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# Paper Machine Grade Changes: Closed-Loop Control

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# Abstract

This study handles problems and solutions related to the paper machine grade change. The perspective is in the qualitative study of mass-flow phenomena during manipulation of the variables that change the production rate either locally as a transient or permanently.

In many cases, the grade changes are done using a method where the machine speed is left out from the set of manipulated variables. The weakness of this method is that almost all changes include basis weight change and when done at constant machine speed, it results in a production rate change even when the process wouldn't allow this to occur.

The phenomena related to the speed change through the drying section are simulated using ramp-like excitation signals for several variables. Some of the simulation cases are such that they can only be implemented in a simulation environment.

Basic principles of the multivariable model predictive grade change control are introduced utilising target value trajectories for the controlled variables. Trajectory target values are based on mass-flow calculations while trajectory timing is based on simultaneous machine speed change timing.

The problem related to the usage of mass-flows as measurement during the machine speed change in a delay-system is studied. A simple compensation in addition to trajectory timing changes is developed to solve the problem.

Finally, the head-box flow change, a typical disturbance source in all paper machine grade changes, is analysed and a non-linear prediction-based disturbance compensation method is proposed.

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Risto Kuusisto

# Notation

## Notation

The following notation is used:

### Short Forms

| | |
|---|---|
| CD | Cross direction. In perpendicular to the MD. The direction from the paper machine tender side to the drive side, paper width direction. |
| CTMP | Thermo-mechanical pulp with chemical treatment. |
| CV | Controlled variable. In industry de facto standard language this means a process output which has a set-point or target. In control theory text-books this usually corresponds to $y$. |
| DCS | Distributed control system. |
| DDE | Distributed differential equation. |
| DE | Dry end. |
| DIP | De-inking plant. |
| DMF | Dry mass-flow. |
| DV | Disturbance variable or feed-forward term. In industry de facto standard language this means a process input whose value and process model is known but it can not be changed. In control theory text-books this usually corresponds to $d$. |
| GC | Grade change. |
| HB | Head-box |
| LWC | Light-weight coated paper. |

| | |
|---|---|
| MD | Machine direction. Starting from the head-box slice lip towards the reel. |
| MI | A system with multiple inputs. |
| MMPC | Model predictive controller especially multivariable. |
| MO | A system with multiple outputs. |
| MPC | Model predictive controller or multivariable model predictive controller. |
| MV | Manipulated variable. In industry de facto standard language this means a process input whose value is set in the controller algorithm. In control theory text-books this usually corresponds to $u$. |
| OD | Dry basis weight, oven-dry weight. |
| ODE | Ordinary differential equation. |
| PLS | Partial least squares. |
| RCF | Recycled fibre. |
| SC | Supercalendered magazine paper. |
| SI | A system with a single input. |
| SO | A system with a single output. |
| TMP | Thermo-mechanical pulp. |
| WE | Wet end. |
| WMF | Water mass-flow. |

## General Variables

| | |
|---|---|
| $c$ | Dimension, CVs. |
| $d$ | Process input, disturbance. See also DV above. |
| $\hat{\varepsilon}$ | Error between prediction and target. |
| $h$ | Prediction horizon maximum. |
| $i$, $j$ | Indices of time points or general indices. |
| $J$ | Penalty. |
| $k$ | Control horizon. |
| $k_i$ | Gain of a transfer function. |

| | |
|---|---|
| $m$ | Dimension, MVs. |
| $N$ | Model prediction length |
| $p$ | Prediction horizon minimum. |
| $\boldsymbol{Q}$ | Weight factor matrix, prediction error. |
| $Q_{in}$ | Mass-flow input. |
| $Q_{out}$ | Mass-flow output. |
| $r$, $r(i)$ | Set-point or future set-point trajectory for the controller. Also called as a reference trajectory in some literature. |
| $\boldsymbol{R}$ | Weight factor matrix, control actions. |
| $s$ | Laplace variable. |
| $t$, $t(i)$, $t_i$ | Time. |
| $\tau_d$, $\tau_{d-i}$ | Time delay. |
| $\tau$, $\tau_1$, $\tau_i$ | Time constant. |
| $u$ | Process input, often the controller output as well. See also MV above. |
| $\Delta\hat{\boldsymbol{u}}$ | Predicted control action. |
| $w_i$ | Individual weight value for a variable. |
| $\boldsymbol{w}(i)$ | Weight vector at time $i$. |
| $\boldsymbol{W}(i)$ | Weight matrix at time $i$. |
| $\boldsymbol{W}_0$ | Nominal weight matrix. |
| $\widehat{X}$ | Prediction in general for the variable $X$. |
| $y$ | Process output. See also CV above. |
| $\hat{\boldsymbol{z}}_{\boldsymbol{d}}(i)$ | External disturbance for free response. |
| $\hat{\boldsymbol{z}}_{\boldsymbol{u}}(i)$ | Free response from past MV actions. |
| $z$ | Process output, sometimes. See also CV above. |

## Paper Machine Process Variables

| | |
|---|---|
| $A$, $A_Y$ | Ash proportion in general and at location $Y$, proportion of inorganic filler of the total mass-flow excluding water, usually [%]. |
| $B$, $B_Y$ | Total basis weight including all of the sub-components in general and at the location $Y$, usually [g/m$^2$]. |
| $B_x$, $B_{x\_Y}$ | Basis weight of the sub-component $x$ and the sub-component $x$ at location $Y$. |
| $C_Y$ | Total consistency (all of the sub-components except water) at location $Y$, usually [ g/l ]. |
| $C_x$, $C_{x\_Y}$ | Consistency of the sub-component $x$ and the sub-component $x$ at location $Y$. |
| $D$ | Density, [kg/dm$^3$]. |
| $D_x$ | Consistency of the sub-component $x$. |
| $\delta$ | Draw, [1]. |
| $F_Y$ | Liquid volumetric flow at location $Y$, [l/s]. |
| $F_S$ | Screen reject flow. |
| $F_B$ | Head-box by-pass flow. |
| $F_L$ | Wire-pit overflow to long circulation. |
| $g$ | Gravitation factor [m/s$^2$]. |
| $h$ | Height, in [m]. |
| $H$ | Average slice opening excluding CD actuator changes, [m] but the practical unit [mm]. |
| $h$ | Slice opening future target trajectory. |
| $J$ | Jet/wire ratio, [1]. |
| $k_c$ | Head-box constraction coefficient. |
| $k_{CMB}$ | Combined factor in press moisture ratio. |
| $k_{comp}$ | Mass-flow compensation gain. |
| $L_{DS}$ | Web length in the drying section [m]. |
| $M_Y$ | Moisture at the location $Y$, proportion of water of the total mass-flow, usually [%]. |

| | |
|---|---|
| $p$ | Proportion, usually [%]. |
| $P$ | Pressure in general [kPa]. |
| $P_Y$ | Pressure at location $Y$, [kPa]. |
| $P_S$ | Steam pressure in general, [kPa]. |
| $Q_Y$ | Mass flow including all of the sub-components at location $Y$, usually [kg/s]. |
| $Q_x$, $Q_{x\_Y}$ | Mass flow of the sub-component $x$ and the sub-component $x$ at location $Y$. |
| $\rho$ | Density [kg/dm$^3$]. |
| $R_d$ | Dry mass-flow retention [1]. |
| $R_S$ | Delayed machine speed ratio. |
| $R_H$ | Delayed slice opening ratio. |
| $S$ | Speed in general, [m/s]. |
| $s$ | Speed future target trajectory. |
| $S_Y$ | Web speed at location $Y$, in [m/min] or [m/s]. |
| $t_e$, $t_s$ | End time and start time. |
| $t_H$ | Pure time delay of .the head-box approach system. |
| $t_{start\_i}$ | Start time for variable i. |
| $\tau_a$ | Advance time. |
| $\tau_{comp}$ | Total delay for mass-flow compensation. |
| $\tau_{scan}$ | Scanning time. |
| $\tau_{d\_DE}$ | Dry end time delay. |
| $\tau_H$ | Time constant of the head-box approach system transfer function. |
| $V$ | Volume, in [m$^3$]. |
| $W_Y$ | Paper width at location $Y$, in [cm] or [m]. |

## Sub-components

| | |
|---|---|
| $w$ | Flow sub-component, water. |
| $a$ | Flow sub-component, ash/filler. |
| $f$ | Flow sub-component, fibres. |
| $r$ | Flow sub-component, retention aid. |
| $d$ | Dry components. Sum of flow sub-components $a$ and $f$, excluding water. |

## Process Location Points

| | |
|---|---|
| $A$ | At the retention aid feed point. |
| $D$ | Drying section as a whole. |
| $Dn$ | After drying section n (n = 1...N, where N is machine dependent, typically 4 ... 8). |
| $F$ | At the filler feed point. |
| $H$ | At the head-box. |
| $M$ | At the thick stock and white water mixing point at the bottom of the wire pit. |
| $P$ | After press section. |
| $R$ | At reel. |
| $R1$ | At reel (intermediate result). |
| $T$ | At the thick stock feed point. |
| $W$ | At the wire section. |

## Special Units

| | |
|---|---|
| $[kgH_2O]$ | Amount of water. |
| $[kgD.C]$ | Amount of dry content. |

# Contents

# Chapter 1

# Introduction

The paper mill in a large sense is a complex combination of sub-units or even small scale sub-mills. The production scheduling in a modern mill in the best case is based on mill-wide optimisation which tries to take into account the total economic optimum of the whole mill. It is possible to do it in this way if the mill order log is long enough that e.g. the individual orders can be run in the best optimal way. Here the present inventory of the mill, storages in general, is a key factor but also the degree of technical difficulty to change paper grade from one order to another is significant. Usually it is preferable to arrange the production schedule in such a way that the specifications of successive paper grades are as near as possible. If the order log allows, the preferred production schedule for different grades is planned to run from the lowest to the highest basis-weight in an ascending order and then back down in a descending order so that the increments between any consequential grade runs is kept to a minimum change in basis-weight or production rate. This kind of group of runs starts and ends usually at the planned machine wash and maintenance. From the optimisation point of view, the market situation forces the mills, at least the smaller mills in a production schedule with very short delivery times. This makes the mill-wide optimisation difficult in a single mill. In a group company type operation the actions are spread between different mills. At the same time higher profitability requirements seem to force cuts in the operating, automation and service personnel. Technically all of the above mentioned considerations require that grade changes are carried out as reliably and efficiently as possible.

