an essential part of the mathematical model of the wet end of the machine.

a) Jet to Wire Speed Ratio

The jet to wire speed ratio is defined as the ratio between the velocity of the stock jet emerging from the the slice opening of the headbox and the velocity of the wire in the forming section (Fourdrinier Machine).

The jet to wire speed ratio strongly influences some

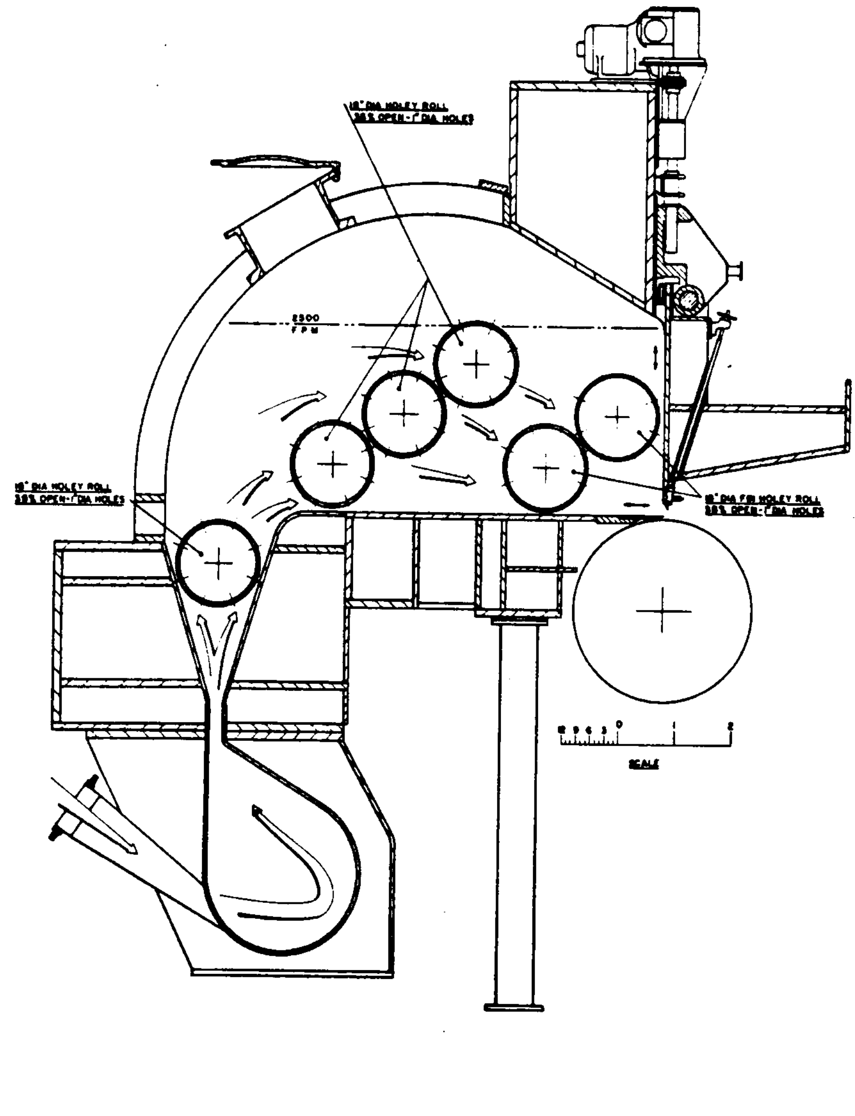
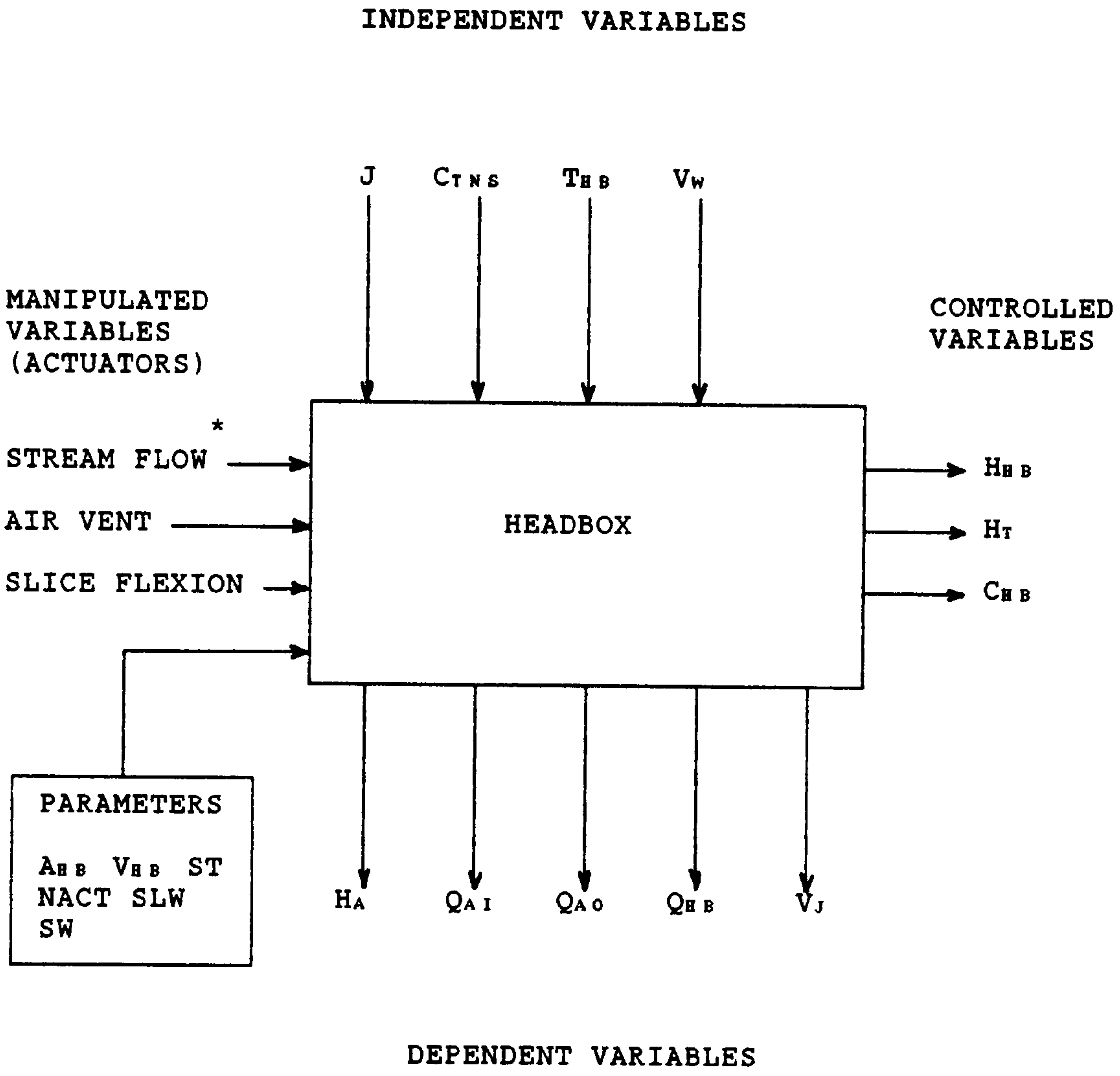


FIGURE 4.3.1 - General View of a Paper Machine Headbox.
(Source - Libby (1962))



* In some systems can be the fan pump speed

FIGURE 4.3.2 - Block Diagram of the Headbox

paper properties such as strength, tear, curl and formation.

The jet to wire speed ratio is given by:

$$J = \frac{V_J}{V_W} \qquad \text{eq. 4.3.1}$$

Given a jet to wire set point J_{SP}, the required jet velocity can be determined from equation 4.3.1.

$$H_{TSP} = \frac{J_{SP}^2 * V_{WSP}^2 * 10000}{C_V^2 * 2 * G} \qquad \text{eq. 4.3.2}$$

b) Level of the Headbox

Another important dynamic variable of the headbox operation is the stock level inside it. The dynamics of its variations is governed by:

$$\frac{d}{dT} H_{HB}(T) = \frac{1}{A_{HB}} * (Q_{TNS}(T) - Q_{THB}(T)) \qquad \text{eq. 4.3.3}$$

The total headbox head is defined by:

$$H_T(T) = H_A(T) + H_{HB}(T) \qquad \text{eq. 4.3.4}$$

The headbox emerging stock velocity is defined by:

$$V_J(T) = C_V * SQRT(2*G*H_T(T)) \qquad \text{eq. 4.3.5}$$

The total discharge flow from the headbox is:

$$Q_{THB}(T) = C_D * A_{SL} * V_J(T) \qquad \text{eq. 4.3.6}$$

The theoretical discharge flow for each section of the slice bar (or actuator of the slice bar) can be represented by the following equation:

$$Q_{HB}(I) = C_D * SLP(I) * SLW * C_V * SQRT(2*G*H_T(T)) \qquad \text{eq. 4.3.7}$$

Substituting equations 4.3.5 and 4.3.6 in 4.3.3 it is found the dynamic equation of the stock level variation inside the headbox.

$$\frac{d}{dT} H_{HB}(T) = \frac{1}{A_{HB}} * (Q_{TNS}(T) - C_D * A_{SL} * C_V * $$
$$* SQRT(2*G*H_T(T)) /10 \qquad \text{eq. 4.3.8}$$

If the system sampling time, ST, is much smaller than the time constant of the process, equation 4.3.8 can be can be discretized in terms of the time quantizer K. The result of this quantization is shown in equation 4.3.9.

$$H_{HB}(K+1) = H_{HB}(K) + \frac{ST}{A_{HB}} * (Q_{TNS}(K) - C_D * C_V *$$
$$* A_{SL} * SQRT(2*G*H_T(K)) /10 \qquad \text{eq. 4.3.9}$$

where K varies from 0 to the required simulation time divided by the sampling time ST.

c) Air Pad Pressure

The AIR PAD is the volume of air contained in the headbox, above the stock level.

The air pressure is affected by changes in the headbox stock level and also by net flow of air through it.

The air pressure dynamics can be obtained from the ideal gas law approximation.

$$(V_{HB} - A_{HB}*H_{HB})*H_A = \frac{m_A}{M_A}*R*T_{HB} \qquad \text{eq. 4.3.10}$$

Differentiating equation 4.3.10 with relation to time and assuming the temperature inside the headbox constant,

$$\frac{d}{dT} H_A(T) = \frac{H_A(T)}{(V_{HB} - A_{HB}*H_{HB}(T))}*(Q_{TNS}(T) - C_D*C_V*A_{SL}*$$

$$*SQRT(2*G*H_T(T))*\frac{R*T_{HB}}{M_A*(V_{HB} - A_{HB}*H_{HB}(T))}*$$

$$*(Q_{AI}(T) - Q_{AO}(T)) \qquad \text{eq. 4.3.11}$$

If the system sampling time ST is much smaller than the process time constant, equation 4.3.11 can be discretized in terms of the time quantizer K. The result of this quantization is shown in equation 4.3.12.

$$H_A(K+1) = H_A(K) + \frac{ST*H_A(K)}{(V_{HB} - A_{HB}*H_{HB}(K)/100)}*(Q_{TNS}(K) -$$

$$- C_D*C_V*A_{SL}*SQRT(2*G*H_T(K)/1000) +$$

$$+ \frac{ST*R*T_{HB}}{M_A*(V_{HB} - A_{HB}*H_{HB}(K)/100)}*(Q_{AI}(K) - Q_{AO}(K)) \quad \text{eq. 4.3.12}$$

where K varies from 0 to the required simulation time divided by the sampling time ST.

d) Headbox Consistency

The term consistency, as used in the pulp and paper industry, is defined as a percentage by weight of dry fibrous material in any combination of pulp and water or stock (pulp + additives + water). Consistency is expressed by equation 4.3.13.

$$C = \frac{F}{W}*100 \qquad \text{eq. 4.3.13}$$

where

C = sample consistency (%)

F = weight of dry fibrous material in the sample

W = total weight of the wet sample

However, the definition of consistency used in this work is equal to the weight ratio of dry solids to total water. This is a variation from the standard definition *given above, but as the consistencies are normally very low in this situation, the introduced error is very small and so, can be neglected. Equation 4.3.14 shows this definition.

$$C_{HB} = \frac{\text{weight of fibrous material in the headbox}}{\text{total volume of stock}}$$

$$C_{HB}(T) = \frac{F_{HB}(T)}{A_{HB}*H_{HB}(T)} \qquad \text{eq. 4.3.14}$$

The rate of fiber accumulation inside the headbox is given by equation 4.3.15.

$$\frac{d}{dT} F_{HB}(T) = Q_{TNS}(T)*C_{TNS} - Q_{THB}(T)*C_{HB}(T) \qquad \text{eq. 4.3.15}$$

So, differentiating equation 4.3.14 with relation to time and substituting equation 4.3.15 in it, is obtained the dynamic equation of the consistency variation inside the headbox and consequently the consistency of the stock going to the formation section of the paper machine.

$$\frac{d}{dT} C_{HB}(T) = \frac{1}{A_{HB}*H_{HB}(T)} * \Big(Q_{TNS}(T)*C_{TNS}(T) -$$

$$- Q_{THB}(T)*C_{HB}(T) - A_{HB}*C_{HB}(T)*\frac{d}{dT} H_{HB}(T) \Big) \qquad \text{eq. 4.3.16}$$

If the system sampling time is much smaller than the process time constant, equation 4.3.16 can be discretized in terms of the quantizer K. The result of this quantization is shown in equation 4.3.17.

$$C_{HB}(K+1) = C_{HB}(K) + \frac{ST}{A_{HB}*H_{HB}(K)}*\Big(Q_{TNS}(K)*C_{TNS}(K) - Q_{THB}(K)*C_{HB}(K) - A_{HB}*C_{HB}(K)*\frac{H_{HB}(K+1) - H_{HB}(K)}{ST*(1/10)} \Big) \quad \text{eq. 4.3.17}$$

where K varies from 0 to the value of the required simulation time divided by the sampling time ST.

e) Slice Actuators

The performance of the headbox of a paper machine is deeply embodied in the characteristics of the SLICE BAR that provides the thin jet of stock delivered to the sheet forming section of the machine. In reality, the slice bar is the forward wall of the headbox, whose lower edge forms the upper boundary of the orifice or slice opening.

Figure 4.3.3 presents some typical slice bar and actuators in paper machines.

The characteristics of the jet coming out of the slice bar are determined by the slice design and the flow conditions prior to it.

The jet emerging from the headbox slice, contracts in thickness and deflects downward as a result of the slice geometry. The jet contraction governs the jet thickness, which together with the jet velocity, determines the rate of discharge flow from the headbox. The deflection angle

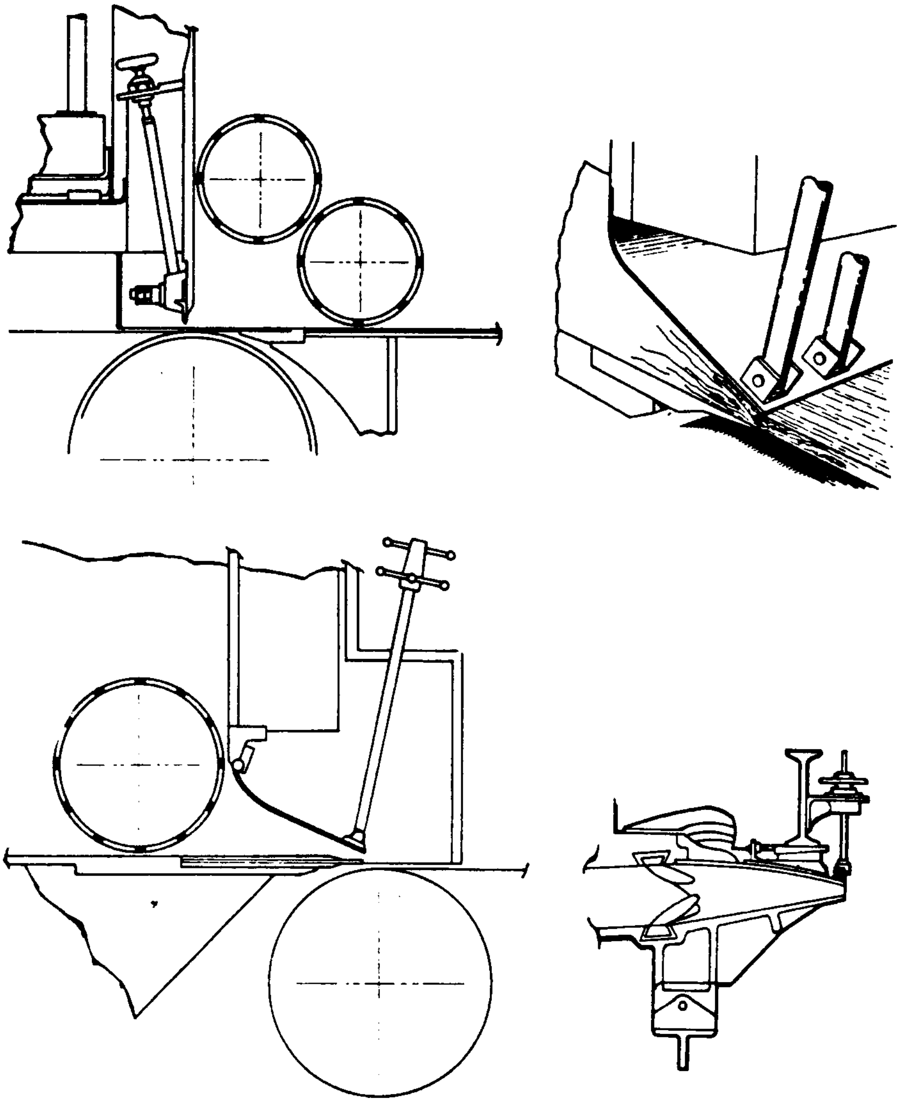


FIGURE 4.3.3 - Typical view of Slice Actuators.
(Source - Libby (1962))

determines the point and direction of the jet impingement upon the forming wire. These effects have long been known to be important in paper machine operation for their effect on drainage and various paper properties such as tensile ratio, formation and curl.

The magnitude of the jet contraction and the angle of outflow caused by the slice geometry, used in this work, are determined from the empirical equations developed by Kerekes and Koller (1981) and reinforced by TAPPI standards TIS-014 2/3/4/5 (1981). These equations are:

$$C_D = \left(\frac{A_0 - A_1 * Y}{1 - A_2 * Y} \right) * EXP\left(- \frac{A_3 - A_4 * Y}{1 - A_5 * Y} * X^F \right) + \frac{A_6 - A_7 * Y}{1 - A_8 * Y} \qquad \text{eq. 4.3.18}$$

where C_D is the contraction coefficient.

$$B = \left(\frac{B_0 + B_1 * X - B_2 * Y + B_3 * Y^2 - B_4 * X * Y + B_5 * X * Y^2}{(1 - B_6 * Y)^2} \right) * EXP\left(\frac{- B_7 - B_8 * X + B_9 * Y + B_{10} * X * Y}{(1 - B_6 * Y)} \right) \qquad \text{eq. 4.3.19}$$

where B is the deflection angle.

$$X = \frac{L}{b} \qquad \text{eq. 4.3.20}$$

$$Y = \frac{b}{B}$$ eq. 4.3.21

The coefficients used in equations 4.3.20 and 4.3.21 can be found in Koller (1981) or TAPPI TIS-014.

The types of slices considered in this work are:

. 10° of inclination

. 45° of inclination

. 90° of inclination

4.3.3 Major Assumptions Used in the Model

a) The headbox is considered a well mixed tank.

b) The temperature inside the headbox is homogeneous and constant.

c) The consistency inside the headbox is homogeneous and constant.

d) The thin stock is considered an incompressable fluid.

e) The point at which the pressure is measured, in the headbox, is at the same elevation point of the jet to the wire.

f) No substantial friction losses occur between the point of pressure measurement and the slice.

g) The stock flow velocity is small at the point of pressure measurement.

h) The air pad dynamics was obtained from the ideal gas law approximation.

i) The sampling time ST is much smaller than the time constant of the process.

4.4 Wire Section

The paper is a web of fibers, forming a tri-dimensional network. The predominant method of making paper, involves the filtration from a dilute fiber suspension in water onto an endless wire mesh, that is fine enough to retain most of the fibers. The section of the paper machine performing this function is called FORMING SECTION, and it receives the fiber suspension in a continuous jet coming from the headbox at a consistency in a range of 0.1 to 2 %.

The forming section delivers to the press section a self supporting sheet with consistency between 10 to 25 %. This is because most of the water contained in the stock coming from the headbox is retained in this section of the machine (approximate 97 %).

The basic properties of the final paper, like : fiber orientation, strength, isotropy, fines distribution through the sheet, wire marks, surface uniformity, etc. are primarily determined in the forming section.

The demand on the forming section of the paper machine varies substantially due to the type of paper produced, basis weight and speed of the machine. This demand resulted in the development of different types of forming methods, each of them preferred for each different application. In this work the focus will be on the FOURDRINIER type or open wire former.

The basic configuration of an open wire former can be seen in figure 4.4.1.

4.4.1 Process Variables

The process variables involved in the operation of the wire section of the paper machine is summarized in figure 4.4.2, and their descriptions can be found in appendix A (Nomenclature).

4.4.2 Mathematical Development

For the purpose of basis weight control, it is of major interest to understand the dynamics which describes, how fluctuations in stock concentration propagate through the the wire section. The hydrodynamical processes involved, mixing and water-fiber separations are very complicated and a detailed understanding and modeling of them is still not available.

The approach used in this work is similar to the one proposed by Astrom (1974), but instead of considering the average retention in the all width of the sheet, this sheet was divided in equal spaced sections, and the average taken individually for each section. The number of sections equals the number of slice actuators and the width is equal to the

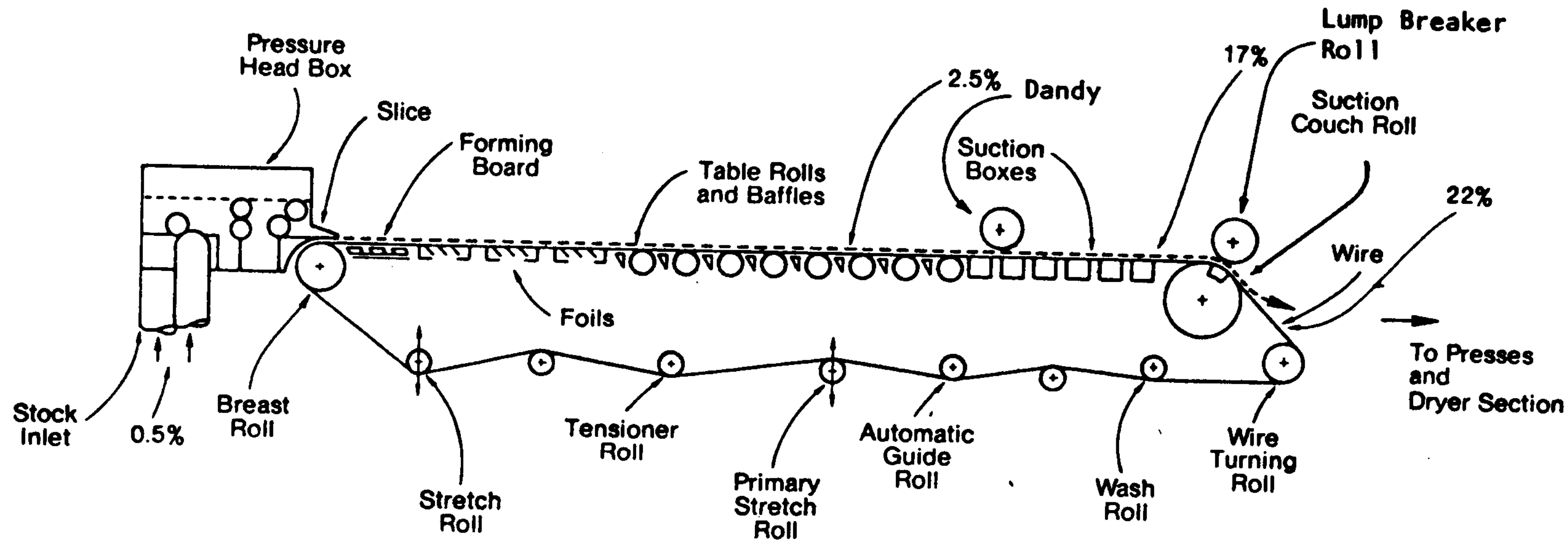


FIGURE 4.4.1 - Wire Section of a Paper Machine.
(Source - Casey (1980))

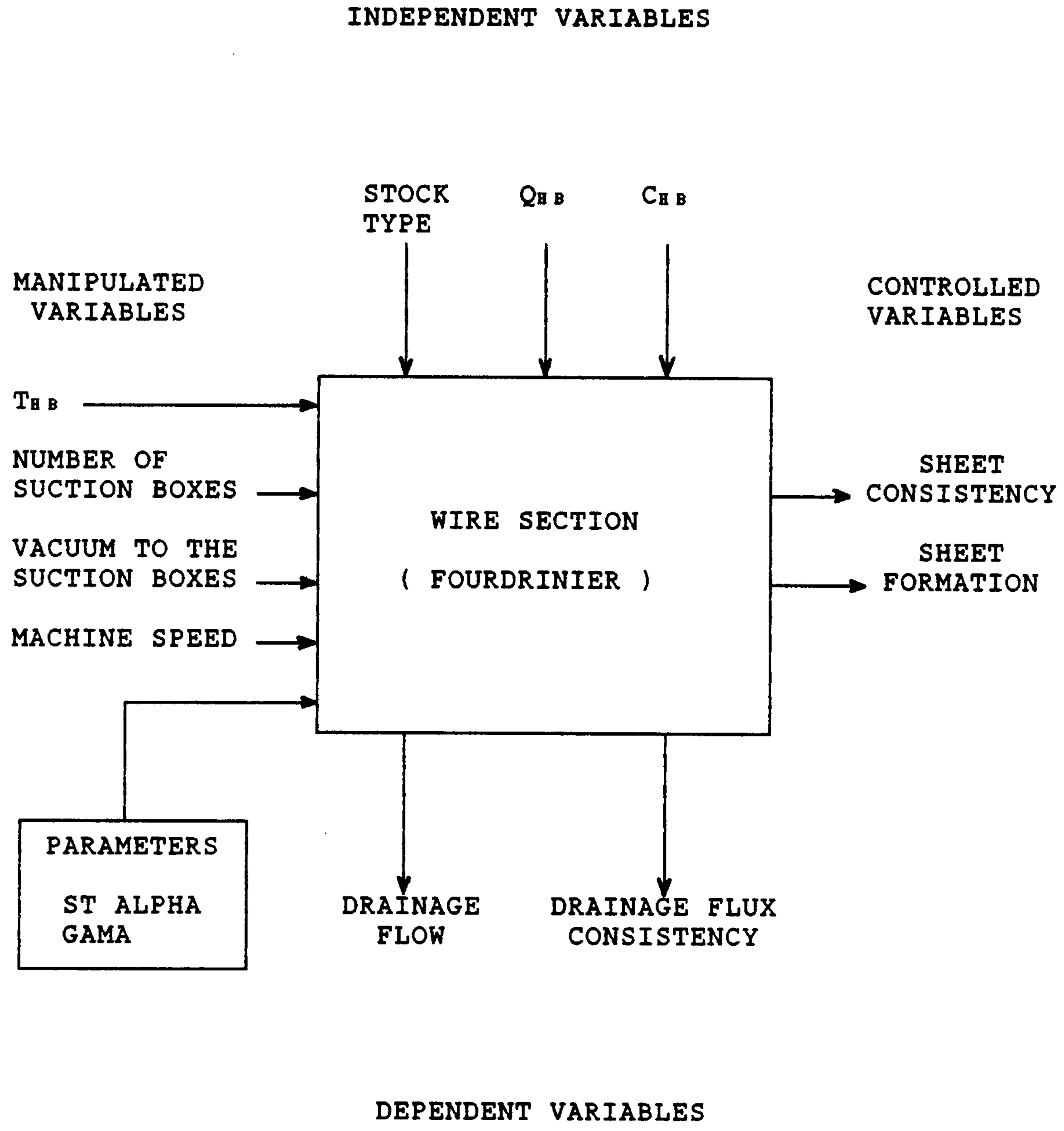


FIGURE 4.4.2 - Block Diagram of the Wire Section

width of an slice actuator as can be seen in figure 4.4.3.

The average retention for each section of the wire can be described by equation 4.4.1.

$$DW = \ln \frac{EXP(-GAMA*BW(I)) - \dfrac{1}{1 - ALPHA}}{EXP(-GAMA*BW(I))}$$

$$RW(I) = \frac{BW(I)}{\dfrac{1}{GAMA}*DW - \dfrac{1}{GAMA}*\ln\left(1 - \dfrac{1}{1 - GAMA}\right)} \qquad \text{eq. 4.4.1}$$

The equation describing the variation of the basis weight throughout each section of the sheet, as shown in figure 4.4.3, is equation 4.4.2.

$$BW(I) = \frac{RW(I)*Q_{HB}(I)*C_{HB}(I)}{SLW*SW} \qquad \text{eq. 4.4.2}$$

4.4.3 Major Assumptions Used in the Model

a) The wire section of the paper machine is of Fourdrinier type.

b) Since the basis weight varies along the wire, it is necessary to take the average in order to obtain the average retention for the wire. Astrom (1973) showed that the harmonic mean is appropriate and is represented by equation 4.4.3

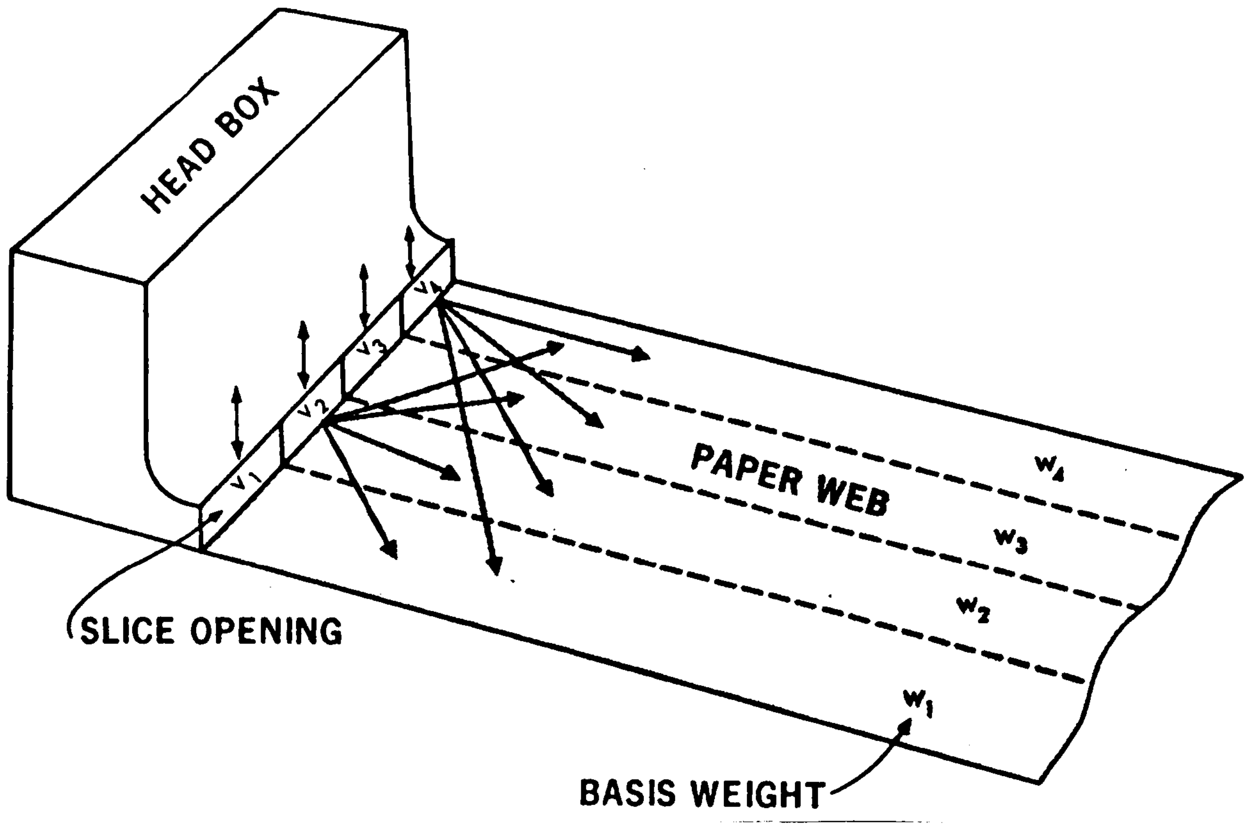


FIGURE 4.4.3 - Conformation of the Wire Section of a Paper Machine.
(Source - Beecher and Bareiss (1970))

$$RW(BW) = \frac{BW}{\int_0^W \left(\frac{BW}{R_H(BW)} \right) d(BW)} \qquad \text{eq. 4.4.3}$$

where

$$R_H(BW) = 1 - (1 - ALPHA)*EXP(-GAMA*BW) \qquad \text{eq. 4.4.4}$$

c) The wire is homogeneous through all its extension.

d) The sampling time ST is much smaller than the time constant of the process.