The paper as an end product has several quality requirements from which only a certain set is realised at the actual paper machine. First, the stock itself from where the paper is produced consists of different kind of fibres: long, short, mechanical, chemical, and/or re-cycled etc. The raw materials can be produced in the same factory starting from wood through the chemical or mechanical fibre plant to produce either cellulose or mechanical pulp; TMP, CTMP or ground-wood. The final stock pulp contents depend on the produced paper. This has an effect on the wood handling also. First the wood is cut and debarked but if the next phase is ground-wood production then no additional handling is needed. In the case of TMP/CTMP or chemical pulp, additional chip-cutting is needed before further treatment.

An increasing material source for paper production is re-cycled fibre in which case the factory can include a re-cycled fibre (RCF) treatment with the possible de-inking plant (DIP). It is possible but rare that all the raw material is coming to the mill as final products without need to any after-treatment. Also several combinations exist where some raw-material is bought outside and some of them are produced in-house.

Nowadays it is also typical that the amount of in-organic material called filler or ash is increasing. Maximum dry proportion of ash in the case of SC-papers can be almost as high as 35 %. At the same time some special paper grades produced from pure cellulose have almost no ash at all. There are two reasons to increase the ash proportion: the possibility to get better surface properties for the paper after calendering, and take the advantage of the better production economy. The filler cost per mass-unit is cheaper than fibres.

In addition to the fibres and fillers, the present day paper production requires a lot of chemicals. Some of the chemicals are used in the process for controlling the retention of the base-paper on the wire section, or to control the chemical state of the liquid before and in the short-circulation, some other remove the air from the stock before head-box, or to prevent any biological growth in pipes, or to prevent dusting problem in and after the drying section etc. From grade change point of view, the retention aid for the fibre retention control or the filler retention control at the wire is the most important. Other related chemicals are those that control the cationic demand of the suspension.

Another aspect of grade change is the paper colour whose handling during a grade change is a special area of knowledge. In general, to make the colour grade change in an on-line manner is normally not possible for certain colour transitions, because in the case of distant colours the machine washing is necessary between grades. In the case of so called shade-changes, it is possible to make the change in a running machine. At the moment the known applications are based on predetermined actuator set-point ramps without colour measurement feedback during grade-change.

A common aspect of all paper and sheet-form cellulose production is drying. In all cases nowadays the drying sections consist of, at least partly, the drying cylinders heated by steam. Other possibilities are air-drying for cellulose but also for drying the coating layer. For coating the electrical or gas-burner based infra-red drying is also in use. Another drying unit that uses hot air is the so called impingement dryer, whose drying energy comes from burning gas.

The paper machine produces a product that can be called base-paper. Sometimes the base-paper itself is the end-product but often the final product includes further processing either coating or other surface-treatment. Both surface treating calenders or coating stations can be integrated in the paper machine after the first drying section but they can be also independent units after paper machine. If the final paper is such that it requires coating, coating kitchen produces the required coating paste for this purpose.

Additional finishing phases are different kinds of calenders such as super- or soft-calenders depending on the surface property requirements of the produced paper grade (gloss, smoothness, caliper).

After coating or/and calendering the paper is cut in the length direction in a winder and packaged in customer rolls in a packaging line. This is the most typical case. At the winder, the big paper machine size rolls are cut to order-specified widths and roll-weight. The rolls can be the end-product as such after packaging or there can be one more phase for, sheet cutting before the final customer packaging.

The paper machine is only a part, but a necessary part in the production chain of integrated factory consisting of wood handling for pulp production, chemical or mechanical pulping, coating kitchen for coating paste mixing, chemical preparation, power plant for drying steam and stock preparation to make the suspension for the paper machine. After the actual paper-machine, there may possibly be after-treatment sections like coating and calendering and paper is cut in a winder to customer rolls for final packing.

As said above, the paper mill needs energy for heating and drying, typically steam, which is generated often in a small power plant. In the case of a chemical pulp line, the power plant is an essential part of recycling of the chemicals in pulp production. The steam can be seen to some extent as a by-product used in paper machines for drying the paper web. From the economic point of view, the power plant produces electricity in addition to the recovery of chemicals.

Stock preparation takes care of partly storing (intermediate storage tanks) the stock components. The main purpose of stock preparation is to deliver even and correctly proportioned mix of stock components, chemicals and recycled stock to the paper machine.

## The Effects of the Surrounding Units to the Paper Machine

From the long term point of view, all the above mentioned parts/departments are important for the paper production. From the grade change point of view the pre-paper machine processes are the most important ones. Most often their effect can be negative for performance. They create either disturbances (see e.g. [Nis99]) or they set constraints for the manipulated variables during grade change as well as during a normal run. There is not much material in literature of controlling these to support grade change.

A typical disturbance coming from stock preparation is the change in stock composition. A change in the broke-ratio of the stock is a strong disturbance. The latter can affect the incoming stock filler (recycling filler) content but also change the actual ratio between long/short fibres or mechanical/chemical pulps. Even more radical are the cases when the broke comes from another machine and includes coating. In all of those cases, the chemistry and the charge conditions change affecting the retention levels. The effect of these disturbances at the paper machine can be observed as quality deviations in both paper ash and moisture. This is not tied only to grade change but happens during normal run as well.

Another typical disturbance is the change in the mechanical/chemical pulp ratio in the stock, which is often tied to the grade change when the paper grade class changes from one to another. In this case moisture and retention are affected severely. A similar effect can happen when the chemical pulp form is changed e.g. from liquid cellulose to sheet form that has been dried already once in a pulp drying machine. This seems to have a viable effect in drying properties, which has something to do with different drying properties during second drying at the paper machine (see also Section 5.1.1) (actually it is not clear if the change happens already at the press section or does it change the drying/evaporation properties of the paper-web inside drying).

Retention chemical mixing can have strong effects on the paper machine. Even if the original non-diluted chemical flow is stable but the dilution water flow is fluctuating, the net result in the final feed-point is uneven retention-aid concentration. The strongest effect can be seen on high-ash machines where this type of disturbance changes the final paper ash significantly.

One constraint-type disturbance comes from the power plant. It is common that the machine is run pushing the production rate against the maximum steam consumption limit. This leads to a situation where steam pressure target required by the moisture control at that production level can not be reached. This can happen both during normal run but especially it is possible if there is a production rate increase included in the grade change.

From grade change point of view the high ash proportion adds more challenge to the grade changes. The paper is weaker which increases the break-probability and sets limits for the speed of the grade change in that way. Another reason is the low total retention of high-ash grades. The short circulation process dynamics is determined by the container and pipe volumes and the wire retention. The amount of filler circulating back in the process depends on the retention. When this is low the dynamics of the short circulation is also slow setting also a limit from that direction to the best achievable grade change speed.

# Earlier Work on Paper Machine Grade Changes

The traditional way of changing grade was done manually without paper quality control feedback. Then certain partly feedback-controlled methods have evolved.

## Open-loop Grade Change

In a manual method of grade change the operator modifies the set-points of the low-level loop controllers according to some calculations and his personal experience, and then follows the response and adjusts the set-points until the results fulfil the requirements. In this method the paper quality control loops are not active during grade change. With experienced personnel this can sometimes work well but the final performance depends a lot on the individual operator in question. An early simulation method for predicting the grade change has been described in [MII88] including also some long circulation. The model includes fibres and fillers. The authors even simulated filler overdosing to speed-up the paper ash change.

The next automation step in open-loop grade changes is the automated low-level loop ramping. Low-level loops are called MVs later in this text. In an open-loop method, the MV target set-points are calculated from the paper quality targets of the new grade and then these targets are changed in a predefined manner. Typically, the values are changed using linear ramps in time. The target calculations of MVs are based on process gains from the MVs to the corresponding CVs handling each pair as an independent SISO process. In [Pel93, Pel96] there are examples of such target value calculations. The calculation has been later extended to utilise fuzzy calculation [VPK00]. Another target value calculation method based on PLS-techniques is introduced in [Vii04].

Timing and synchronisation of the ramps is based on dominating time delays and first order response times. Timing principle has been handled e.g in [MC99] and later the head-box pressure control effect has been considered as an addition to this [MRC00].

The practical start-up time optimisation, and usage of operator experiences for fine-tuning has been handled in [BNS$^+$01]. Some attempts to utilise more complicated open loop control forms instead of simple linear ramps has been mentioned in [Vii04] without any details how to calculate them.