CHAPTER 5

BASIS WEIGHT CONTROL STRATEGY

The task of correcting eventual basis weight variations in a paper machine is a formidable and time consuming task for the machine operator if he has to do it manually. Imagine, for example, a paper machine with 50 slice actuators, if a basis weight deviation from the required profile is detected and must be corrected. The operator has to change the position of one or more of the slice actuators to try to bring the profile back to the desired value. Figure 5.1.1 shows what happens. As soon as he changes the position of one of the actuators, it interferes with some of the adjacent actuators meaning that they are spatially coupled, which makes the control much more difficult. But this correction is not as difficult if a computerized control system and suitable actuators are available.

The subject of this chapter is the development of a mathematical algorithm which can be used to automatically calculate the actuator position changes necessary to maintain a good basis weight profile. The algorithm is developed to be implemented in a small computed based control system environment. Most of the considerations used in the design are found in the mentioned bibliographic references.

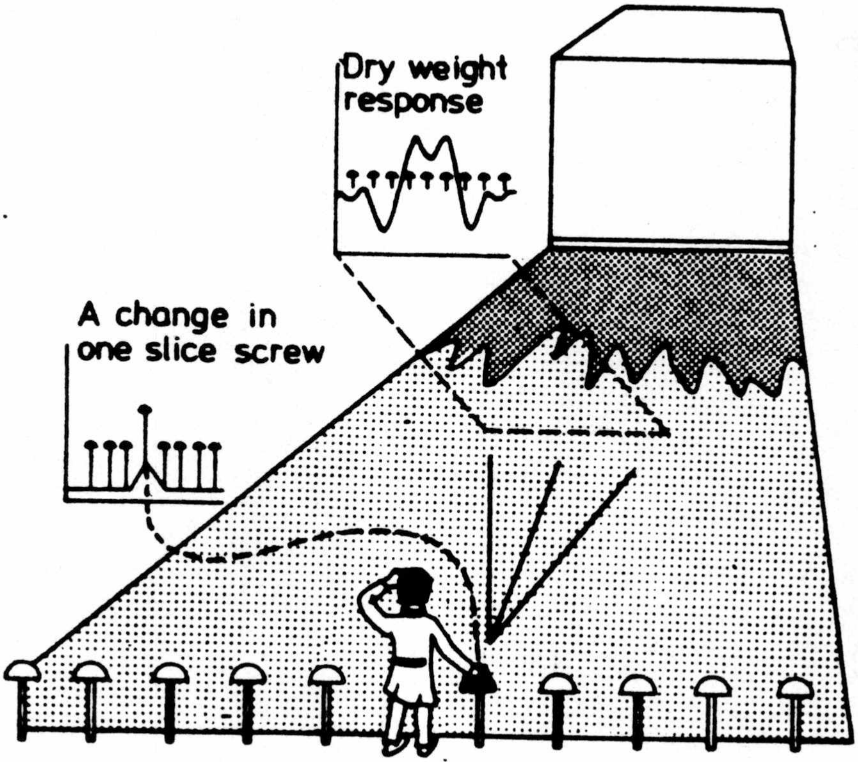


FIGURE 5.1.1 - Manual Adjustment of Slice Actuators by the Machine Operator.
(Source - Karlsson et al. (1982))

5.1 General

Chapter 3.2.1 mentioned that basis weight variations in the sheet being produced in a paper machine is a two dimensional function of the position on this sheet. Due to the characteristics and operation stability of a paper machine, these variations can be split in three separate components:

$$BW(x,y) = BW_{MD}(x) + BW_{CD}(y) + BW_{R}(x,y)$$

where

$BW_{MD}(x)$ = pure machine direction basis weight variation.

$BW_{CD}(y)$ = pure cross machine direction basis weight variation.

$BW_{R}(x,y)$ = residual or random variation of the basis weight.

The variance of these three components is essentially of the same magnitude in an uncontrolled machine, and so are equally worthy of attention in order to produce a good final paper in that machine.

The possibility of this function separation turns the solution of the "cross direction control problem" a lot easier.

It is usual to treat Machine Direction (MD) and Cross Machine Direction (CD) problems as separable, where MD variations are viewed as dynamic and CD variations as static. In terms of CD profile control, not only the CD component should be considered, but also the residual part. This is because the CD term represents only the constant or steady state component of the whole spectrum of time variations in the profile. The residual component contains the remainder of the spectrum that can be reduced by control ranging from slowly varying components to very short term variations. The variance of this residual term is noted by Wilhelm (1984) to be substantial and should be considered in a total CD profile control system.

However the introduction of this residual term in the control strategy is not straightforward, and is out of the scope of this work.

So, the control system designed in this work adresses only the problems related with pure CD variations. Figure 5.1.2 presents a block diagram of the designed system.

5.2 Assumptions and Limitations

5.2.1 Assumptions

The assumptions made for the development of a control strategy for the CD profile control are:

a) the time varying component of the basis weight profile, that is normally due to machine design and operation problems, has not to be compensated by the control system, but corrected in the field

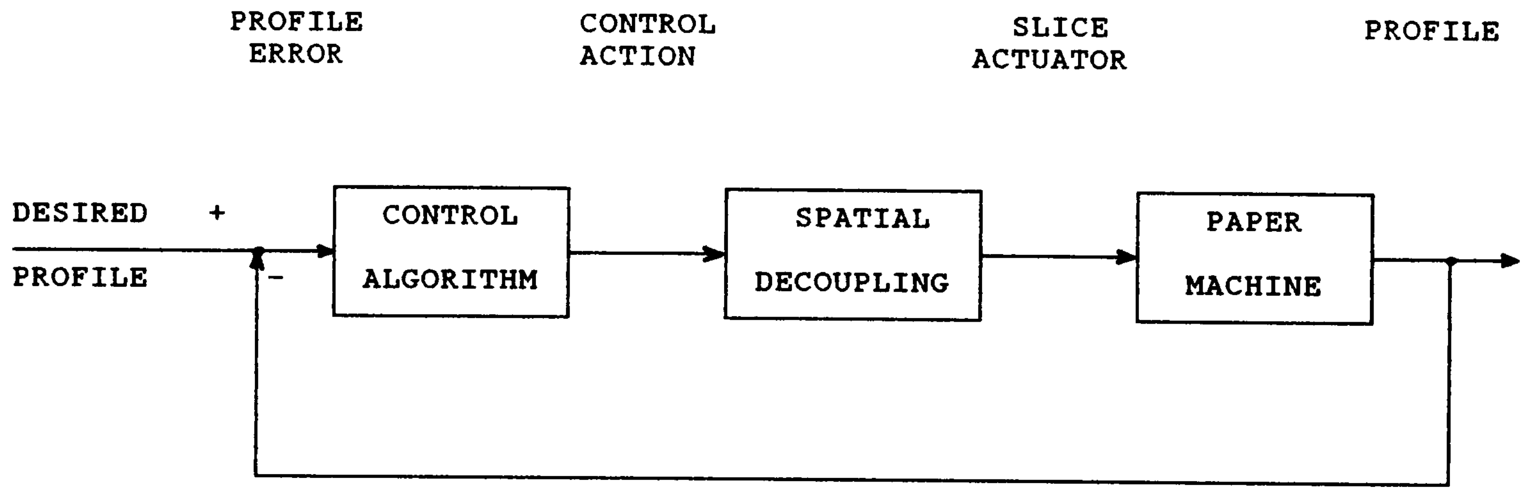


FIGURE 5.1.2 - Block Diagram of the Designed Control System

solving eventual problems;

b) the model of the process response to an actuator adjustment is linear and constant;

c) the dynamic or temporal response of the process is independent of the cross direction position;

d) the spatial coupling among the slice actuators is considered to be instantaneous;

e) the spatial profile response to an actuator adjustment, except for edge effects, is independent of the actuator location, with the response only shifted in space;

f) the spatial profile response to a single actuator adjustment, except for edge effects, is symmetric about the center of influence of that actuator.

5.2.2 Limitations

As any other feedback control system, the CD profile control system has limitations in terms of bandwidth, or the range of frequencies which it can control. The limitations are in the temporal and spatial bandwidths.

The temporal bandwidth is determined by:

- transport delay time between the slice actuators and the scanning sensor;
- dynamic response of the process and actuators;
- filters present in the control loop;

- sampling period.

The spatial bandwidth is determined by:

- the shape of the profile response to an adjustment made in a single actuator (spatial coupling);
- any spatial filtering or smoothing which may be done to the measurement, or which may result from the method of measurement itself;
- the spacing between the actuators.

5.3 Mathematical Development

5.3.1 General

The basis weight profile of a sheet being produced in a paper machine is strongly related to the slice opening, the flow pattern through the slice and wire section of the machine, variations in the hydrodynamic pressure inside the headbox and many other factors. Their functional relationship is also very complex and additionally the control efforts to adjust the CD basis weight profile are subject to constraints such as limitations on the actuators path, in the bending stress limit of the slice bar and also the possibility of having locked or broken slice actuators.

A relationship between the basis weight profile, the control efforts and disturbances could be represented by :

$$BW(t) = f(X(t), V(t), t, \ldots) \qquad \text{eq. 5.3.1}$$

BW(t) = is a vector that represents the discretized points of CD basis weight profile at time t.

X(t) = is a vector that contains the slice actuators settings at time t.

V(t) = is a vector that represents the disturbances affecting the profile at time t.

In the paper making process, that is relatively stable, the relationship indicated by equation 5.3.1 is only slowly varying over a reasonable time horizon and so, it can be considered time invariant. Another consideration that has to be made is that the profile deviations that have to be corrected are normally very limited. Therefore it is reasonable to derive a linearized static relationship between the control settings for the slice actuators and the basis weight profile changes.

$$BW - BW_B = K * (X - X_B) \qquad \text{eq. 5.3.2}$$

BW = vector containing the basis weight profile after the control adjustment X.

BW_B = vector containing the basis weight profile before the new control setting X.

K = matrix containing the steady state gains of the profile changes with respect to control adjustments changes. The terms K_{ij} represent the static gain between the control adjustment at the i-th CD actuator and the profile change at that corresponding location. The terms K_{IJ} represent the spatial coupling gains between the control adjustment at the j-th CD actuator and the profile change at the i-th position. The dimension of matrix K is n x n where n is the number of slice actuators.

X = vector containing the new control settings.

X_B = vector containing the control settings before the control adjustment X.

In general, the discretized basis weight profile BW, can reasonably be described by the point corresponding to the slice actuators, resulting that the dimensions of the vectors BW and X are the same and equal to n. This assumption does not necessarily mean that the basis weight has to be measured in only one point at a particular slice actuator location, but an average of some points in that region is taken, according to the profile resolution of the sensor.

5.3.2 Spatial Coupling

The spatial response of the basis weight cross machine profile to a single actuator move, as was mentioned before, is often strongly coupled (overlapping) with that of adjacent actuators. This spatial response may assume complex shapes and these shapes can change substantially from one grade to the other or as the machine operating conditions change, as can be seen in figure 5.3.1.

The spatial response due to an actuator adjustment, usually spreads over a certain width in the cross machine direction, beyond which, its effect is almost negligible. Therefore, matrix K can be considered band diagonal where the terms after a certain width from the diagonal are all zeroes. The values for the non-zero terms in matrix K varies according to the degree of coupling observed. Wilhelm and Fjeld (1983) presented values of 0.2 as weak coupling and 0.5 as strong coupling. Figure 5.3.2 shows the structure of a typical K matrix.

Karlson, Lundqvist and Ostman (1982) showed that the spatial response spreads differently according to the paper that is being produced. For example, the spatial response in a newsprint machine (BW=45 g/sq.m) was not much wider than a few times the slice screw spacing (typically 150 mm) but for a paper board machine (BW=160 g/sq.m) the spread can reach 2.0 meters. Their conclusion was that, when a slice actuator is adjusted, the wave pattern on the wire section is changed and the amplitude of the response is higher than a proportional change in basis weight relative to the change in the slice opening. This means that the generated water waves dominates basis weight changes and this is even more

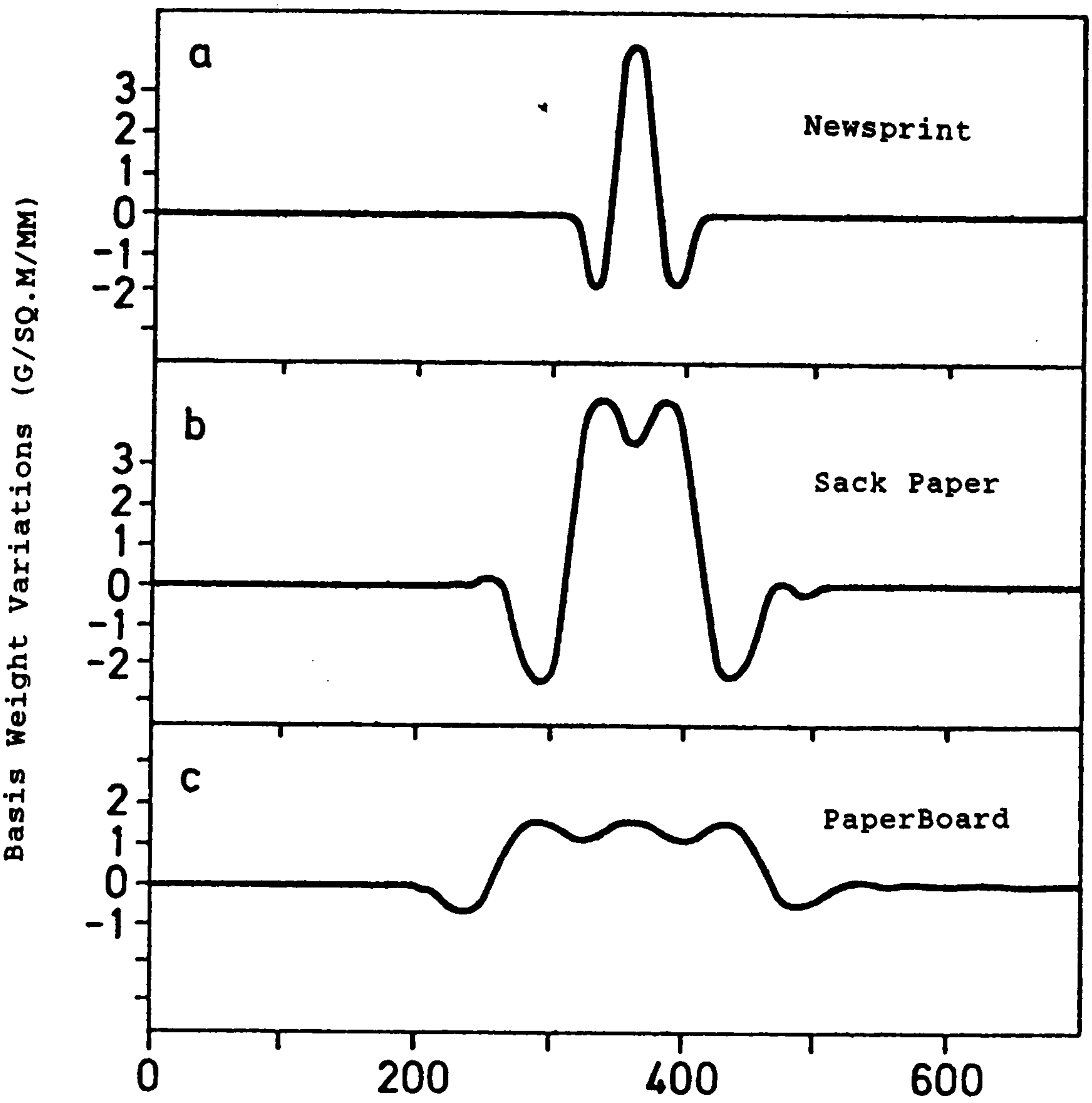


FIGURE 5.3.1 - Basis Weight Responses for Different Paper Grades.(Source - Karlsson et al. (1982))

$$
\begin{bmatrix}
1.0 & 0.5 & 0.5 & 0.0 & 0.0 & \cdots & & & 0.0 \\
0.5 & 1.0 & 0.5 & -0.5 & 0.0 & \cdots & & & 0.0 \\
-0.5 & 0.5 & 1.0 & 0.5 & -0.5 & 0.0 & \cdots & & 0.0 \\
0.0 & -0.5 & 0.5 & 1.0 & 0.5 & -0.5 & \cdots & & 0.0 \\
\cdots & & & & & & & & \cdots \\
\vdots & & & & & & & & \vdots \\
\cdots & & & -0.5 & 0.5 & 1.0 & 0.5 & -0.5 \\
\cdots & & & 0.0 & -0.5 & 0.5 & 1.0 & 0.5 \\
\cdots & & & 0.0 & 0.0 & -0.5 & 0.5 & 1.0
\end{bmatrix}
$$

FIGURE 5.3.2 - Structure of Matrix K

pronounced in higher grades.

To summarize, a control action on a single slice actuator will result in water waves on the wire section which affects the basis weight at several adjacent slice positions. At certain positions the basis weight decreases although the slice opening is increased, as can be seen in figure 5.3.1.

5.3.3 Objective Function and Constraints

Boyle (1977) and (1978), Wilhelm and Fjeld (1983) and others have shown that a reasonable criteria to measure the basis weight CD profile performance in a paper machine is well defined as a quadratic index of the profile deviation from the desired set point.

$$J = 0.5*(BW - BW_{SP})^{T}*W*(BW - BW_{SP}) \qquad \text{eq. } 5.3.3$$

where

W = diagonal matrix of weighing factors.

So, the ideal control law considering the process model indicated by equation 5.3.2 and the objective function 5.3.3 is:

$$X = K^{-1}*(BW_{B} - BW_{SP}) + X_{B} \qquad \text{eq. } 5.3.4$$

Normally, this ideal control law should take the system to a final deviation from the set point equal to zero, but the real world is "not all roses", the process model has inaccuracies and the control action may require actuator positions that are physically unrealizable or that could overstress the slice bar. So, constraints have to be introduced to overcome these situations.

The constraints, for the CD basis weight control can be formulated as:

a) limitation in the range of the actuators path or adjustment:

$$X_{min} < X < X_{max}$$

X_{min} = low limit for the actuator adjustment or path, assumed to be equal to 0.0

X_{max} = high limit for the actuator adjustment or path, assumed to be equal to 1.0

b) limitation on the slice bar bending stress, and according to Chen and Wilhelm (1986):

$$BI_{min} < BI < BI_{max}$$

the bending moment of the slice bar is proportional to the vector, BI, whose elements are the discretized second moments of the actuator sets.

$$BI(I) = X(I-1) - 2*X(I) + X(I+1)$$

the values used for BI_{min} and BI_{max} are - 0.5 and 0.5;

c) consideration about the possibility of having immobile (broken or manually controlled) actuators.

Chen and Wilhelm (1986) showed that incorporating all these constraints or penalty factors in the quadratic index represented by equation 5.2.3, a more realistic objective function can be obtained.

$$J = 0.5*(BW - BW_{SP})^T *W*(BW - BW_{SP}) + P*(X - X_M)^T *(X - X_M) + Q*(BI)^T *(BI) + (X - X_B)^T *V*(X - X_B) \qquad \text{eq. 5.3.5}$$

where

a) the first term represents the weighted sum of squares of basis weight deviations of the final basis weight profile and the desired set point. W is a diagonal weighing matrix that can be arranged in such a way to control the extent to which basis weight deviations, in particular regions of the web,are counted in the minimization process. For example, edges that are to be trimmed can be discounted, or special weight streaks can be ignored if they are known to be beyond the range of the control mechanism;

b) the second term represents the sum of squares of the actuators positions deviations from the mid-range positions. P is a non-negative scalar that assures that the actuators final positions X, lie between the high and low limits of the control range. X_M is a vector representing the mid-range positions of these actuators;

c) the third term represents the sum of squares of second moments of the actuators settings. Q is a non-negative scalar that guarantees that the slice bar stays within its bending stress limits;

d) the fourth term takes care of the possibility of having immobile actuators. Matrix V is diagonal with large values on the diagonal elements corresponding to fixed actuators and zeroes elsewhere.

5.3.4 Control Adjustment

Boyle (1977) and (1978) and Chen and Wilhelm (1986) showed that the optimal control subjected to the mentioned constraints can be obtained by quadratic programming, using "PENALTY FUNCTIONS METHODS", Himmelblau (1972). So, the minimization of the quadratic index represented by the equation 5.3.5 subjected to the process equation 5.3.2, was shown by Chen and Wilhelm (1986) to yield the following solution for the control adjustment X:

$$X = -\ (K^T*W*K + P*I + Q*BI^T*BI + V)^{-1} *$$

$$(K^T*W*(BW_B - BW_{SP}) - (K^T*W*K + V)*X_B -$$

$$- P*X_M) \qquad \text{eq. 5.3.6}$$

In order to transform equation 5.3.6 in a form more suitable to be solved in a computer, it was subdivided in the following equations :

$$A = A_0 + P*I + Q*F^T*F \qquad \text{eq. 5.3.7}$$

where

$$A_0 = K^T*W*K + V$$

and

$$Z = Z_0 + P*X_M \qquad \text{eq. 5.3.8}$$

where

$$Z_0 = A_0*X_B - K^T*W*(BW_B - BW_{SP})$$

So, equation 5.3.6 can be re-written as :

$$X = A^{-1}*Z \qquad \text{eq. 5.3.9}$$

where X is the necessary control adjustment.

5.3.4 Computer Implementation of the Control Algorithm

The program for the control algorithm, as well as, for the wet end section of the paper machine were implemented on an XT personal computer with 640 KB of memory, 10 MHz of speed and a 30 MB hard drive.

The programs were written in Micro-Soft Fortran and the following software packages were used :

- Fortran, Scientific Subroutines Library
  Wiley Professional Software.
- Statgraphics, Statistical Graphics System
  STSC, Inc.
- Saslgraf, Scientific Applications Software
  Mountain Home Systems.

5.4 Results and Discussion

In order to evaluate the validity and robustness of the developed cross machine direction control algorithm, several different cases or process situations were analyzed and the results of this analysis for some of these cases are presented.

The system parameters used in all cases are:

- unless otherwise noted, the values for the terms K_{IJ} (I=J) used in matrix K are equal to 0.2;
- limits for slice actuators positions 0.0 and 1.0;
- bending limit for all actuators 0.5;
- number of slice actuators 30;
- scan time for the sensor 30 seconds;
- dead time between the movement of an actuator and the basis weight change to be sensed by the scanner in the dry end of the machine is 41 seconds;
- the time between two consecutive control actions is equal to the dead time plus one complete scan after

elapsed the dead time.

The algorithm is initialized with values for the penalties P and Q equal to 0.1. This is a more conservative approach, because it does not give chance to the algorithm consider the case of ideal control (no constraints or P=Q=0 and $V_I=0$) but assures a smoother control through all the required range and makes the control algorithm more robust.

The effectiveness of the control algorithm is analyzed by the evaluation of the basis weight profiles before and after the control action has taken place, considering the the following performance parameters:

- standard deviation from the average basis weight value;
- variance of basis weight values;
- range of basis weight variations.

Table 5.4.1 presents a summary of the above mentioned parameters for the cases analyzed in this work, that are listed below.

1) random basis weight profile needs to be corrected (see figure 5.4.1);
2) a basis weight streak occurs in the middle of the sheet (see figure 5.4.2);
3) a basis weight streak occurs at the edge of the sheet (see figure 5.4.3);

TABLE 5.4.1 - Performance of the Cross Machine Direction (CD) Profile Control Algorithm in a Paper Machine.

Case Number	Basis Weight Statistics		
	Standard Deviation	Variance	Range
CASE 1			
Before Control	0.265	0.070	1.15
After Control	0.045	0.002	0.18
CASE 2			
Before Control	0.091	0.008	0.50
After Control	0.062	0.004	0.40
CASE 3			
Before Control	0.091	0.008	0.50
After Control	0.047	0.002	0.31
CASE 4			
Before Control	0.127	0.016	0.50
After Control	0.055	0.003	0.31
CASE 5			
Before Control	0.127	0.016	0.50
After Control	0.066	0.004	0.30
CASE 6			
Before Control	0.0	0.0	0.0
After Control	0.0	0.0	0.0
CASE 7			
Before Control	0.265	0.070	1.15
After Control	0.175	0.031	0.78
CASE 8			
Before Control	0.265	0.070	1.15
After Control	0.119	0.014	0.60

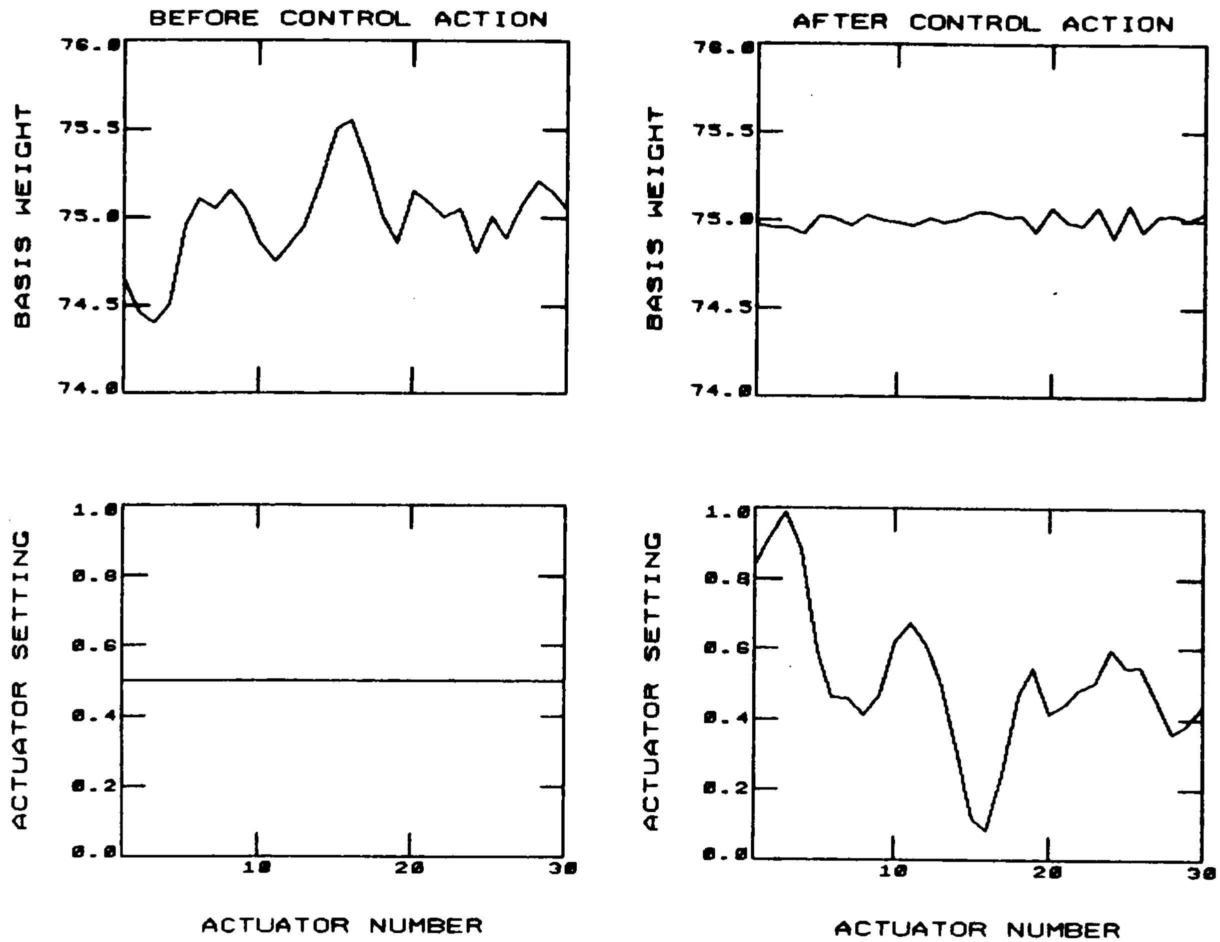


FIGURE 5.4.1 - Basis Weight and Actuators Positions Profiles Before and After the Control Action.
Initial Profile : Random
Penalty Values : P = 0.1 Q = 0.1

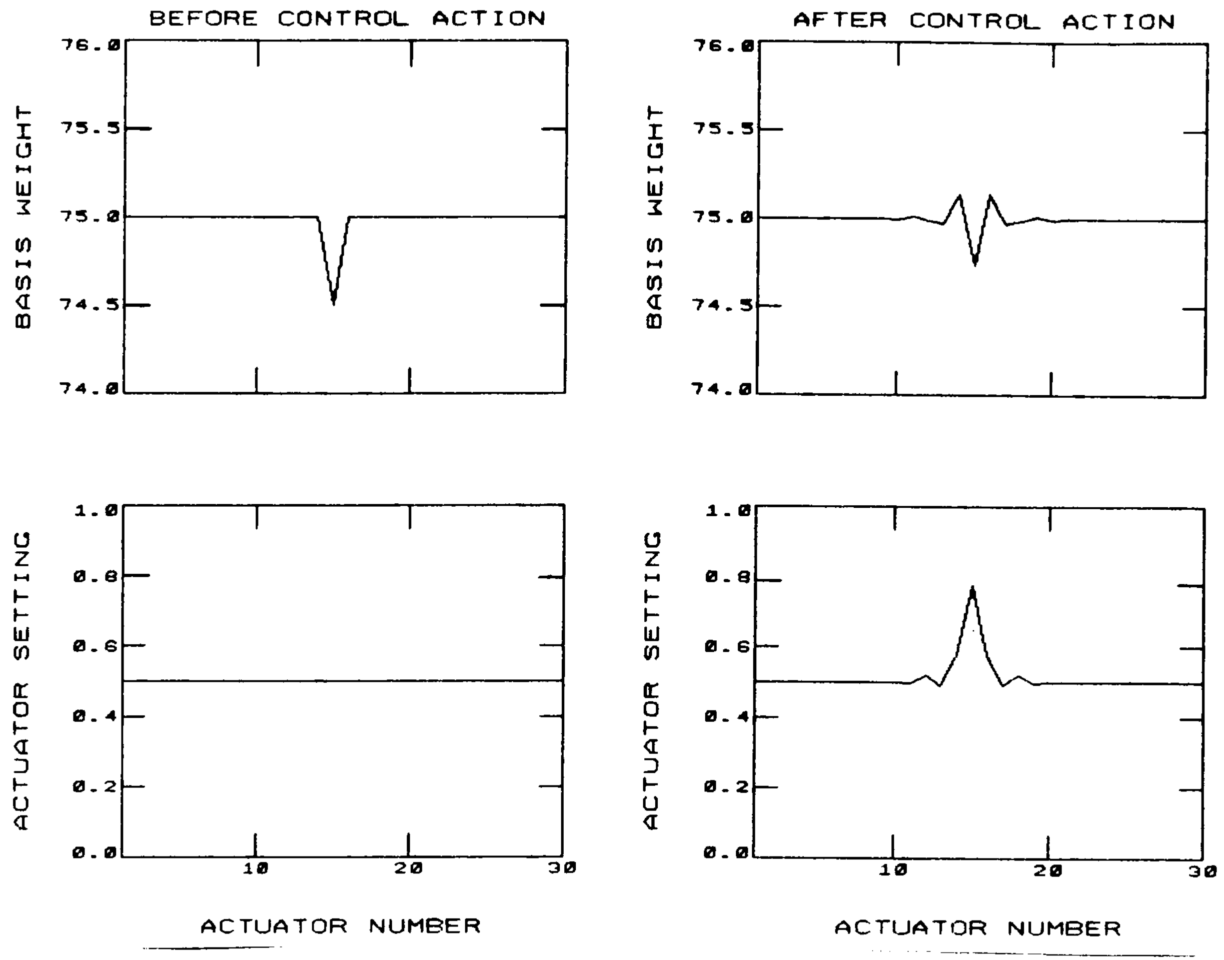


FIGURE 5.4.2 - Basis Weight and Actuators Positions Profiles Before and After the Control Action.
Initial Profile : Streak in the Middle
Penalty Values : P = 0.1 Q = 0.1