The paper moisture seems to be a difficult quality variable to be controlled properly during grade change. There are some articles concerning paper machine simulation including some kind of physical model based simulator of drying. [MST00, SKiTM02] explain an ODE approximation (so called “iron-model”) of the drying section for moisture control purposes to predict the required final steam pressure target. There are also some results from real machines to show the effectiveness of the method. The simulation in [Per98] is based on Matlab environment and gives also some suggestions how to speed-up the standard ramp-based open-loop grade change. APMS [NLL+98] is another simulation environment especially targeted for paper machines developed in VTT Finland (Technical Research Centre Finland). The principle of a simulator and results from a board machine simulation are handled in [Lap03]. Before that there was an article written in 1996 [VVS+96] giving a kind of overall view about the future among grade change management. At that time the idea was "The basic model structure and most of the parameters are based on laws of physics and knowledge on plant structure". At the moment the implementation of the idea seems to be still far away from reality.

### Model Feedback with Open Loop

The work in [Men96] is an attempt to include a kind of feedback in the traditional open-loop grade change method by updating the grade change models in every grade change. Here the standard grade change ramps are used as excitation signals to the process for modelling purposes. In this way, the result is a dynamic model of the grade change itself but in principle it is not possible to distinguish which process condition models the present grade or the target one. In feedback situation, the method can not be used because the form of each excitation signal is not a predetermined ramp anymore.

### Combination of Closed and Open Loop Control

The article [MRC00] handles also the possibility of controlling the MVs in a predetermined way having at the same time closed loop controls on. The CV-values (basis-weight, ash and moisture) are predicted using the MV-curves by feeding these to a dynamic paper machine process model. The output of the prediction is fed to the set-points of the CV-controllers. If disturbances occur during grade change, the CV-controller makes control actions otherwise relying on these predictions. The article gives an example of basis-weight control during a simultaneous speed-change.

### Closed Loop Control

There are not many articles about pure closed loop grade change methods at the paper machine. Because of the predictive nature of the grade change i.e. the point in time when the grade change happens in the future is known in advance. Therefore all of the examples given here are utilising some kind of MPC. [MH94] handles almost only performance related items, but tells very little about the actual technical principles or process circumstances related to the paper machine grade changes. Another article handling the same control product [SKPS96] mentions a little bit of technical details related to the question of when it is possible to do the grade change having quality controls on. The changes are classified here in two classes:

1. Close grade changes without or with minimal broke having closed loop control on and
2. Changes where the change will be done open-loop (far-away grades) trying to minimise the amount of broke without considering the actual CV measurement values.

[KKSH01] describes the possibilities of closed loop MPC-based grade change with simulation examples without cases from real machines. In [Hau03] there is an example of an operator display from a grade change. The level of technical details here is also very general.

GC optimisation has been handled in [IR96]. This seems to be also the only document that includes attempts to formally evaluate grade changes.

## The Process Scope of the Thesis

The process area in this thesis is limited to the basic paper machine. It excludes both sections before the machine like stock preparation but also the sections after the machine like e.g. re-wetting (typical in SC-machines) or coating. Many articles have been published about grade changes at the paper machine already so is there any need for further discussion? There have been at least the following reasons why there is still some room for handling this item restricted to the paper machine alone: there is no detailed material about closed-loop grade changes and the available material includes only general discussion about using MPC for grade changes at the paper machine. The mass-flows have been used in balance calculations and simulation model construction but there are no articles known to author on using mass-flows as measurements in paper-machine grade change control and possibly problems resulting from this. Especially any speed-change specific information has not been shown for the feed-back controlled grade change.

## Methods

The results in this thesis rely on simulation. Two simulation platforms have been used: Matlab and APMS. Matlab with the Simulink Toolbox is a fast and flexible environment for testing basic ideas and phenomena. On the other hand, in order to include such detailed information in a general simulation/calculation environment that is possible with APROS/APMS would be very time-consuming task in Matlab.

APMS offers simulation accuracy adequate for even process dimensioning. The drawback of the APMS environment is that a certain simulation happens in a certain "machine" where the simulation needs a considerable amount of physical and/or measured parameters from the real machine. Results of APMS simulation have to be evaluated keeping always in mind that they are from a certain specific process. This item is handled partly in Section 5.1.1. In principle the APMS model used here could be seen as a paper machine that could exist and the results are generalisable.

There are also two case examples from production machines, which are from totally different (opposite) categories. The machine A (Appendix A.1) is a relatively fast LWC machine while machine B (Appendix A.2) is a slow 3-layer board machine.

## Results

For the paper machine grade change it is necessary to take into account the speed change either as a production rate change or as a part of the grade change. In this thesis, this problem has been handled by using the unit-conversion from direct quality measurements to mass-flow, hence giving the possibility to introduce meaningful future target trajectories to all basic values. These trajectories are used to construct an MMPC-based grade change control. During speed change the acceleration generates difference in mass-flow measurements (fibres, filler) between head-box and scanner. This problem has been solved for the case of dry matter and partly for the case of moisture (=water). In the case of water removal from the paper-web the problem is not only related to drying section delay and machine speed but the acceleration introduces a temporary water mass-flow change which shows also in drying conditions. Another special feature of any paper machine is the head-box pressure change added with the possible slice opening change during speed change. In most cases the head-box pressure follows the machine speed in order to keep the jet-speed the same as the machine speed with so called J/W-ratio. This creates another standard disturbance which has been handled in earlier work but not in the non-linear disturbance prediction form presented here. The earlier published articles don't also propose anything about how to take into account slice opening changes. The method solves both problems.

## Contributions

The main contributions of this thesis are:

- Pointing out the possible problems of the open-loop grade change.

- Studying drying section internal behaviour by tests whose results are useful for grade change but which can be done only in simulation environment in practise.
- Development of the basic MMPC based paper machine grade change control utilising future target trajectories in the form of mass-flows.
- Adding the compensation calculation for mass-flow measurement values and timing modification during machine speed change.
- Solving the head-box flow and slice-opening disturbance handling during speed change as a unique non-linear disturbance prediction for the MMPC.

## Thesis Structure

This thesis consists of nine chapters including this introduction. Chapter 2 describes the typical manipulated variables and their effect in the process but in more detailed fashion than it has been presented normally. The usual simplification for quality control purposes is given.

Chapter 3 covers different types of grade changes and their general requirements.

Chapter 4 discusses Matlab-simulations of open-loop grade changes and especially those with certain process model deviations. This chapter shows how much typical MV-based open-loop control GC results can deviate from the targets when the model parameters have certain error in them.

Chapter 5 gives results of APMS-simulations, where most of the tests had a special nature. Special means are discussed to get results faster than it is possible in a production machine or the test itself can not be done at a production machine at all. Also lack of instrumentation narrows the usefulness of similar tests at production machines.

Chapter 6 presents the basic principles of closed-loop MMPC-based GC for the paper machine based on mass-flows as variables.

Chapter 7 deals with the problems of mass-flows during speed change. The solution for these problems is given.

Chapter 8 presents the head-box flow change related disturbance and the compensation using prediction and MMPC.

The final conclusions and suggestions for future research are given in Chapter 9.

# Chapter 2

# The Paper Machine Process

This chapter describes in more details the paper machine process and its behaviour when typical MVs are changed.

Figure 2.1 shows a general and a simplified structural diagram of the paper machine. The reference points, which are used as subscripts or partial subscripts in equations are marked also in the figure.

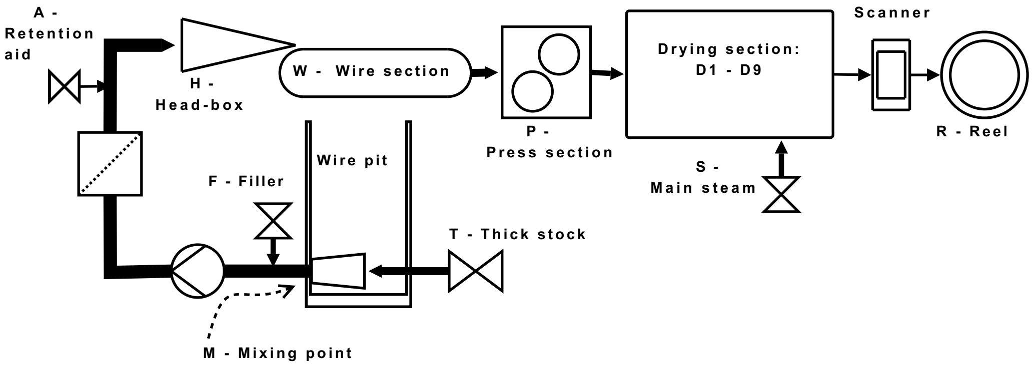

Figure 2.1: Structural diagram of a paper machine.

## 2.1 Thick Stock Feed

The thick stock flow $F_T$ at point T can be the starting point of the process description. The thick stock (sometimes called machine stock) is a mixture of water, fibres, fillers and additional chemicals. The fibre content is normally dominating the dry content of thick stock ( $> 80\%$). The typical consistency of thick stock is around 3.5 % and the goal is to keep the consistency as stable as possible. A typical feeding point of thick stock is the centre area of the mixing conical at the bottom of the wire pit, point M. Here the mixing of the circulating white water flow from wire and the thick stock takes place. Normally the circulating flow consistency is supposed to stay much lower than the consistency of thick stock. A way to describe the effect of change in thick stock flow is as follows:

1. Change in thick stock flow.
2. Change in mixing point consistency including the ash content because of filler in the broke or in the recycled fibre stock.
3. Change in head-box consistency and ash content but also change in head-box output dry mass-flow and filler mass-flow
4. Change in wire dry basis weight but also wire dry mass-flow and filler mass-flow
5. Change in white water dry mass-flow and filler mass-flow that can be seen in white water total consistency and ash content changes.
6. Change in the basis weight out of the press section but also change in both the dry mass-flow, filler mass-flow and water mass-flow
7. Change in the scanner basis weight (dry basis weight, ash percentage and moisture) out of the drying section but also change both in the dry mass-flow, ash mass-flow and water mass-flow

So we can see that in addition to the basic usage of thick stock flow as the main dry basis weight actuator, this quantity affects several other variables including the mass-flow which, in other words is the machine production rate. The purpose of changing the thick stock flow is to change the incoming dry mass-flow (constant consistency) to correct dry basis-weight error or change the production rate. Actually this happens indirectly by changing the mixing point consistency which then makes the controlling action when the consistency change arrives at the head-box.