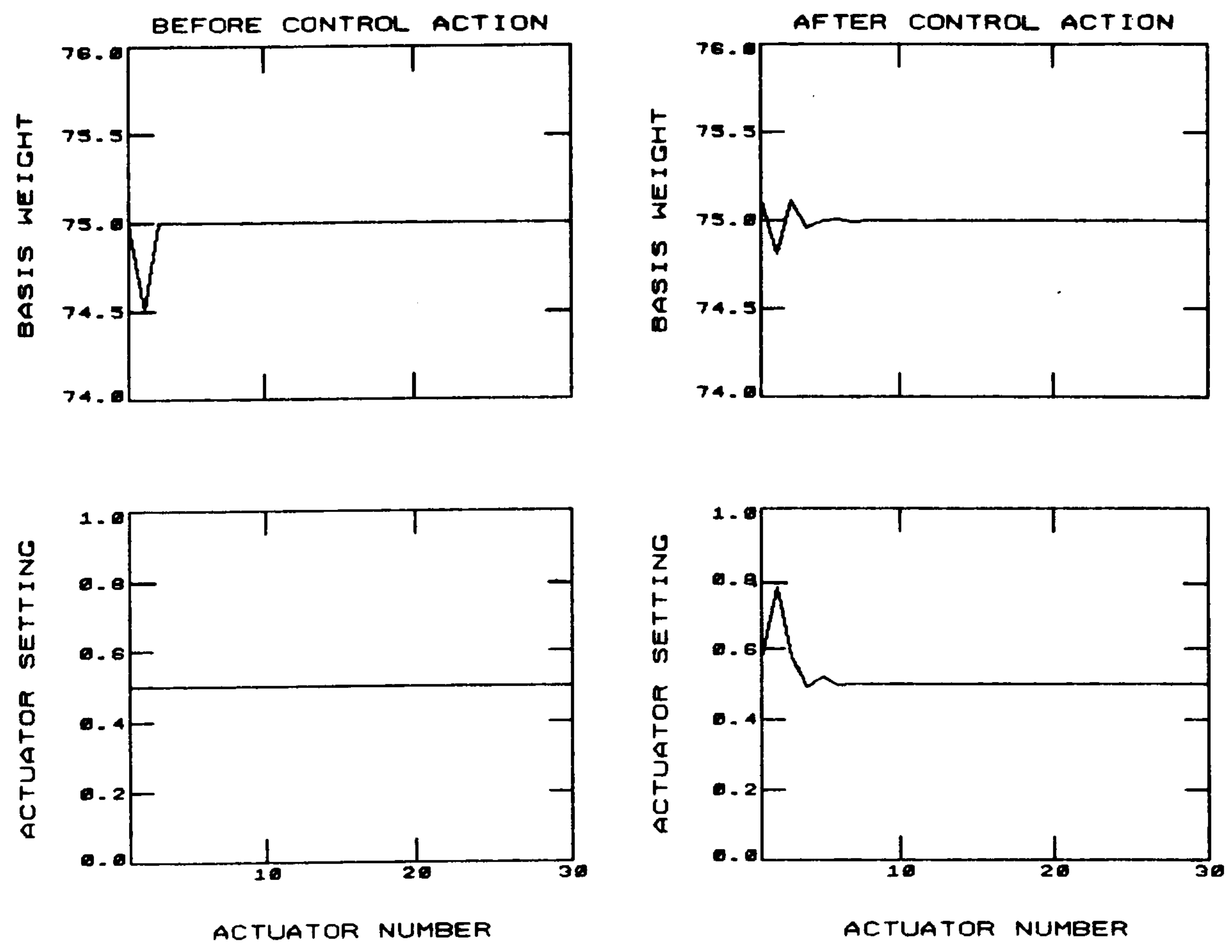


FIGURE 5.4.3 - Basis Weight and Actuators Positions Profiles Before and After the Control Action.
Initial Profile : Streak at the Edge
Penalty Values : P = 0.1 Q = 0.1

4) basis weight streaks occur at both edges of the sheet (see figure 5.4.4);

5) basis weight streaks occur at positions symmetric to the middle of the sheet (see figure 5.4.5);

6) initial profile is constant but there is an instantaneous upset in the actuator number 15 that takes it to position 0.8 (see figure 5.4.6);

7) one slice actuator is locked or in manual control (see figure 5.4.7);

8) the value of the coupling coefficient of matrix K is changed from 0.2 to 0.5 (see figure 5.4.8).

In general, as can be observed in table 5.4.1 and in figures 5.4.1 to 5.4.8, the developed cross machine direction profile control algorithm improved the control of the basis weight profile in the paper machine.

The eight cases that were analyzed, basically can be divided in four groups:

a) figures 5.4.1 to 5.4.5 shows what happens when the system has to correct a pre-established profile bringing it back as close as possible to the desired profile. In all these cases, the speed of the algorithm is very fast, because it finds the values of P and Q that makes the system satisfies the constraints and minimizes the total cost in the first iteration;

b) figure 5.4.6 shows the situation where the machine has

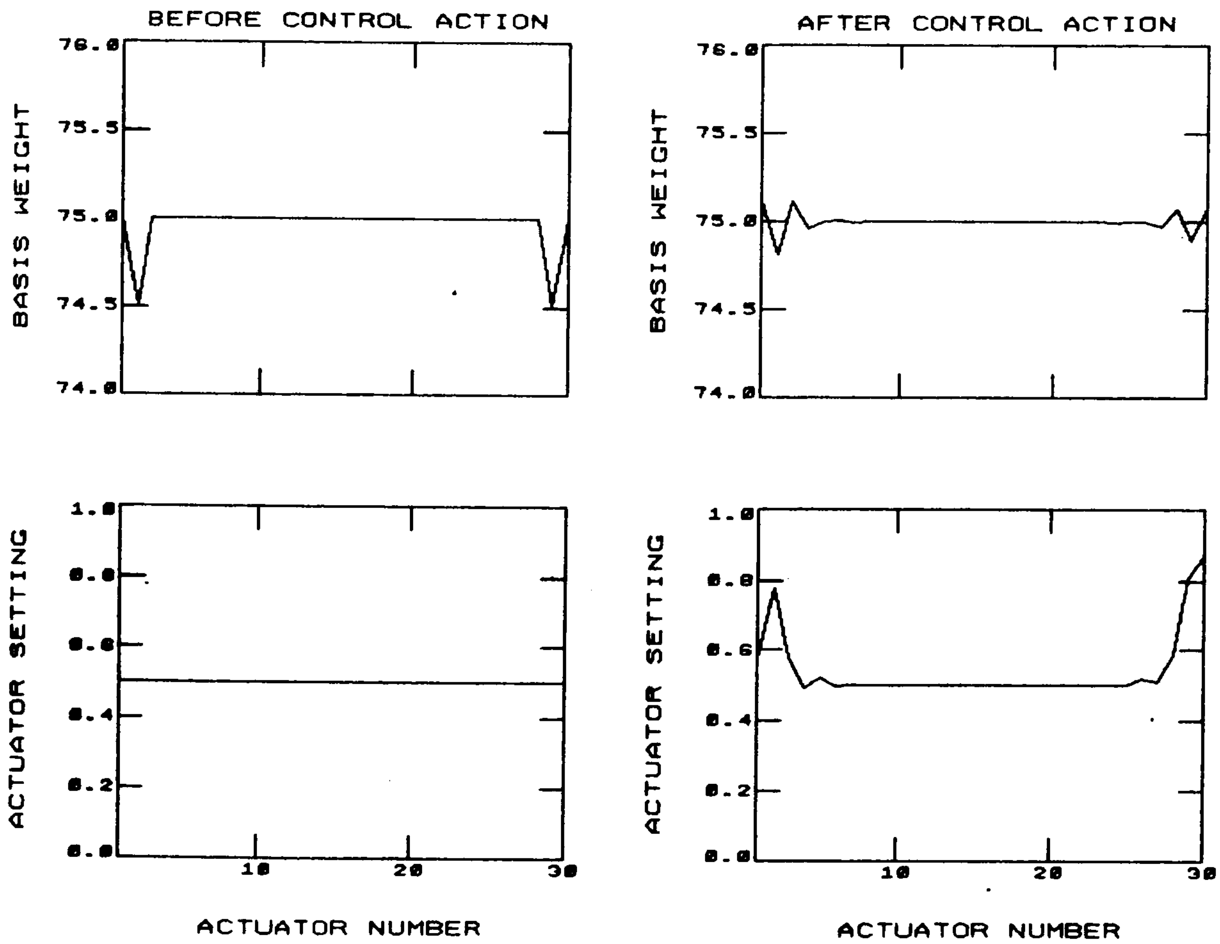


FIGURE 5.4.4 - Basis Weight and Actuators Positions Profiles
Before and After the Control Action.
Initial Profile : Streaks on Both Edges
Penalty Values : P = 0.1 Q = 0.1

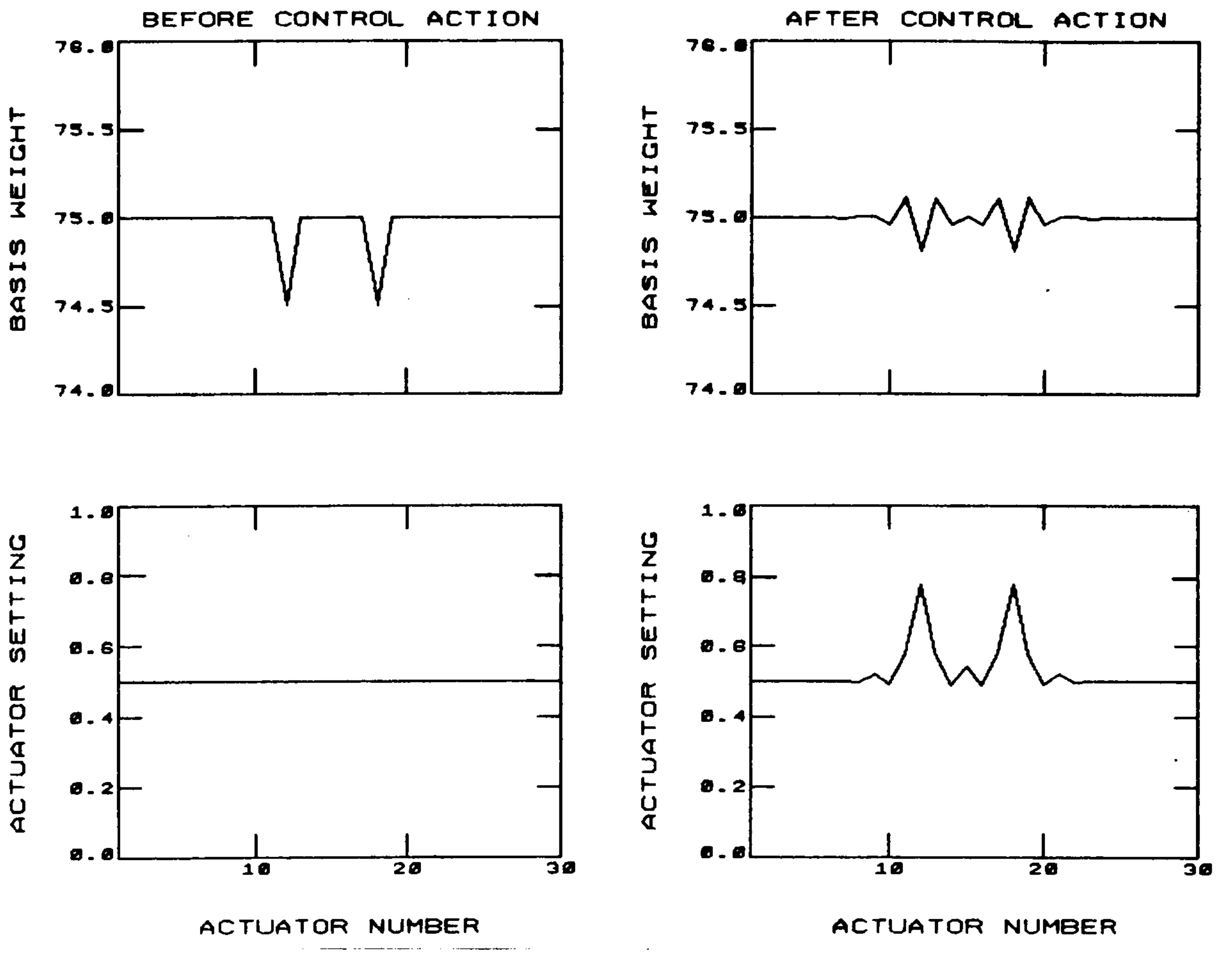


FIGURE 5.4.5 - Basis Weight and Actuators Positions Profiles
Before and After the Control Action.
Initial Profile : Symmetric streaks in the Middle
Penalty Values : P = 0.1 Q = 0.1

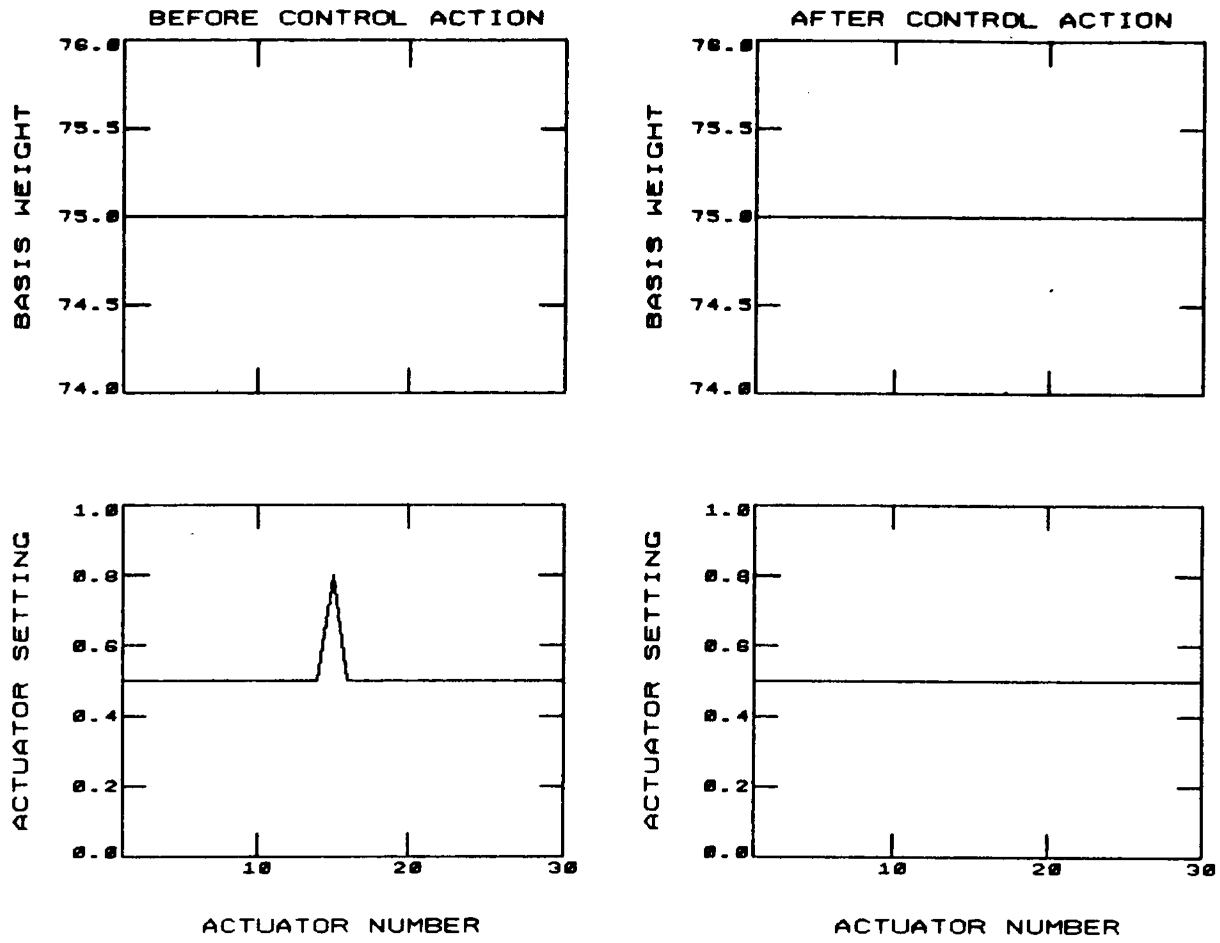


FIGURE 5.4.6 - Basis Weight and Actuators Positions Profiles Before and After the Control Action.
Initial Profile : Flat on Set Point
Penalty Values : P = 0.1 Q = 0.1

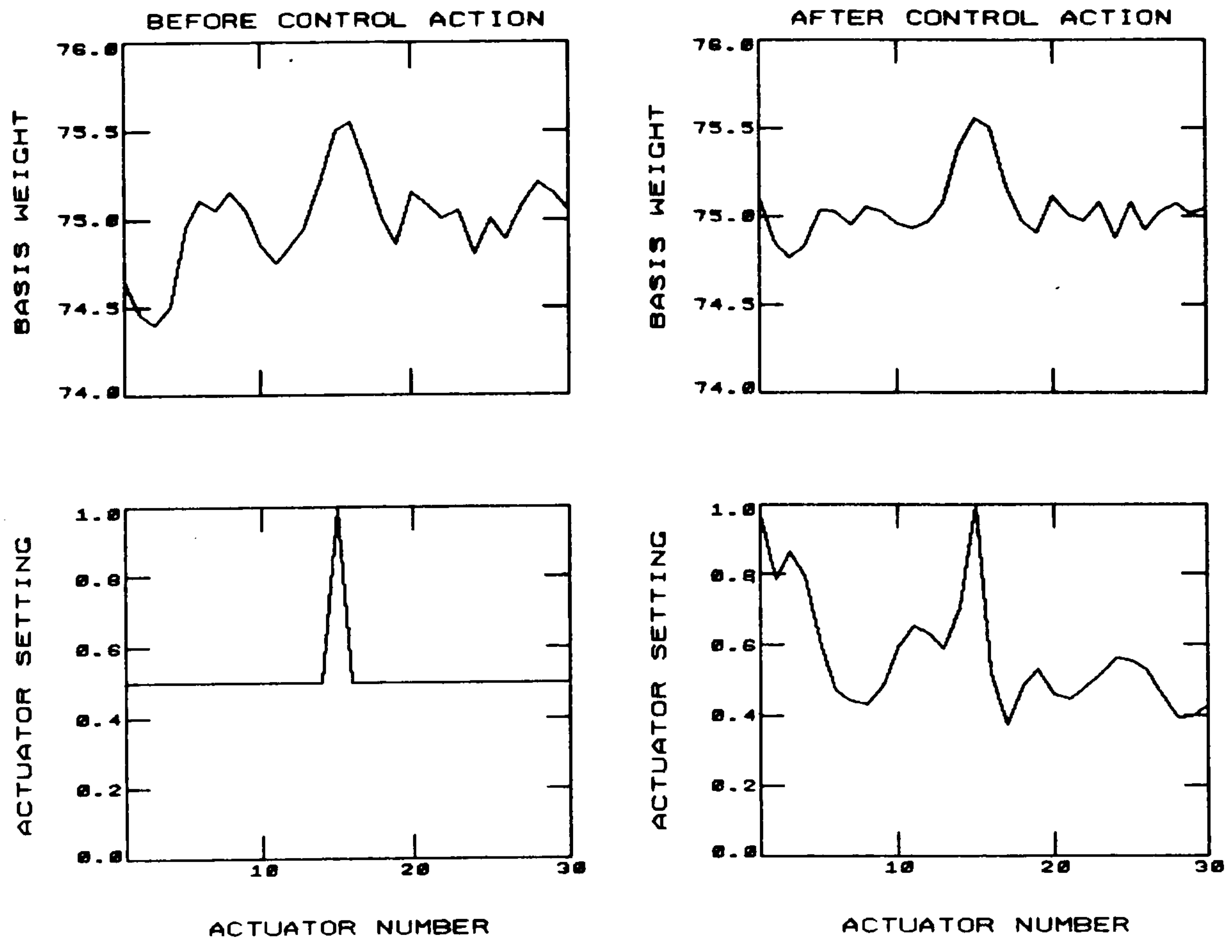


FIGURE 5.4.7 - Basis Weight and Actuators Positions Profiles Before and After the Control Action.
Initial Profile : Random
Penalty Values : P = 0.3 Q = 0.5

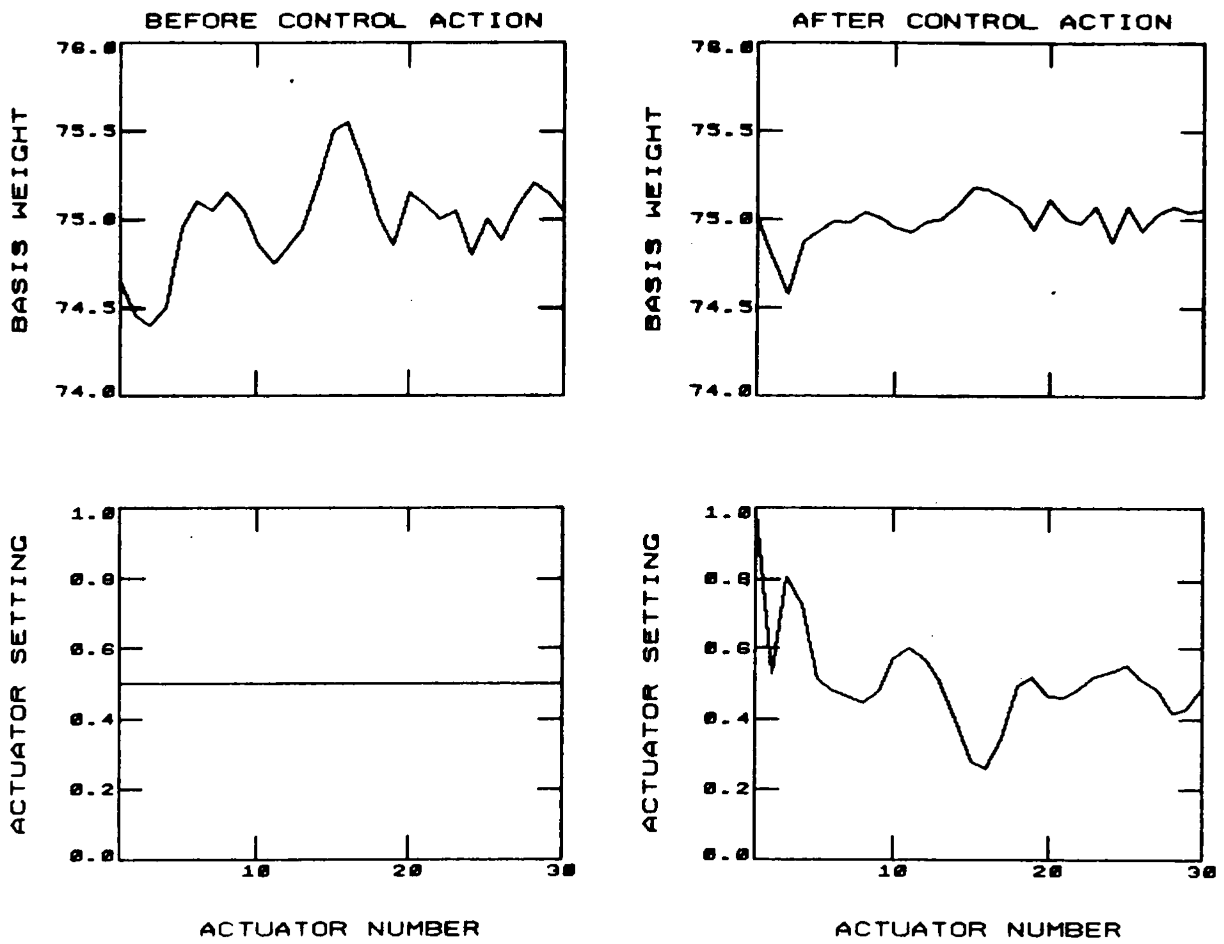


FIGURE 5.4.8 - Basis Weight and Actuators Positions Profiles Before and After the Control Action.
Initial Profile : Random
Value of K_{IJ} : $K_{IJ} = 0.5$
Penalty Values : $P = 1.0$ $Q = 0.2$

flat basis weight profile, and at time zero the slice actuator number 15 is instantaneously moved to position 0.8. In this case, as is expected, the controller brings the basis weight and slice actuators profiles back to the original position, just after the first iteration;

c) figure 5.4.7 analyzes another situation, where the machine, originally, presents a random profile that needs to be corrected, but the actuator number 15 is locked. In this case the controller corrects a good portion of the variation of the profile, but around the locked actuator the level of correction is smaller;

d) figure 5.4.8 shows the same situation of figure 5.4.1 but with one difference, the coupling between adjacent actuators is not 0.2 anymore, but 0.5. This means that the movement of one actuator interferes much more with the adjacent actuators than before. And, as can be seen in this figure 5.4.8, the bigger the coupling coefficient the more interactive is the process and the more difficult is the control.

The computation time required for the developed control algorithm is very reasonable, but improvements can be made in order to run it more efficiently. For example, one of the more time consuming parts of the program is the inversion of matrix A. The program used in this work for this purpose, is a simple Gauss Elimination program. This method besides being time consuming, may lead to error accumulation during the calculations. If a closer look is taken to matrix A it can be seen that this matrix is band diagonal and so, can easily be factorized leading to triangular and diagonal matrices that can be inverted very fast, minimizing eventual error accumulations and requiring less memory space to store the resulting matrices.

Another point that could improve the processing speed of the control algorithm, is to convert the program that was written in Fortran, to C language.

The program should be run in a faster computer than an XT, for example, an AT or 386 following the line of IBM or IBM compatibles personal computers, a Micro-Vax or other faster computer.

CHAPTER 6

CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

6.1 Conclusions

The cross machine direction profile control algorithm developed and presented in this thesis works quite well in the simulation cases tested. The tests demonstrated that in every case the algorithm reduced the standard deviation in the cross machine basis weight profile significantly, as can be seen in table 5.4.1. The main restriction on the performance in each case, was not the algorithm itself, but the limits imposed on each actuator and the limits of the allowable stress on the slice bar.

The basis weight control algorithm compensates for the complex multivariable interactions on the paper machine, yet it is mathematically straightforward and simple enough that it can be implemented in a small computer environment. The form of the algorithm is such that with some minor adaptation it could also be the foundation for the control of other paper machine profiles (such as moisture and thickness) and could perhaps be used in other industries such as plastics, metal sheets, coating, etc.

6.2 Suggestions for Further Research

During the development of this work, some improvements for the developed control algorithm were devised, and should be considered as possible candidates for further research in the field of profile control in web handling machines. A summary of these points is presented below.

a) The developed control algorithm had its structure and robustness tested using a simulation model, and so, needs to be exposed to data of a real paper machine and have its performance more fully evaluated.

b) A simplification is made when the profile response is assumed to be fixed, symmetric and uniform. This assumption is not always completely true, and a good approach would be to have an estimator algorithm working together with the control algorithm, in order to continuously update the process model used by the control strategy.

c) The control model was obtained using the penalty functions approach and the algorithm is re-tuned in each control action, to find new values for P and Q. Another very reasonable approach that should be tested is the quadratic least squares method, that could determine the movements X of the slice actuators directly, respecting the constraints and without calculating P and Q.

d) Study the possibility of using a dead time compensator algorithm.

e) A filter should be introduced in the control algorithm in order to separate the CD machine variations from the MD variations of basis weight, in order to get a truer CD profile.

f) A filter should also be introduced to eliminate the noise caused by the scanning sensor.

g) Study the influence of basis weight variations in other profiles, like moisture and caliper.

h) Implement the required modifications to transform the model developed to basis weight control, suitable to moisture and thickness profile control.

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APPENDIXES

APPENDIX A

Nomenclature

Nomenclature

A = Coefficient of empirical equation to determine contraction coefficient.

A_{HB} = Area of free liquid surface in the headbox (SQ.M).

ALPHA = Initial wire retention.

A_{SL} = Individual area of each section of the slice bar (SQ.M).

B = Coefficient of empirical equation to determine the deflection of emerging jet.

BW = Basis Weight (G/SQ.M)

BWSP = Basis Weight set point (G/SQ.M).

C_C = Contraction Coefficient.

C_{HB} = Consistency inside the headbox (%).

C_{TKS} = Consistency of the thick stock (%).

C_{TNS} = Consistency of the thin stock (%).

C_V = Viscosity Coefficient.

C_{WW} = Consistency of the white water (%).

DTD = Drying Section dead time (S).

DTH = Headbox dead time (S).

DTP = Pipe Section dead time (S).

DTPR = Press Section dead time (S).

DTW = Wire section dead time (S).

F = Coefficient of empirical equation to determine the deflection angle of the emerging jet from headbox

F_{HB} = Total fiber concentration inside the headbox (G/CU.CM).

G = Gravity Constant (CM/SQ.S).

GAMA = Pulp characterization factor (SQ.CM/G).

H_A = Air pad head (CM wc.).

H_{HB} = Headbox stock level (CM).

H_T = Total headbox head (CM wc.)

J = Jet to wire speed ratio.

J_{SP} = Jet to speed ratio set point.

L = Apron adjusted length (CM).

m_A = Air net flow to headbox (KG/S).

M_A = Air average molecular weight (G).

NACT = Number of slice actuators.

Q_{AI} = Air in-flow to the headbox (KG/S).

Q_{AO} = Air out-flow from the headbox (KG/S).

Q_{HB} = Stock out-flow from the headbox (L/S).

Q_R = Reject flow (L/S).

Q_{THB} = Total stock out-flow from the headbox (L/S).

Q_{TKS} = Thick stock flow (L/S).

Q_{TNS} = Thin stock flow (L/S).

Q_{WW} = White water flow (L/S).

R = Gases Constant ((KGF/SQ.CM)*L/(G.MOL*K degree))

R_H = Wire retention

RW = Average wire retention (per wire strip).

SLP = Slice position.

SLW = Individual slice actuator width (CM).

ST = Sampling time (S).

SW = Slice Width (CM).

T_{HB} = Headbox temperature (C degree).

V_{HB} = Headbox volume (CU.M).

V_J = Emerging jet velocity (CM/S).

V_P = Volume of pipe section (CU.M).

V_W = Wire velocity (CM/S).

V_{WSP} = Wire velocity set point (CM/S).