Normally these effects and their dynamic models are considered in the paper quality control during normal run; from thick stock flow

**to dry basis weight** (the main controlled variable of thick stock flow, later dry mass-flow) and

**to** ash proportion (later ash mass-flow) and

**to** white water consistency and

**to** moisture (later water mass-flow).

## 2.2 Filler Feed

Quite often the next important MV in the process is the filler flow $F_F$ at point F. The filler is a mixture of water and inorganic materials e.g. kaolin. The typical consistency of filler is around 30 - 40 %. Nowadays a typical feeding point of the filler is somewhere near and after the mixing conical M at the bottom of the wire pit. The filler is mixed with the circulating white water and the thick stock. In the case of high-ash machines the circulating ash mass-flow can be a lot higher than the added fresh filler. A way to describe the effect of filler flow change is as follows:

1. Change in filler flow.
2. Change in mixing point ash content.
3. Change in head-box ash content but also change in head-box output dry mass-flow and filler mass-flow.
4. Change in wire ash content and dry basis weight but also wire dry mass-flow and filler mass-flow.
5. Change in white water filler mass-flow that can be seen in white water total consistency and ash content changes.
6. Change in the ash content and basis weight out of the press section but also change in both the dry mass-flow, filler mass-flow and water mass-flow.
7. Change in the scanner dry basis weight, ash percentage and moisture out of the drying section but also change both in the dry mass-flow, ash mass-flow and water mass-flow (ash affects drying).

In addition to the basic usage of filler flow as the main paper ash content actuator, it also affects several other variables. Another philosophy in feeding the filler is to feed filler partly already in the blend chest. The idea is to keep the thick stock filler content inside a range in order to keep the trim filler in short circulation also inside the operating range especially during broke flow changes[1]. Unfortunately the total filler calculation including the filler portion coming from broke seems to give unreliable results for the trim filler control.

Normally these effects and their dynamic models are considered in the paper quality control during normal run; from filler flow

**to** dry basis weight (as dry mass-flow) and

---

[1] Sometimes all added filler is feed-in into the blending chest. Then the filler as MV is one part of the dry content of the thick stock. This case is not handled here.

**to ash proportion** (the main controlled variable of filler flow, as ash mass-flow) and

**to** white water consistency and

**to** moisture (as water mass-flow).

## 2.3 Retention Aid Feed

Before the head-box is the retention aid flow $F_A$ at point A. The retention aid is a mixture of water and polymer whose purpose is to create flocks to tie filler in them. A typical feeding point of retention aid is somewhere between the wire pit mixing point and head-box. The optimal connection point of retention aid depends on the reaction time of the retention aid in question (see e.g. [Kos04]). A way to describe the effect of retention aid flow change is as follows:

1. Change in retention aid flow.
2. Change in filler and fines retention and thus their mass-flow distribution ratio between wire-pit and press directions.
3. Change in wire ash content and dry basis weight but also wire dry mass-flow and filler mass-flow. However retention aid can not make a permanent change because it is controlling only the distribution ratio.
4. Change in white water filler mass-flow (almost only) that can be seen in white water total consistency and ash content changes.
5. Change in mixing point ash content (mainly).
6. Change in head-box ash content but also change in head-box output dry mass-flow and filler mass-flow.
7. Change in the ash content and basis weight out of the press section but also change in both the dry mass-flow, filler mass-flow and water mass-flow. This change is temporary.
8. Change in the scanner basis weight, ash percentage and moisture out of the drying section but also change both in the dry mass-flow, ash mass-flow and water mass-flow. This change is also temporary.

In addition to the basic usage of retention aid flow as the white water consistency actuator it affects several other variables.

Normally these effects and their dynamic models are considered in the paper quality control during normal run; from retention aid flow

**to** dry basis weight (as dry mass-flow) and

**to** ash proportion (as ash mass-flow) and

**to white water consistency** (the main controlled variable of retention aid flow) and

**to** moisture (as water mass-flow).

It has to be noted that the main effect from retention to white water consistency is permanent while for the mass-flow cases, the effect is more temporary. There is however also a permanent level change in mass-flows because of retention change causing changes in the mass-flow balance of the short circulation and changing the amount of losses out of the short circulation. Typical response models from retention aid to CVs consist of dead-time and first or second order dynamics which can be sometimes misleading because the actual response is almost temporary with very small final level.

## 2.4 Steam Pressure

The purpose of the next MV, steam pressure $P_D$ is to control the energy that is available for the water evaporation in drying section D. The amount of energy flowing from the inside of the drying cylinders to the water to be evaporated on the outer surface of the drying cylinders depends on the temperature difference between the paper web surface and the cylinder inner layer. One way to describe the effect of steam pressure change is as follows:

1. Change in the drying cylinder inner surface temperature which follows change in steam pressure.
2. Change in the temperature difference between the drying cylinder inner and outer surfaces.
3. Change in the warming energy flow because of the change in the temperature difference.
4. Change in the steam volumetric flow because of the change of steam pressure controlled by the steam pressure valve opening.
5. Change in the condensate flow out of the cylinder because of the new energy balance where the energy transfers to evaporation by means of the condensing steam.
6. Change in paper web surface temperature.

7. Change in the evaporation rate.
8. Change in water mass-flow out of the drying section as a result of change in the evaporation rate which shows as a change in the scanner moisture.

In addition to this simplified description concentrating only on the main steam pressure, the following items have to be considered in practise:

- Suitable steam pressure ( = temperature) profile between successive drying groups, which is implemented as a cascade of steam pressure controllers getting their set-points calculated based on the main steam pressure set-point.
- Enough steam pressure difference between each group steam input and output.
- Proper condensate removal.

Normally the only dynamic model considered in the paper moisture control during normal run is the model from steam pressure to paper moisture.

## 2.5 Mixing Point

As already mentioned, the thick stock and circulating white water is mixed at the mixing point M. The main part of the white water flow is determined by the thick stock flow and head-box flow. From the mixing point, the flow continues through the pressure screen and possibly through conical cleaning section. Also some paper grades require the deculator before the head-box. Deculator over-flow and screen rejects cause a certain amount of mass-flow losses. From the process modelling point of view there is no big difference in these configurations.

## 2.6 Head-box

Most of the board-machines and older paper machines utilise the air-pad head-box whose basic controlled variables are the head-box pressure and liquid level which have strong interactions between each other. Because of the multivariable nature this type of head-box, it is a good process candidate for multivariable control trials with both in simulation and in practise. Generally, the most common “decoupling” in the control system in practise is done by using separate PID-loops for both of the variables but tuning the head-box level control loop relatively slow and pressure loop as fast as possible.

The other type of head-box is the hydraulic head-box, which has only one basic variable to be controlled, the head-box pressure. The hydraulic head-box is becoming more common nowadays.

Both types of head-boxes include a “slice”, whose vertical opening determines the head-box consistency in a certain operating point. The required head-box pressure is determined by the required jet-speed and the requirement for a certain jet-speed comes from the required J/W-ratio, $\frac{\text{jet speed}}{\text{wire speed}}$. A numerical value of this ratio is typically around one. The values differing from one affect the average fibre orientation and thus directional strengths in paper and board quality.

The jet-speed calculation[2] is based on head-box pressure measurement. The pressure measurement used for the calculation is based on Bernoulli equation, but contains several correction factors taking into account the specific head-box geometry. The most simple type of calculation is used in the simulation cases for head-box pressure control described later Section 5.2.4.

There are also other parameters, the positioning angle and the distance between the head-box and the wire which have to be taken into account in an accurate jet speed calculation.

Nowadays many head-boxes include also the dilution flows [Nis99] inside the head-box to make it possible to adjust certain CD profiles. The dilution flows normally follow the main head-box flow with a certain ratio. In principle, the total dilution flow has a certain effect on the head-box behaviour analysis even if the flow follows the main flow. Anyway the dilution flow part has been left out from the later sections in this thesis because the basic effect is still the same.

## 2.7 Wire Section

The first water removal happens at the wire at point W where the jet spreads from the head-box. The removal is based on vacuums and shear forces (blades under wire). In the so-called twin former case, also centrifugal forces are in use. Most of the water from the suspension is removed already at the wire. Also a lot of fillers are “lost” in the white water because of low filler retention. The fillers lost in the white water return back to the mixing point. The white water consistency behaviour has been analysed in [Kos04].

The wire-pit includes also an over-flow to long-circulation to keep steady level in the pit but also to keep the volumetric flow of the short circulation in balance. The value of the over-flow is approximately the same as the volumetric input flow of thick stock.

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[2] Laser-based measurement devices measuring the actual jet-speed are already on the market, but they are not common yet.

## 2.8 Press Section

After the wire section the web continues in low dry-content (20%) to the press-section at point P, where the rest of the mechanical water removal takes place. Here most of the material that is sent to the wire pit is water, but some filler also. After the press section the moisture of the web is around 40% - 55%, which is one key factor when discussing about the required drying energy in drying section. The water content behaviour in press seems to be largely an unknown area, where only press-specific models exist. The units themselves include several pressure controllers. From the grade change control point of view, the unit could be seen as a simple water content divider. In principle it would be possible to use the press section actively to help moisture control (fast water proportion change in the drying section ingoing water mass-flow) but other process constraints limit this kind of usage.