APPENDIX B

Computer Programs

```
$NOFLOATCALLS
$LARGE
C******************************************************************
C
C         CROSS DIRECTION PROFILE CONTROL OF BASIS WEIGHT
C
C                IN A FOURDRINIER PAPER MACHINE
C
C******************************************************************
C
      DIMENSION QTKS(100),QWW(100),QTNS(100),QR(100),CTKS(100)
      DIMENSION CWW(100),QTHB(100),QAI(100),QAO(100)
      DIMENSION HA(100),HT(100),CTNS(100)
      DIMENSION QHB(200,31),CC(65),HHB(100),X(100),Y(100)
      DIMENSION A(9),B(11),FC(3),A0(30,30)
      DIMENSION Q(34),U(30),BI(30),BW(45,30),SLP(35)
      DIMENSION YBR(30),QFTF(30,30),G(30,30),BWR(30)
      DIMENSION FTF(30,30),GTWG(30,30),F(30,30),W(30),V(30)
      DIMENSION GTW(30,30),YB(30),BWS(35),AK(31,31)
C
      CHARACTER*84 BNAME
      REAL*8 G1,G2,Z0(30),Z(30),U,T1F,T2F,T3F,T4F,COST,BI
C
C     FRONT DISPLAY DEFINITION
C
      DO 10 I=1,9
 10   WRITE(*,*)' '
      WRITE(*,*)' '
      WRITE(*,*)' '
      WRITE(*,20)'CROSS DIRECTION PROFILE CONTROL OF BASIS WEIGHT'
 20   FORMAT(16X,A47)
      WRITE(*,30)'IN A FOURDRINIER PAPER MACHINE'
 30   FORMAT(25X,A30,/)
      WRITE(*,*)' '
      DO 40 I=1,9
 40   WRITE(*,*)' '
      PAUSE
C
      OPEN(1,FILE='PARAM.DAT')
      READ(1,'(F5.2)')(Q(I),I=1,9)
      CLOSE(1,STATUS='KEEP')
      NACT=NINT(Q(6))
      BWSP=Q(9)
C
C     FIRST LEVEL OF DECISION
C
 45   AM=1.0
      DO 46 I=1,24
 46   WRITE(*,*)' '
      WRITE(*,50)'ACTION    (1) EDIT   (2) RUN    (3) QUIT'
 50   FORMAT(1X,A40,5X,\)
      READ(*,*)IP1
      IF(IP1.EQ.3)GOTO 580
      IF(IP1.EQ.2)GOTO 184
```

```
C
C     SECOND LEVEL OF DECISION
C
 55   AM=1.0
      DO 60 I=1,24
 60   WRITE(*,*)' '
      WRITE(*,70)'EDIT  (1) SIMULATION TIME   (2) PARAMETER   (3) QUIT'
 70   FORMAT(1X,A53,5X,\)
      READ(*,*)IP2
      IF(IP2.EQ.3)GOTO 45
      IF(IP2.EQ.2)GOTO 99
C
C     DEFINITION OF SIMULATION TIME
C
      WRITE(*,80)'* ENTER REQUIRED SIMULATION TIME (SEC) : '
 80   FORMAT(1X,A41,5X,\)
      READ(*,82)ISIM
 82   FORMAT(I4)
      GOTO 55
C
C     DEFINITION OF PARAMETERS MODIFICATIONS
C
 99   AM=0.0
      DO 100 I=1,8
 100  WRITE(*,*)' '
      WRITE(*,*)' '
      WRITE(*,*)' '
      WRITE(*,110)'DEFINITION OF PROGRAM PARAMETERS'
 110  FORMAT(24X,A32,/)
      WRITE(*,*)' '
      WRITE(*,*)' '
      WRITE(*,120)'(1) INITIAL PROFILE FOR BASIS WEIGHT    '
      WRITE(*,120)'(2) NUMBER OF SLICE ACTUATORS           '
      WRITE(*,120)'(3) INITIAL POSITION FOR SLICE ACTUATORS'
      WRITE(*,120)'(4) GAIN MATRIX G                       '
      WRITE(*,120)'(5) WEIGHT MATRIX W                     '
      WRITE(*,120)'(6) PENALTY VALUE PI(0)                 '
      WRITE(*,120)'(7) PENALTY VALUE QI(0)                 '
      WRITE(*,120)'(8) INCREMENT FOR PI AND QI             '
 120  FORMAT(20X,A39,/)
C
      WRITE(*,'(1X,A35,5X,\)') '* ENTER REQUIRED OPTION  (QUIT=9) : '
      READ(*,'(I1)')IP3
      IF(IP3.GE.9)GOTO 55
      IF(IP3.EQ.8)GOTO 188
      IF(IP3.EQ.7)GOTO 187
      IF(IP3.EQ.6)GOTO 186
      IF(IP3.EQ.5)GOTO 185
      IF(IP3.EQ.4)GOTO 184
      IF(IP3.EQ.3)GOTO 183
      IF(IP3.EQ.2)GOTO 182
C
C     INITIAL PROFILE FOR BASIS WEIGHT
C
```

```
181  AM=0.0
     DO 31 I=1,24
31   WRITE(*,*)' '
     WRITE(*,'(1X,A32,3X,\)')'* ENTER BASIS WEIGHT SET POINT :'
     READ(*,'(F5.2)')BWSP
     Q(8)=BWSP
     DO 32 I=1,24
32   WRITE(*,*)' '
     WRITE(*,'(1X,A43,3X,\)')'* ENTER NAME OF INITIAL BASIS WEIGHT FILE
    * :'
     READ(*,'(A)')BNAME
     OPEN(2,FILE=BNAME)
     READ(2,'(F7.3)')(BWR(I),I=1,NACT)
     CLOSE(2,STATUS='KEEP')
     WRITE(*,*)' '
     WRITE(*,*)' '
     WRITE(*,*)' '
     WRITE(*,*)' '
     WRITE(*,*)' '
     WRITE(*,*)' '
     WRITE(*,*)'                    INITIAL PROFILE FOR BASIS WEIGHT'
     WRITE(*,*)' '
     WRITE(*,*)' '
     WRITE(*,*)' '
     WRITE(*,*)' '
     WRITE(*,*)' '
     WRITE(*,*)'        __1__ __2__ __3__ __4__ __5__ __6__ __7__ __8__
    *__9__ __10_'
     WRITE(*,315)(BWR(I),I=1,10)
     WRITE(*,*)' '
     WRITE(*,*)' '
     WRITE(*,*)'        __11_ __12_ __13_ __14_ __15_ __16_ __17_ __18_
    *__19_ __20_'
     WRITE(*,315)(BWR(I),I=11,20)
     WRITE(*,*)' '
     WRITE(*,*)' '
     WRITE(*,*)'        __21_ __22_ __23_ __24_ __25_ __26_ __27_ __28_
    *__29_ __30_'
     WRITE(*,315)(BWR(I),I=21,30)
     WRITE(*,*)' '
     WRITE(*,*)' '
     WRITE(*,'(1X,A22,5X,\)')' (1) MODIFY   (2) QUIT'
     READ(*,297)IS1
     IF(IS1.GE.2)GOTO 99
     WRITE(*,296)'* ENTER REQUIRED POINT NUMBER :          '
     READ(*,297)IS2
     WRITE(*,296)'* ENTER NEW VALUE              :          '
     READ(*,298)BWR(IS2)
     OPEN(2,FILE=BNAME)
     DO 720 IJ=1,NACT
720  WRITE(2,298)BWR(IJ)
     CLOSE(2,STATUS='KEEP')
     GOTO 181
C
```

```
C     INITIAL POSITION FOR THE SLICE ACTUATORS
C
 182  WRITE(*,'(1X,A35,3X,\)')'* ENTER NUMBER OF SLICE ACTUATORS :'
      READ(*,'(I2)')NACT
      GOTO 99
 183  OPEN(2,FILE='SLICE.DAT')
      READ(2,'(F7.3)')(SLP(I),I=1,NACT)
      CLOSE(2,STATUS='KEEP')
      WRITE(*,*)' '
      WRITE(*,*)' '
      WRITE(*,*)' '
      WRITE(*,*)' '
      WRITE(*,*)' '
      WRITE(*,*)' '
      WRITE(*,*)'             INITIAL POSITION FOR SLICE ACTUATORS'
      WRITE(*,*)' '
      WRITE(*,*)' '
      WRITE(*,*)' '
      WRITE(*,*)' '
      WRITE(*,'(1X,A25,3X,\)')'NUMBER OF SLICE ACTUATORS'
      WRITE(*,'(I2)')NACT
      WRITE(*,*)' '
      WRITE(*,*)' '
      WRITE(*,*)'        __1__ __2__ __3__ __4__ __5__ __6__ __7__ __8__

     *__9__ __10_'
      WRITE(*,316)(SLP(I),I=1,10)
      WRITE(*,*)' '
      WRITE(*,*)' '
      WRITE(*,*)'        __11_ __12_ __13_ __14_ __15_ __16_ __17_ __18_

     *__19_ __20_'
      WRITE(*,316)(SLP(I),I=11,20)
      WRITE(*,*)' '
      WRITE(*,*)' '
      WRITE(*,*)'        __21_ __22_ __23_ __24_ __25_ __26_ __27_ __28_

     *__29_ __30_'
      WRITE(*,316)(SLP(I),I=21,30)
 315  FORMAT(7X,10(1X,F5.2))
 316  FORMAT(6X,10(1X,F5.2))
      WRITE(*,*)' '
      WRITE(*,*)' '
      WRITE(*,299)' (1) MODIFY   (2) QUIT'
 299  FORMAT(1X,A22,5X,\)
      READ(*,297)IS1
      IF(IS1.GE.2)GOTO 99
      WRITE(*,296)'* ENTER REQUIRED ACTUATOR NUMBER :'
 296  FORMAT(1X,A34,5X,\)
      READ(*,297)IS2
 297  FORMAT(I2)
      WRITE(*,296)'* ENTER NEW POSITION VALUE       :'
      READ(*,298)SLP(IS2)
 298  FORMAT(F7.3)
      OPEN(2,FILE='SLICE.DAT')
      DO 722 IJ=1,NACT
 722  WRITE(2,298)SLP(IJ)
```

```
      CLOSE(2,STATUS='KEEP')
      GOTO 183
C
C     GAIN MATRIX PARAMETERS
C
 184  WRITE(*,'(1X,A54,3X,\)')'* ENTER VALUE FOR THE COUPLING COEFFICIEN
     *T (0.2<G<0.5)'
      WRITE(*,'(F4.2,3X,\)')Q(1)
      READ(*,'(F4.2)')Q(1)
      GOTO 99
C
C     WEIGH MATRIX PARAMETER
C
 185  WRITE(*,'(1X,A49,3X,\)')'* ENTER POSITION OF W DIAGONAL TO BE CHAN
GED
     * 1-30'
      READ(*,'(I2)')IA2
      WRITE(*,'(1X,A35,19X,\)')'* ENTER NEW VALUE FOR DIAGONAL TERM'
      READ(*,'(F5.2)')Q(2)
      GOTO 99
C
C     PENALTY VALUE PI(0)
C
 186  WRITE(*,'(1X,A36,\)')'* ENTER INITIAL VALUE FOR PENALTY PI'
      WRITE(*,'(3X,F5.2,3X,\)')Q(3)
      READ(*,'(F5.2)')Q(3)
      GOTO 99
C
C     PENALTY VALUE QI(0)
C
 187  WRITE(*,'(1X,A36,\)')'* ENTER INITIAL VALUE FOR PENALTY QI'
      WRITE(*,'(3X,F5.2,3X,\)')Q(4)
      READ(*,'(F5.2)')Q(4)
      GOTO 99
C
C     INCREMENTS FOR PENALTIES PI AND QI
C
 188  WRITE(*,'(1X,A39,\)')'* ENTER NEW VALUE FOR PENALTY INCREMENT'
      WRITE(*,'(3X,F5.2,3X,\)')Q(5)
      READ(*,'(F5.2)')Q(5)
      GOTO 99
C
 194  AM=0.0
      Q(6)=FLOAT(NACT)
      OPEN(1,FILE='PARAM.DAT')
      WRITE(1,'(F5.2)')(Q(I),I=1,8)
      CLOSE(1,STATUS='KEEP')
      DO 195 I=1,24
 195  WRITE(*,*)' '
      WRITE(*,*)' PROGRAM IS RUNNING - PLEASE WAIT'
C
C     SIMULATION AND DEAD TIME DETERMINATION
C
      IS=NINT(ISIM/Q(7))
      IDT=NINT(Q(8)/Q(7))
```

```
C
C     CONSTANTS DEFINITION
C
      FLFB=1.0
      FLJ=0.0
      FLK=0.0
      IPRF=1
      NDT=1
      PT=3.26
      GR=980.0
      ICC=0
      FA=0.3
      UM=.5
      PI=0.0
      QI=0.0
      IFL1=0
      IFL2=0
      JAG=1
C
C     DETERMINATION OF MATRIX "G"
C
      A1=Q(1)
      G(1,1)=1.0
      G(1,2)=A1
      G(1,3)=-A1
      DO 1000 J=4,NACT
 1000 G(1,J)=0.0
      G(2,1)=A1
      G(2,2)=1.0
      G(2,3)=A1
      G(2,4)=-A1
      DO 1010 J=5,NACT
 1010 G(2,J)=0.0
      G(3,1)=-A1
      G(3,2)=A1
      G(3,3)=1.0
      G(3,4)=A1
      G(3,5)=-A1
      DO 1023 J=6,NACT
 1023 G(3,J)=0.0
      J=4
      DO 1030 I=4,NACT-3
      IF(J.GT.NACT-3)GOTO 1030
      DO 1021 J1=1,J-3
 1021 G(I,J1)=0.0
      G(I,J-2)=-A1
      G(I,J-1)=A1
      G(I,J)=1.0
      G(I,J+1)=A1
      G(I,J+2)=-A1
      DO 1022 J2=J+3,NACT
 1022 G(I,J2)=0.0
      J=J+1
 1030 CONTINUE
```

```
      DO 1040 J=1,NACT-5
 1040 G(NACT-2,J)=0.0
      G(NACT-2,NACT-4)=-A1
      G(NACT-2,NACT-3)=A1
      G(NACT-2,NACT-2)=1.0
      G(NACT-2,NACT-1)=A1
      G(NACT-2,NACT)=-A1
      DO 1050 J=1,NACT-4
 1050 G(NACT-1,J)=0.0
      G(NACT-1,NACT-3)=-A1
      G(NACT-1,NACT-2)=A1
      G(NACT-1,NACT-1)=1.0
      G(NACT-1,NACT)=A1
      DO 1060 J=1,NACT-3
 1060 G(NACT,J)=0.0
      G(NACT,NACT-2)=-A1
      G(NACT,NACT-1)=A1
      G(NACT,NACT)=Q(3)
C
C     DETERMINATION OF "W"
      W(1)=Q(2)
      DO 1 I=2,NACT-1
 1    W(I)=1.0
      W(NACT)=Q(2)
C
C     DETERMINATION OF "TRANSP(G)" AND THE PRODUCT "TRANSP(G)*W"
C
      DO 1210 I=1,NACT
      DO 1220 J=1,NACT
 1220 GTW(I,J)=G(J,I)
 1210 CONTINUE
      DO 1213 I=1,NACT
      DO 1214 J=1,NACT
 1214 GTW(I,J)=GTW(I,J)*W(J)
 1213 CONTINUE
C
C     DETERMINATION OF "TRANSP(G)*W*G"
C
 1212 LRA=31
      DO 1215 I=1,NACT
      DO 1216 J=1,NACT
      G1=0.0
      DO 1217 K=1,NACT
 1217 G1=G1+GTW(I,K)*G(J,K)
 1216 GTWG(I,J)=G1
 1215 CONTINUE
C
C     DETERMINATION OF "V"
C
      DO 1230 I=1,NACT
      V(I)=0.0
      IF(SLP(I).EQ.1.0)V(I)=10000.0
 1230 CONTINUE
C
```

```
C      DETERMINATION OF "AO=GTWG+V"
C
       DO 1233 I=1,NACT
       DO 1234 J=1,NACT
 1234  AO(I,J)=GTWG(I,J)
 1233  CONTINUE
       DO 1235 I=1,NACT
 1235  AO(I,I)=GTWG(I,I)+V(I)
C
C      DETERMINATION OF MATRIX "F"
C
       F(1,1)=-1.0
       F(1,2)=1.0
       DO 1300 J=3,NACT
 1300  F(1,J)=0.0
       F(2,1)=1.0
       F(2,2)=-2.0
       F(2,3)=1.0
       DO 1310 J=4,NACT
 1310  F(2,J)=0.0
       J=3
       DO 1320 I=3,NACT-2
       IF(J.GT.NACT-2)GOTO 1320
       DO 1321 J1=1,J-2
 1321  F(I,J1)=0.0
       F(I,J-1)=1.0
       F(I,J)=-2.0
       F(I,J+1)=1.0
       DO 1322 J2=J+2,NACT
 1322  F(I,J2)=0.0
       J=J+1
 1320  CONTINUE
       DO 1330 J=1,NACT-3
 1330  F(NACT-1,J)=0.0
       F(NACT-1,NACT-2)=1.0
       F(NACT-1,NACT-1)=-2.0
       F(NACT-1,NACT)=1.0
       DO 1340 J=1,NACT-2
 1340  F(NACT,J)=0.0
       F(NACT,NACT-1)=1.0
       F(NACT,NACT)=-1.0
C
C      CALCULATION OF "TRANSP(F)*F"
C
       DO 1345 I=1,NACT
       DO 1346 J=1,NACT
       G1=0.0
       DO 1347 K=1,NACT
 1347  G1=G1+F(I,K)*F(K,J)
 1346  FTF(I,J)=G1
 1345  CONTINUE
C
C      DELAY TIME TABLE
C
```

```
      OPEN(10,FILE=BNAME)
      DO 7150 I1=1,NACT
 7150 READ(10,'(F7.3)')BWR(I1)
      CLOSE(10,STATUS='KEEP')
      DO 7250 I2=1,IDT
      DO 7350 I3=1,NACT
 7350 BW(I2,I3)=BWR(I3)
 7250 CONTINUE
      OPEN(10,FILE='SLICE.DAT')
      DO 7450 I4=1,NACT
 7450 READ(10,'(F7.3)')SLP(I4)
      CLOSE(10,STATUS='KEEP')
C
C    MODEL CALCULATIONS
C
      DO 400 I=1,IS
C
      DO 7550 I1=1,IDT
      DO 7650 I2=1,NACT
 7650 BW(I1-1,I2)=BW(I1,I2)
 7550 CONTINUE
C
C     Pipe Section of the Paper Machine
C
      C2=QTKS(I)*CTKS(I)+QWW(I)*CWW(I)-QTNS(I)*CTNS(I)-QR(I)*CTNS(I)
      C1=Q(29)/(Q(8)*1000.0)
      CTNS(I+1)=CTNS(I)+C1*C2
C
C     Headbox Section of the Paper Machine
C
C     Determination of stock level inside the headbox.
C
      HHB(I+1)=HHB(I)+((ST/AHB)*(QTNS(I)-QTHB(I)))/10.0
C
C     Determination of the air pad head inside the headbox.
C
      D1=VHB-(AHB*HHB(I))/100.0
      D2=(ST*HA(I)/D1)*((QTNS(I)-QTHB(I))/1000.0)
      HA(I+1)=HA(I)+D2+(((ST*R*THB)/(RMA*D1))*(QAI(I)-QAO(I)))
C
C     Determination of stock concentration variation inside the HB.
C
      D3=(HHB(I+1)-HHB(I))/ST
      D4=QTNS(I)*CTNS(I)-QTHB(I)*CHB(I)-AHB*CHB(I)*D3*10.0
      CHB(I+1)=CHB(I)+(ST/(AHB*HHB(I)*10))*D4
C
C     Determination of total head and new jet/wire ratio
C
      HT(I+1)=HHB(I+1)+HA(I+1)
      RJSP=(CV*SQRT(2.0*GR*HT(I+1)))/(VW*100.0)
C
C     Determination of the headbox emerging flow rate.
C
      Q10=0.0
```

```
      Q20=0.0
C
C     Calculation of contraction coefficient.
C
      OPEN(10,FILE='SLICE.DAT')
      DO 729 JM=1,NACT
  729 READ(10,731)SLP(JM)
  731 FORMAT(F8.3)
      CLOSE(10,STATUS='KEEP')
      OPEN(10,FILE='SLTYPE.DAT')
      READ(10,*)ISLT
      CLOSE(10,STATUS='KEEP')
      IF(ISLT.EQ.3)GOTO 860
      IF(ISLT.EQ.2)GOTO 830
C
C     Loading A and B for 10 degrees slice CC calculation.
C
      OPEN(11,FILE='SL10A.DAT')
      DO 810 IJ=0,8
      READ(11,730)A(IJ)
  810 CONTINUE
      CLOSE(11,STATUS='KEEP')
      OPEN(12,FILE='SL10B.DAT')
      DO 820 IJ=0,10
      READ(12,730)B(IJ)
  820 CONTINUE
      CLOSE(12,STATUS='KEEP')
      GOTO 890
C
C     Loading A and B for 45 degrees slice CC calculation.
C
  830 OPEN(13,FILE='SL45A.DAT')
      DO 840 IJ=0,8
      READ(13,730)A(IJ)
  840 CONTINUE
      CLOSE(13,STATUS='KEEP')
      OPEN(14,FILE='SL45B.DAT')
      DO 850 IJ=0,10
      READ(14,730)B(IJ)
  850 CONTINUE
      CLOSE(14,STATUS='KEEP')
      GOTO 890
C
C     Loading A and B for 90 degrees slice CC calculation.
C
  860 OPEN(15,FILE='SL90A.DAT')
      DO 870 IJ=0,8
      READ(15,730)A(IJ)
  870 CONTINUE
      CLOSE(15,STATUS='KEEP')
      OPEN(16,FILE='SL90B.DAT')
      DO 880 IJ=0,10
      READ(16,730)B(IJ)
  880 CONTINUE
```

```
      CLOSE(16,STATUS='KEEP')
C
C     Loading of F coefficients.
C
 890  OPEN(17,FILE='SLF.DAT')
      DO 900 IJ=1,3
      READ(17,730)FC(IJ)
 900  CONTINUE
      CLOSE(17,STATUS='KEEP')
C
 730  FORMAT(F12.7)
C
C     Calculation of contraction coefficient CC.
C
      OPEN(18,FILE='CCSLICE.DAT')
      DO 950 IJ=1,NACT
      XI=L/SLP(IJ)
      YI=SLP(IJ)/HHB(I)
      CC1=(A(0)-A(1)*YI)/(1.0-A(2)*YI)
      CC2=DEXP(-((A(3)-A(4)*YI)/(1.0-A(5)*YI))*(XI**FC(ISLT)))
      CC(IJ)=CC1*CC2+((A(6)-A(7)*YI)/(1.0-A(8)*YI))
      WRITE(18,*)CC(IJ)
 950  CONTINUE
      CLOSE(18,STATUS='KEEP')
      GOTO 960
C
C     Calculation of outflow angle BETA
C
      B1=B(0)+B(1)*XI-B(2)*YI+B(3)*YI**2-B(4)*XI*YI+B(5)*XI*YI**2
      B2=EXP((-B(7)-B(8)*XI+B(9)*YI+B(10)*XI*YI)/(1.0-B(6)*YI))
      BETA=(B1/((1.0-B(6)*YI)**2))*B2
C
C     Calculation of jet thickness D
C
      D=CC(I)*SLP(I)
C
 960  IMC=0
C
C     Calculation of individual flow per slice section and total flow
C
      DO 210 J=1,NACT
      QHB(I,J)=CC(J)*SLP(J)*SLW*CV*SQRT(2*GR*HT(I+1))
      Q20=Q10+QHB(I,J)
      Q10=Q20
 210  CONTINUE
      QTHB(I+1)=Q20/1000.0
C
C
C     SCANNER BASIS WEIGHT READINGS
C
      IF(FLFB.EQ.0.0)GOTO 2010
C
C     SCANNER READING "FRONT TO BACK"
C
```

```
      IF(FLJ.EQ.1.0)GOTO 2020
      JFB=1
      FLJ=1.0
 2020 BWS(JFB)=BW(0,JFB)
      JFB=JFB+1
      IF(JFB.GT.31)GOTO 2030
      GOTO 1610
 2030 AM=1.0
      BWS(NACT+1)=FLOAT(IPRF)
      BWS(NACT+2)=FLFB
      SLP(NACT+1)=FLOAT(IPRF)
      SLP(NACT+2)=FLFB
      WRITE(10,'(10F5.2)')(SLP(I1),I1=1,NACT+2)
      WRITE(11,'(10F5.2)')(BWS(I1),I1=1,NACT+2)
      WRITE(*,*)' '
C
      WRITE(*,203)'SCAN NO.',IPRF
 203  FORMAT(1X,A8,3X,I3,/)
      WRITE(*,'(10F5.2)')(BWS(J),J=1,NACT)
      WRITE(*,*)' '
C
      FLJ=0.0
      FLFB=0.0
      IPRF=IPRF+1
      IF(IFL2.EQ.1)GOTO 3010
      IF(IFL1.EQ.1)IFL2=1
      GOTO 1610
C
C     SCANNER READING "BACK TO FRONT"
C
      IF(IFL2.EQ.1)GOTO 3010
 2010 IF(FLK.EQ.1.0)GOTO 2050
      KBF=30
      FLK=1.0
 2050 BWS(KBF)=BW(0,KBF)
      KBF=KBF-1
      IF(KBF.LE.0)GOTO 2060
      GOTO 1610
 2060 AM=1.0
      BW(3,NACT+1)=FLOAT(IPRF)
      BW(3,NACT+2)=FLFB
      SLP(NACT+1)=FLOAT(IPRF)
      SLP(NACT+2)=FLFB
      WRITE(10,'(10F5.2)')(SLP(I1),I1=1,NACT+2)
      WRITE(11,'(10F5.2)')(BWS(I1),I1=1,NACT+2)
C
      WRITE(*,213)'SCAN NO.',IPRF
 213  FORMAT(1X,A8,3X,I3,/)
      WRITE(*,'(10F5.2)')(BWS(I1),I1=1,NACT)
      WRITE(*,*)' '
C
      FLK=0.0
      FLFB=1.0
      IPRF=IPRF+1
```

```
      IF(IFL2.EQ.1)GOTO 3010
      IF(IFL1.EQ.1)IFL2=1
      GOTO 1610
C
C     DETERMINATION OF PENALTIES "P" AND "Q" AND MOVEMENTS "U"
C
 3010 AM=0.0
C
      QIC=0.0
 9101 PIC=0.0
 9201 QI=Q(4)+Q(5)*QIC
      PI=Q(3)+Q(5)*PIC
C
C     CALCULATION OF "Q*FTF"
C
      DO 1465 J1=1,NACT
      DO 1466 J2=1,NACT
 1466 QFTF(J1,J2)=QI*FTF(J1,J2)
 1465 CONTINUE
C
C     CALCULATION OF "AK"
C
      DO 1527 J3=1,NACT
      DO 1526 J4=1,NACT
 1526 AK(J3,J4)=AO(J3,J4)+QFTF(J3,J4)
 1527 CONTINUE
      DO 1528 J5=1,NACT
 1528 AK(J5,J5)=AK(J5,J5)+PI
C
C     CALCULATION OF "INVERSE OF AK"
C
      NROW=NACT
      NCOL=NACT
      MRA=31
      CALL MATINV(ISOL,IDSOL,NROW,NCOL,AK,MRA,KWA,DET)
C
C     CALCULATION OF "ZO"
C
      DO 1450 J=1,NACT
 1450 YBR(J)=BWR(J)-BWSP
      DO 1460 IZ=1,NACT
      G1=0.0
      G2=0.0
      DO 1470 J=1,NACT
      G1=G1+GTW(IZ,J)*YBR(J)
 1470 G2=G2+AO(IZ,J)*SLP(J)
      ZO(IZ)=G2-G1
 1460 CONTINUE
C
C     CALCULATION OF "Z"
C
      DO 1550 I5=1,NACT
 1550 Z(I5)=ZO(I5)+PI*UM
C
```

```
C     CALCULATION OF "U"
C
      DO 1560 I6=1,NACT
      G1=0.0
      DO 1570 I7=1,NACT
 1570 G1=G1+AK(I6,I7)*Z(I7)
      U(I6)=G1
 1560 CONTINUE
      WRITE(*,*)' '
      WRITE(*,*)' '
      WRITE(*,*)'"U" PROFILE'
      WRITE(*,*)' '
      WRITE(*,'(1X,A3,2X,F4.2,2X,A3,2X,F4.2)')'P =',PI,'Q =',QI
      WRITE(*,*)' '
      WRITE(*,'(10F7.4)')(U(I1),I1=1,NACT)
      WRITE(*,*)' '
C
      BI(1)=U(2)-U(1)
      DO 1580 J1=2,NACT-1
      BI(J1)=U(J1-1)-2*U(J1)+U(J1)
 1580 CONTINUE
      BI(NACT)=U(NACT-1)-U(NACT)
      WRITE(*,*)'MATRIX "BI"'
      WRITE(*,*)' '
      WRITE(*,'(10F7.4)')(BI(I1),I1=1,NACT)
      WRITE(*,*)' '
C
C     CONSTRAINTS CHECKING
C
      DO 9500 IU=1,NACT
      IF(U(IU).LE.0)GOTO 9200
      IF(U(IU).GE.1)GOTO 9200
      IF(BI(IU).LE.-.5)GOTO 9200
      IF(BI(IU).GE..5)GOTO 9200
 9500 CONTINUE
      IKLM=1
      GOTO 9300
 9200 PIC=PIC+1
      IF(PIC.LE.10)GOTO 9202
      QIC=QIC+1
      GOTO 9202
 9300 AM=0.0
C
      DO 9302 I1=1,NACT
      G1=0.0
      DO 9304 I2=1,NACT
 9304 G1=G1+G(I1,I2)*(U(I2)-SLP(I2))
 9302 BW(IDT,I1)=G1+BWR(I1)
      WRITE(*,*)' '
      WRITE(*,*)'BASIS WEIGHT AFTER CONTROL ACTION'
      WRITE(*,*)' '
      WRITE(*,'(10F7.2)')(BW(IDT,I1),I1=1,NACT)
      WRITE(*,*)' '
      OPEN(18,FILE='BW1.DAT')
```

```
      WRITE(18,'(F8.4)')(BW(IDT,I1),I1=1,NACT)
      CLOSE(18,STATUS='KEEP')
      OPEN(18,FILE='UPOS.DAT')
      WRITE(18,'(F7.4)')(U(I1),I1=1,NACT)
      CLOSE(18,STATUS='KEEP')
      OPEN(18,FILE='PQ.DAT')
      WRITE(18,'(2F7.2)')PI,QI
      CLOSE(18,STATUS='KEEP')
C
      DO 9400 IUS=1,NACT
      BWR(IUS)=BW(IDT,IUS)
 9400 SLP(IUS)=U(IUS)
C
 9202 AM=0.0
      DO 7100 I1=1,NACT
      G1=0.0
      DO 7200 I2=1,NACT
 7200 G1=G1+G(I1,I2)*(U(I2)-SLP(I2))
 7100 YB(I1)=G1+BW(IDT,I1)-BWSP
      T1F=0.0
      DO 7300 I3=1,NACT
 7300 T1F=T1F+0.5*YB(I3)*W(I3)*YB(I3)
C
      T2F=0.0
      DO 7400 I1=1,NACT
 7400 T2F=T2F+0.5*PI*(U(I1)-UM)*(U(I1)-UM)
C
      T3F=0.0
      DO 7500 I1=1,NACT
 7500 T3F=T3F+0.5*QI*BI(I1)*BI(I1)
C
      DO 7600 I1=1,NACT
 7600 T4F=T4F+0.5*(U(I1)-SLP(I1))*V(I1)*(U(I1)-SLP(I1))
C
      COST=T1F+T2F+T3F+T4F
      WRITE(*,*)'     COST'
      WRITE(*,*)' '
      WRITE(*,'(F10.5)')COST
      IF(IKLM.EQ.1)GOTO 1610
      IF(PIC.LE.10)GOTO 9201
      IF(QIC.LT.10)GOTO 9101
      IFL1=0
      IFL2=0
      IFL3=0
      JAG=0
C
C     PRINTING ON THE SCREEN
C
 1610 IF(JAG.GT.IDT)GOTO 1611
      IF(JAG.EQ.IDT)IFL1=1
      JAG=JAG+1
 1611 WRITE(*,*)' '
      WRITE(*,*)' '
C     IKLM=0
```

```
 400  CONTINUE
C
 580  AM=0.0
      STOP
      END
```

VITA

Pedro Luiz Bocchini was born in Sao Paulo, Brazil on March 7, 1952. He received his Bachelor of Science degree, in Chemical Engineering, in 1975, from the University of Sao Paulo, Brazil.

He worked, from 1975 to 1986, as an instrumentation process control engineer for Promon Engenharia S.A., Setal Instalacoes Industriais S.A. (subsidiary of Combustion Engineering - USA), Jaakko Poyry Engineering Co., Unipar Quimica Ltda. and Altec Industria e Comercio de Instrumentos Ltda.

He is member of several professional associations : Instrument Society of America, Technical Association of the Pulp and Paper Industries, Brazilian Association of Pulp and Paper, Brazilian Association of Chemical Engineers, Brazilian Petroleum Institute.

He is registered as a Professional Engineer in Sao Paulo, Brazil since 1975.

He received his Master of Science degree in Chemical Engineering from the University of Tennessee, Knoxville in August of 1988.