## 2.9 Steam Box

Between the press and drying sections, there is often a steam-box. The steam-box generally includes individually controllable steam shower zones across the paper web. By increasing the water temperature in paper web the evaporation can be affected. The operating range of steam-box is usually limited to control CD moisture even in principle the unit would be suitable for fast feed-forward MD moisture control using the average value of total CD control steam flow.

## 2.10 Drying Section

Nowadays the most common drying units in a paper machine are steam heated steel cylinders where the paper web is transferred via the felts. The water evaporation itself is based both on warming the water in paper web and the speed difference between the air inside hood and moving web.

Another type of dryer is so called impingement drying unit (handled e.g. [Kok02], but there are not many installations of these yet.

# Chapter 3

# Grade Changes in General

The production management sets requirements for grade changes. Partly the production schedule and partly the type of produced paper form the grade change classification. Different classes have different timing requirements.

## 3.1 Production Management Induced Requirements

From production management point of view the main requirement for grade change is efficiency. Main factors of good efficiency are e.g. broke minimisation, production time loss minimisation and grade change time as understood as off-spec time minimisation.

Efficiency understood in this way is always a trade-off between minimum grade change time and higher sheet break probability. On the other hand there are process constraints that limit the change rate. A typical limitation is the maximum steam consumption allowed from the power plant that could be adequate for stable operation but will be exceeded easily when increasing the production during grade change.

## 3.2 Different Grade Change Classes

The cases are divided in the following classes according to the different operation and performance requirements:

- production rate change with basis weight change
- production rate change by the speed change

- no broke
- minimum broke

### Production Rate Change with Basis Weight Change

At certain machine types the most typical way of changing the grade is to change all other target values except machine speed. By keeping the machine speed constant but changing the dry basis weight changes the production rate of the machine by the ratio of the new dry basis-weight v.s. the old dry basis-weight. To change only the production rate as such will be done as a separate procedure (see the following section). There can be traditional ways of working at the mill to make the change without speed change but also some process management related items can prevent any larger changes in speed. One of those is e.g. speed differences between drying sections which the operators have to observe visually and manage manually during the change.

### Production Rate Change by the Speed Change

When the only target variable to be changed is machine speed the production at the machine is changing. The paper quality target values are supposed to stay the same through the change. However changing speed and keeping the other targets at the same level induces production rate change whose size is relative to the speed change ratio. A simple speed change needs in principle all the features required for the whole scale grade change. The only difference is in the time scale and the amount of required change. Usually there are no high time efficiency requirements for this because making the change slowly enough several types of controllers can handle the change quite easily. As the productivity requirements are growing the requirements to speed-up also speed changes grow thus making this type of change more demanding. The pure speed change is related often to a grade change where the only changing item is the grade indication code for the production follow-up. Another reason to make speed changes is to maximise the production within the process constraints.

### No Broke

When two successive grades in the production chain are so near to each other that the acceptance regions of them overlap then it can be possible to do the grade change without any actual broke. The main requirement of this type of grade change is smooth controller operation. The change speed requirements are only modest. Still when it is a question about e.g. SC machine the time constant from filler flow change to paper ash percentage change can be so long that to get proper results the grade change has to be done as a full-scale grade change.

### Minimum Broke

On some machines the minimisation of the broke is the most common goal of the grade change. The change time should be as short as possible to minimise the amount of broke. The mill could also have selected one paper-machine such that all rare grade runs and sudden production program changes are fed to this machine. This leads easily to both unpredictable and large grade changes. This kind of change includes often both speed change, production rate change and dry basis-weight change.

## 3.3 The Timing Principles

The following sections depict typical timing principles used for grade changes. The method used on a particular machine depends on the process sections following the paper-machine (unwinders, winders). Normally the grade changes are synchronised to reel changes resulting to rolls consisting of only one grade product.

Figure 3.1 depicts a typical reel change and grade change synchronisation possibilities. The acceptance region in both figures 3.1 and 3.2 represent the situation in general for any quality variable that is included in the set of acceptance limits. The acceptance limits are tolerances of the quality values of the product to be saleable. The cases shown are:

A. Broke inside a new roll. The broke is gathered in the beginning of the first roll of the new grade.

B. Broke 50/50. The grade change and the possible broke is divided evenly between the last roll of the old grade and the first roll of the new grade.

C. Broke on the old roll. The broke is gathered on the surface of the last roll of the old grade.

Timing B is usually in use for overlapping grade acceptance regions. The rolls do not include broke at all, Figure 3.2.

A special case of timing B is the production rate change or called often also as coordinated speed change. Then the requirement is to have no broke at all. The only changing variable is the machine speed, but at the same time the mass-flows

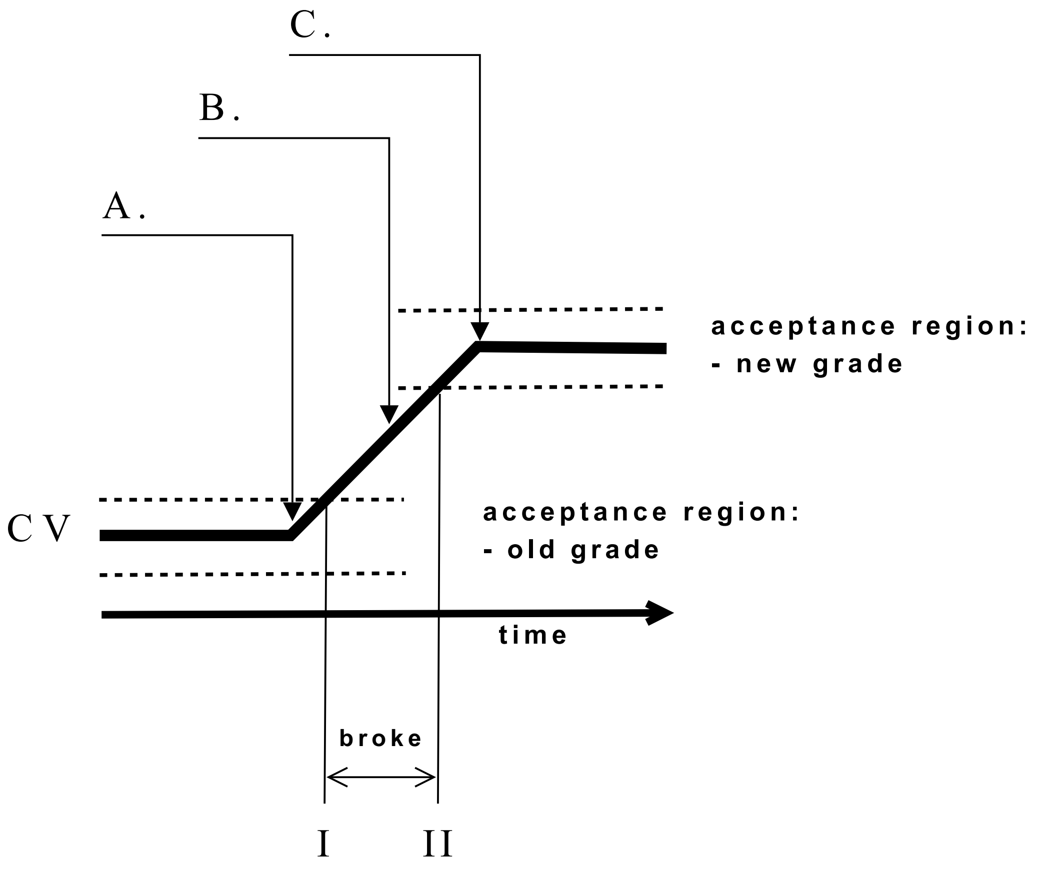

Figure 3.1: Timing principle.

should change accordingly even if the the final paper quality variables should stay constant during the change.

Normally the change rate is not critical but as well as the speed requirements are increasing for the normal grade change also faster production rate changes will be required too.

The point in future time when the reel change happens is normally known before starting the grade change. The time calculation is based on the measured length of the produced paper of the grade in question. With this information and time requirements of the grade change the change can be started at the correct time in advance relative to the reel change.

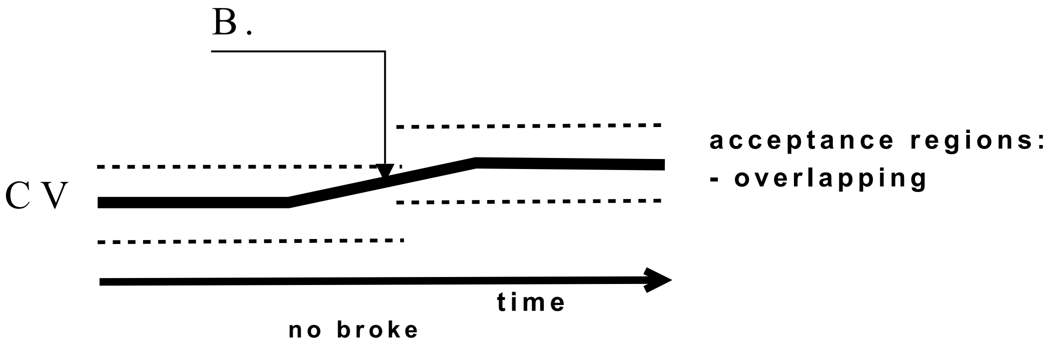

**Figure 3.2:** Overlapping case.

# Chapter 4

# Open-loop Grade Change

Open-loop grade change can work well when modelling of the process has been done properly. When the accurate model parameters are missing there is nothing in the control principle that could compensate this. The following sections illustrate the possible problems with simulation.

## 4.1 Simulation Principle

The following simple simulation illustrates the behaviour of the grade change only from the MV ramp timing point of view. The final paper quality variables used here are ash, moisture and basis-weight, but the process models used are for ash, moisture and dry basis-weight. The purpose of this simulation is to show problems that can appear when the traditional ramp-based non-feedback method is used. Machine speed change and white water consistency effects are mostly ignored. The process models are assumed to be perfect i.e. the final MV targets can be calculated precisely. The timing is done simply by taking into account the time delay and (first order) time constant of each MV to the chosen single main paper quality variable pair:

- thick stock flow → dry basis weight,
- filler flow → ash content and
- steam pressure → moisture.

Speed change is the basis for the MV timing. The synchronisation principle is illustrated in Figure 4.1.

The notation in Figure 4.1:

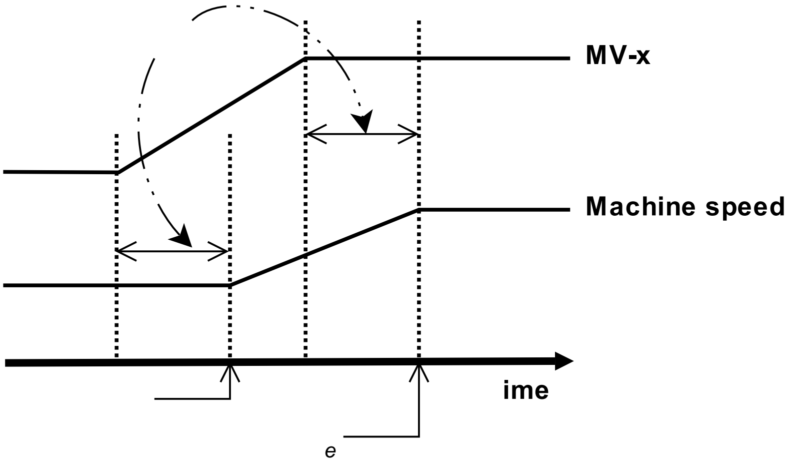

Figure 4.1: MV timing principle.

| | | |
|---|---|---|
| MV-x | Any of the MVs in use. | |
| $\tau_a$ | Total advance time, $\tau_a = \tau_d + \tau_1$, where: | |
| | $\tau_d$ | Process delay[1] in the transfer function from a MV to the related CV. |
| | $\tau_1$ | Time constant of the same first order transfer function. |
| $t_s$ | machine speed change ramp start time. | |
| $t_e$ | machine speed change ramp end time. | |

The motivation to this kind of principle comes from the fact that there has to be at least process time delay amount of advance time in starting the MV change to get any effect from a MV to the corresponding CV. In addition to that the change has to be started earlier than this to compensate the rising time of the process. Here the additional advance time has been selected as the first order transfer function time constant, which gives the typical 63% of the final amount of the total response.

Here are the simulation assumptions and simplifications collected together:

- thick stock consists of only fibres
- filler flow takes care of all of the ash in the paper
- the speed as such does not have any effect on drying
- the retention stays constant

---

[1] If the speed change is large enough it has to be taken to account in the value of $\tau_d$.

- the models (gains) are error-free
- the ratio of water from the press section to the drying section is proportional to the amount of fibres by a constant factor
- the steam pressure control is not limited by steam resources
- the whole drying section is reduced to a single point in the middle of the drying section where all evaporation takes place
- the ash content variation effect to paper drying has been ignored
- the water removal is only proportional to steam pressure (i.e the sheet temperature stays constant along the drying section)
- the mass-flow gains from thick stock and filler flow have a constant value one
- retention and retention-aid effects have been ignored

### About Air Speed

The water removal in the air by evaporation is based on both the temperature of the sheet surface and also on the air speed difference v.s. the sheet speed [Wil95]. When the grade change includes speed change it is possible that the speed change as such affects the final paper moisture also. If the speed increases the drying time decreases at the same time which in should increase the final moisture in principle. However the speed increase most probably increases the speed difference between the sheet and the average air speed thus increasing the evaporation and compensating that way the shorter drying time. Normally the circumstances inside the hood are not measured that well that it could be said what is the average air speed.

### Model - Thick Stock to Paper

The model consists of only a time delay and first order transfer function from thick stock valve to wire (the head-box included). There is no loss at the wire, press section or in the drying section. The flow controller is assumed to be ideal without any dynamics or non-linearities.

### Model - Filler to Paper

The model is similar to thick stock. It includes only a time delay and first order transfer function from filler valve to wire (the head-box included). There is no loss at the wire, press section or in drying section. The flow controller is assumed to be ideal without any dynamics or non-linearities.

### Model - Steam Pressure to Moisture

The steam pressure is ideal. There are no steam consumption related effects included. It includes only a time delay and first order transfer function from steam valve to the subtractive evaporation in the middle of the drying section. The water removal is based linearly only on the steam pressure. The removed water mass-flow is directly proportional to the steam pressure without any non-linearities.

## 4.2 Simulations

The open loop ramp-based grade change has been handled e.g. in [BNS+01]. Most of the articles concentrate on the target value calculation/prediction methods of the MVs involved in the GC. Timing issues have had less importance, mainly because the correct target value prediction is essential for the open-loop grade change. The article [MRC00] gives certain directions how to synchronise individual ramps in relation to each other.

In the following a simple simulation gives insight to the timing problem.

The simulation system was implemented with Simulink. The system structure and principle is depicted in Figure 4.2. The step size was fixed one second using the method ode5.

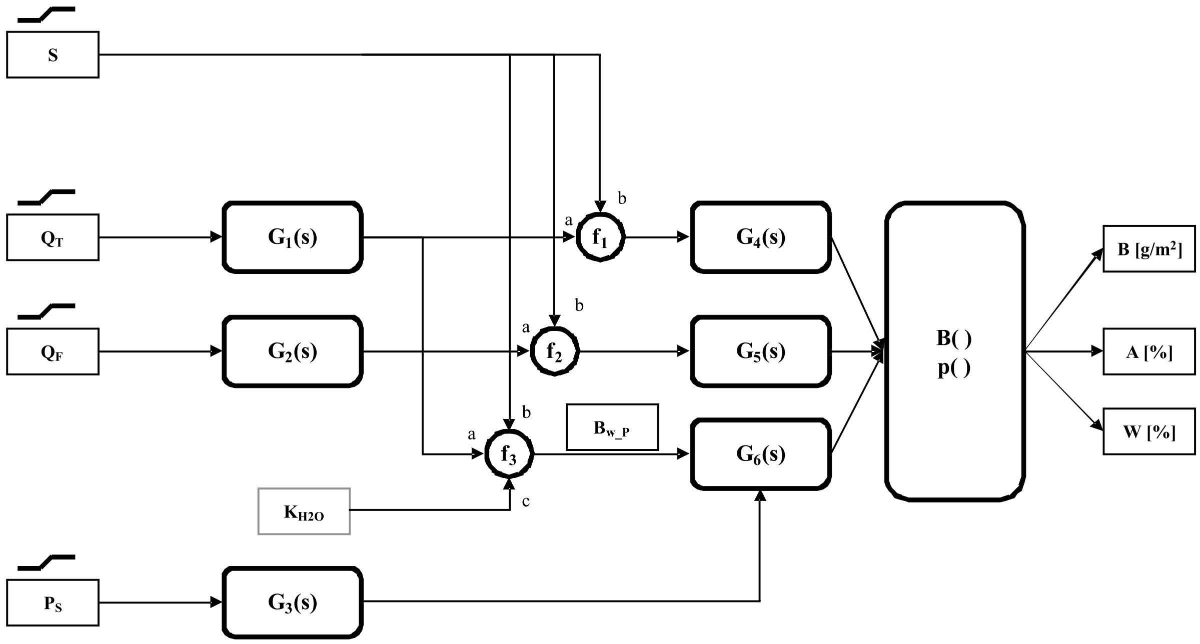

**Figure 4.2:** Simulation system principle.

The simulator itself consists of these main components:

- ramp generator for each MV, machine speed $S$ $[m/min]$, thick stock mass-flow (pure fibres) $Q_T$ $[kg/s]$, filler mass-flow (pure filler) $Q_F$ $[kg/s]$ and steam pressure $P_S$ $[kPa]$
- simple dynamics after each MV, $G_1 \dots G_3$ with the drying section delay as a separate block for thick stock and filler $G_4, G_5$
- simple drying section $G_6$ divided internally in two groups $G_{6a}$ and $G_{6b}$, where the evaporation point is concentrated in the middle of these two
- fibre and filler mass-flow transformation to corresponding basis weights, $f_1 \sim \frac{a}{b}$ and $f_2 \sim \frac{a}{b}$
- drying section feed-in water basis weight calculation proportional to fibre mass-flow at the output of $G_1$, $f_3 \sim \frac{a}{b} \cdot c$
- final quality measurement value calculations, $B(\,)$ for basis weight and $p(\,)$ for proportions of water $W$ and ash $A$ in typical units $[\%]$

It is further assumed that the steam pressure effect is water subtractive without any non-linearities and the water mass-flow feed-in $Q_W$ $[kg/s]$ to the drying section is directly proportional by the factor $K_{H2O}$ to the fibre content of the dry mass-flow on the wire.

Each dynamic MV sub-model $G_i, i = 1...3$ is a first order transfer function(4.1)

$$G_i(s) = \frac{k_i}{1 + s\tau_i} \cdot e^{-s\tau_{d\_i}} \tag{4.1}$$

Model gains in $G_1$ and $G_2$ have been given as a ratio between the change in the output mass-flow and input mass-flow $\frac{\Delta Q_{out}}{\Delta Q_{in}}, \frac{[kg/s]}{[kg/s]}$. Model gain in $G_3$ represents the subtractive effect from steam pressure change to the output water mass-flow $\frac{\Delta Q_{out}}{\Delta P_s}, \frac{[kg/s]}{[kPa]}$.

The blocks $G_4$ and $G_5$ represent the drying section delay for fibres and ash with the similar structure and delay parameter (4.2)

$$G(s) = e^{-s\tau_{d\_DE}} \tag{4.2}$$

The block $G_6$ internal structure consists of two similar delays and the evaporation point shown in Figure 4.3. Both sub-model transfer functions $G_{6a}$ and $G_{6b}$ have the same form (4.3)

$$G(s) = e^{-s\tau_{d\_DE/2}} \tag{4.3}$$

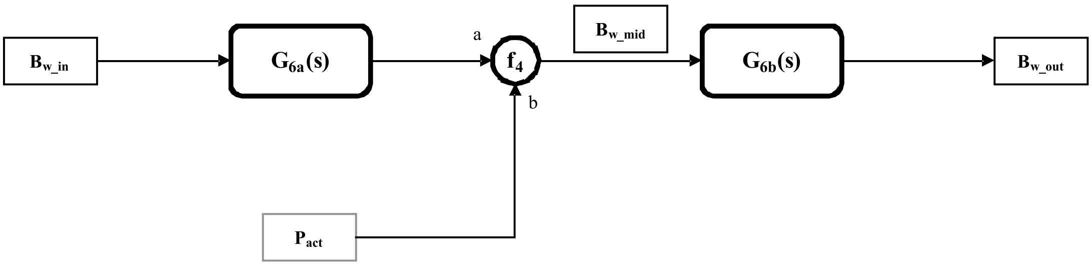

**Figure 4.3:** $G_6$ internal structure.

The evaporation function $f_4$ calculates first the internal water mass-flow before the active steam pressure $P_{act}$ effect as evaporation using the steam pressure water removal model gain $\frac{\Delta Q_w}{\Delta P_s}$. Then the result is transformed back to water basis weight for the input of the rest of the drying section delay $G_{6b}$.

The transfer function parameters in each case are given in Table 4.1. Roughly similar parameter values used here could be found e.g. in a typical LWC or fine paper machine process model.

**Table 4.1:** Transfer function parameters.

| Sub-process $i$: | $k$ | $\tau$ [s] | $\tau_d$[s] |
|---|---|---|---|
| $1 \sim Q_T$ | 1 | 50 | 40 |
| $2 \sim Q_F$ | 1 | 400 | 30 |
| $3 \sim P_S$ | 0.0485 | 120 | 10 |
| $4 \sim B_f$ | 1 | - | 40 |
| $5 \sim B_a$ | 1 | - | 40 |
| $6a, 6b \sim B_{w-in} \rightarrow B_{w-out}$ | | - | 20,20 |

The following simple idea has been used when calculating the internal evaporation in $G_6$ :

- the steam pressure at the starting point removes all of the water evaporated in the drying section
- the dependency from $\Delta P_s$ to $\Delta Q_w$ is linear

The starting point :

| Variable: | Speed | Web width | Basis weight | Moisture | Ash |
|---|---|---|---|---|---|
| Value: | 1400 m/min | 9 m | 60 g/$m^2$ | 3 % | 20 % |

### 4.2.1 Standard Case

By using these restricting assumptions and simplifications it can be seen from the simulations that it should be a straightforward task to find out suitable ramp parameters for GC. The basic timing for the ramps is based on these simple models and drying section delay. The start time relative to the start of speed ramp of each MV ramp is calculated in (4.4). For the paper moisture the drying section delay is only half of the real transportation delay using the idea that when the connection point of the steam in the drying is in the middle of the section the delay is also only half of the total delay.

$$t_{start\_i} = \tau_{d\_i} + \frac{\tau_i}{2} + \tau_{d\_DE} \tag{4.4}$$

The result with basic parameter values can be seen in Figure 4.4. The solid curves are the measured values and the dotted curves are the set-points. The target value changes here are basis weight = +10 g/m$^2$ and speed = -50 m/min.

The basis weight behaves quite acceptably and paper ash percentage almost as well according to the numerical values. Moisture has the typical spike in it. The numerical values could be acceptable except for moisture but the curves show the possible disturbance forms observed in practise when the models are not perfect anymore.

It can be seen from Figure 4.4 that even in the case of perfect models this method can lead to a result that some of the quality variables don't stay inside the acceptance region. For the basis weight this method works well (see [Kos04]) but loops where the process includes more non-linearities or unreliable parameters in the process model the performance can be poor. Certain modifications to the basic set-up exist, e.g:

- more sophisticated modelling (PLS) for static process gains and target calculation [Vii04] with shaping the basic set-up with a certain amount of overshoot in the MV ramps (no method defined for the mentioned overshoot though)
- better drying section handling with an additional compensator based on simplified drying section simulation [MST00, SKiTM02]
- jet speed lag compensation in the pressure control of the head-box [MC99]

One thing that can not be handled properly in practise in any of these modifications as such is the change in water proportion in the beginning of the drying section caused by different type of stock composition. Water removal in the wire and press sections changes according to the composition thus disturbing the final result paper moisture. This kind of change can be a result of the requirements of the paper grade but also more likely an unwanted disturbance as a result of changing the broke ratio at the stock blending.

When the resulting paper includes a lot of filler the parallel management of both filler and retention aid is complicated because of strong interactions.

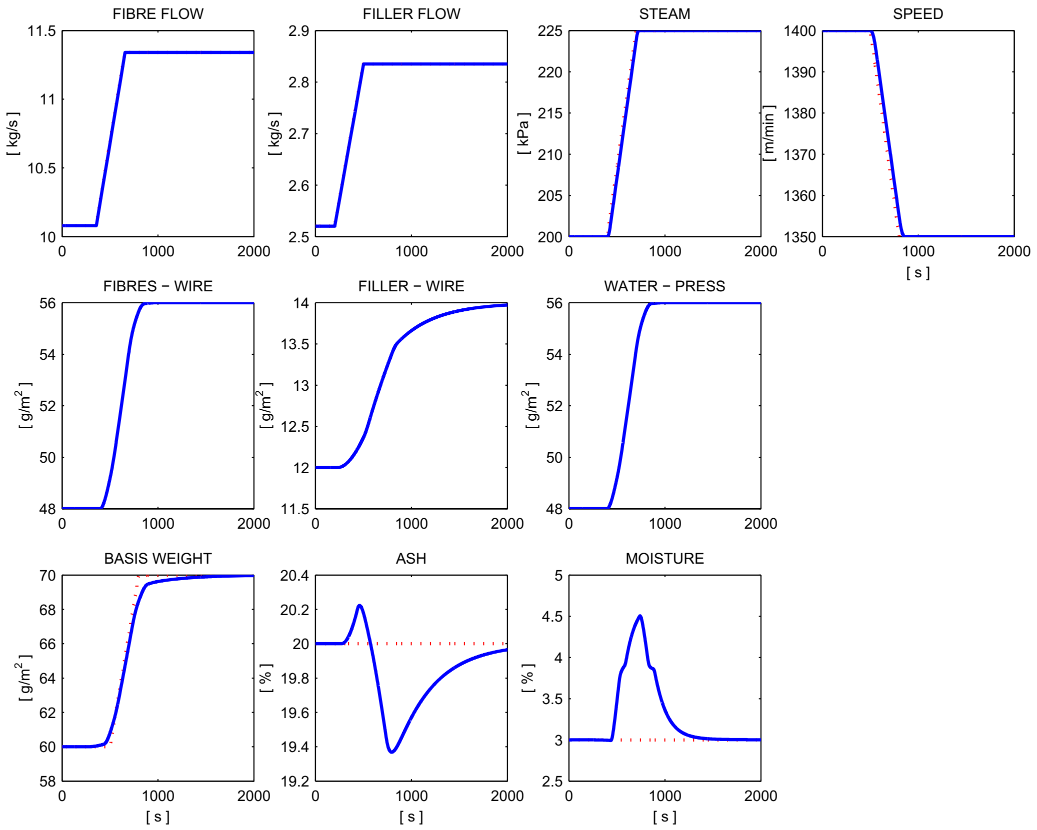

**Figure 4.4:** Basic ramp timing.

### 4.2.2 Varying Steam Pressure Timing

When the steam pressure timing is changed the moisture disturbance portion can be decreased as seen in Figure 4.5. The following timing parameters, which tell the shifting of the steam ramp v.s. the speed ramp, were used:

| | |
|---|---|
| Case 1 | Both ramp start time and ramp end time shifted earlier the amount $\tau_d + \frac{\tau}{2} + \frac{\tau_{d\_DE}}{2}$ |
| Case 2 | Both ramp start time and ramp end time shifted earlier by the amount of $1.5 \cdot \left(\tau_d + \frac{\tau}{2} + \frac{\tau_{d\_DE}}{2}\right)$ |
| Case 3 | Ramp start time shifted earlier the amount $1.5 \cdot \left(\tau_d + \frac{\tau}{2} + \frac{\tau_{d\_DE}}{2}\right)$ but ramp end time shifted earlier more by the amount of $2 \cdot \left(\tau_d + \frac{\tau}{2} + \frac{\tau_{d\_DE}}{2}\right)$ |

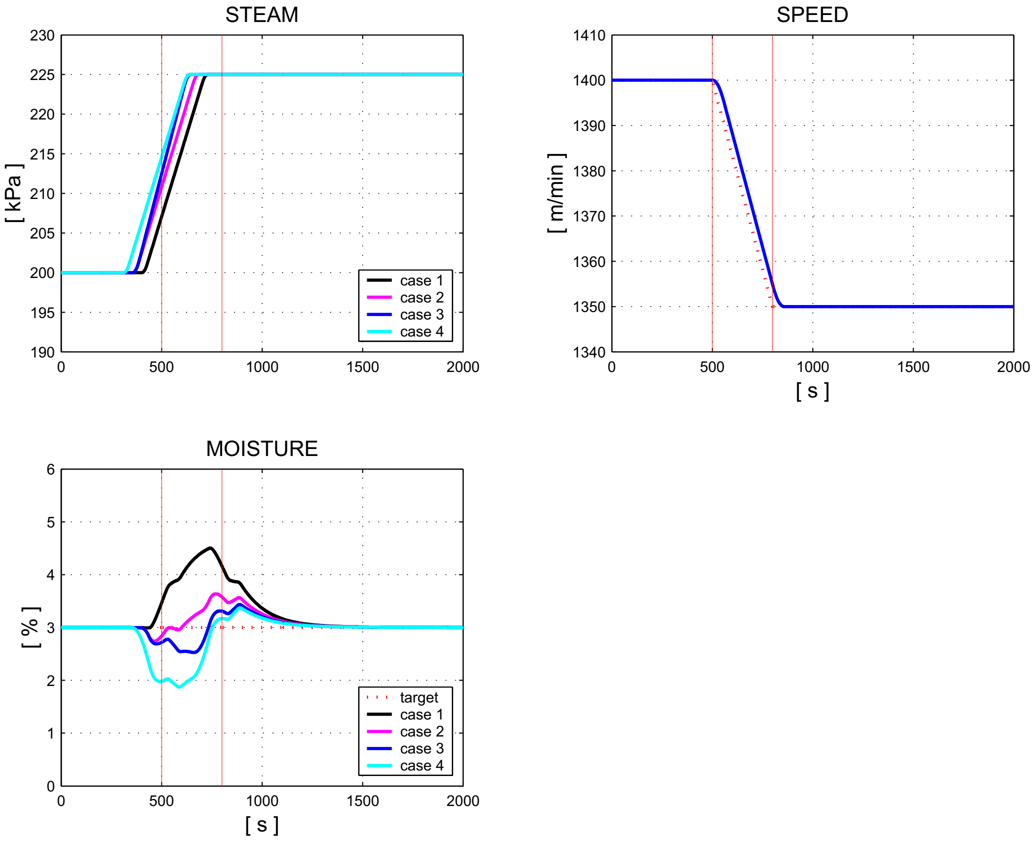

**Figure 4.5:** Steam pressure with different ramp timings.

Case 4 Both ramp start time and ramp end time were shifted earlier by the same amount of $2 \cdot \left(\tau_d + \frac{\tau}{2} + \frac{\tau_{d\_DE}}{2}\right)$

The example shows that it is possible either remove the disturbance or get poor performance. The selected time shifting values were such that the start-up engineer could select in practise as a starting point for the ramp timing trials. In a real case the dynamics of the thick stock flow would probably be also considered in the timing calculations.

### 4.2.3 Model Gain Errors

The comparison in Figure 4.6 has been done using timing of *Case 2* for steam pressure and the basic timing for the others but with gain errors. The simulation depicts a case where the actual MV changes during GC from correct ones are fibre flow 90%, filler flow 60% and steam pressure 80%.

The gains selected are such that if a bump test for modelling purpose is repeated at the machine the result gain variation between individual tests can be of the order above. The gain errors can be even bigger than these in practise especially in filler and steam pressure responses. It's natural under these circumstances that the final measured values for dry basis weight and ash stay below the target and moisture stays above. It depends on timing of the activation of the closed-loop quality control and the tuning of the controllers how fast the final targets would be reached in this kind of case.

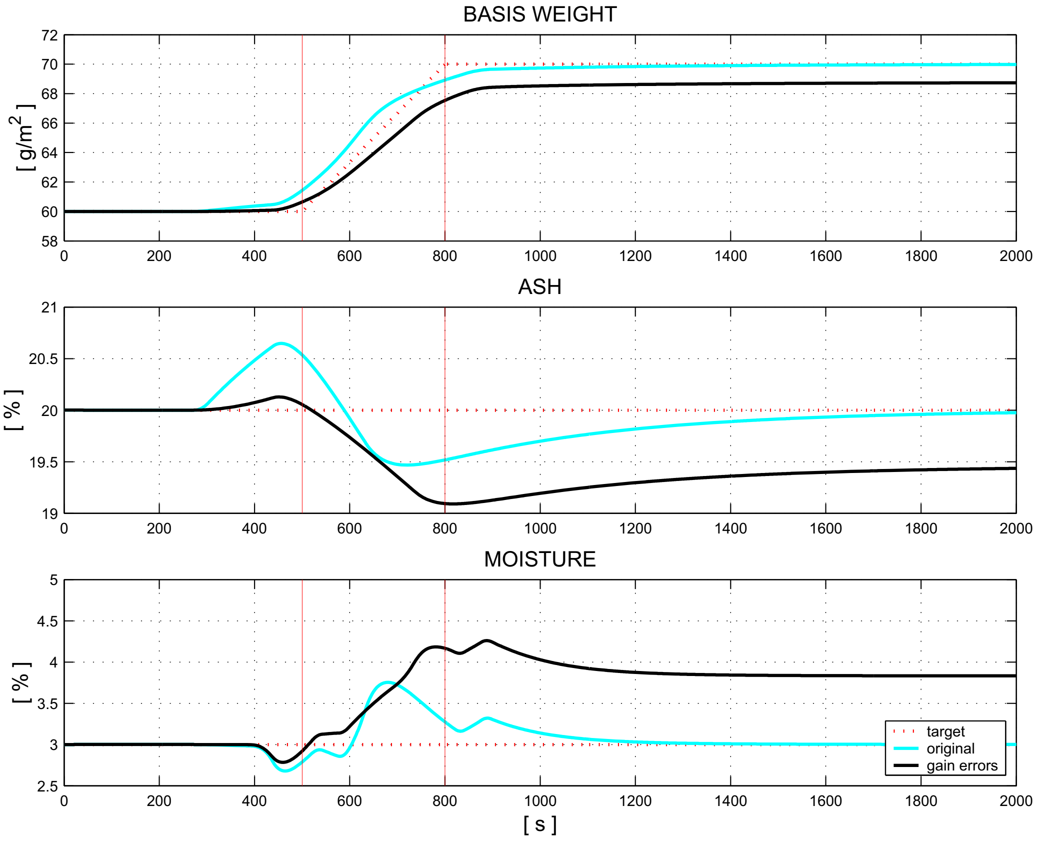

**Figure 4.6:** Ramps with gain errors.

# Chapter 5

# Change Simulations

The simulation in a realistic simulator environment can produce such information of the process behaviour that is not possible to get in practise either because it is difficult to arrange the required testing conditions or normal production does not allow any extra deviation from the production schedule or quality requirements. Typically almost any kind of process test disturbs the normal operation of the paper machine to some extent.

Simulation is used here to get internal information of the drying section behaviour to be used in the disturbance compensation (Chapters 7 and 8). Another usage of simulation is to find out if it is possible to avoid some of the head-box flow change generated disturbance (Chapter 8) by a suitable timing of slice opening change.

The simulation environment is described shortly and some details of internal simulation principles are pointed out. The simulation cases follow and there is a comment section in each simulation case.

## 5.1 Simulation Environment

The background of the simulation environment in the following tests is basically the same that was used in control simulations in [Kos04, LKK00, KFN$^+$02]. The basic simulation structure is APMS paper machine simulation package in APROS platform [NLL$^+$98] connected to metsoDNA DCS through OPC. The control software was a modified IQWetendMD paper machine control package for paper machine quality control. During the open-loop tests presented here the quality controls were not active but standard features of the control package were used to implement the test ramps in machine speed or head-box slice opening. The standard application interface was also useful for data-collection during these open-loop tests. The result data was collected with the internal data collection facilities in metsoDNA.

The latest development steps in the simulation platform have made it possible the simulation in the cases needed in this thesis:

1. A newer APMS-version with more accurate handling of plug flow portion of the consistency behaviour in a pipe.
2. More typical configuration of the J/W control in the new version of simulation model (see the explanation in Section 5.2.4).
3. Additional application for simulations of constant water and dry mass-flows after press-section.

The first two features are essential for realistic simulation of the situations, where the effects of head-box flow changes have to be seen qualitatively correct in time. The last feature is needed to simulate the pure speed effect in drying section during constant input water and dry mass-flow.

The APMS principles, mathematics and physics are discussed in [Lap03].

### Drying Section Model

The paper machine simulation model structure at the short circulation has been described more detailed in [Kos04] but it is worthwhile to describe the drying section structure here because most of the simulation results concentrate on the drying section. The first drying groups 1...7 are standard groups where the set-point of each steam pressure controller is based on the main steam pressure set-point by a group-specific factor. The group 7 acts as a main group whose set-point is the highest and the set-point values are decreasing towards the press section. Groups 8 and 9 have only a certain pressure to keep the cylinders warm but their effect on the total evaporation is minimal. There is also a free draw between groups 7 and 8. Another free draw is located after the ninth group before the scanner.

The drying section model was “perfect” in a sense that the simulator includes simulation of steam flow and energy, the energy transfer from steam to the cylinders and from there to the paper web. The final energy and water transfer takes place from the web surface as evaporation. On the other hand the hood conditions were kept constant (humidity and temperature) which can differ from the real process during transients. The simulation of the condensate flows out of the drying cylinders is based on physical models. The steam source in these simulations was rigid pressure source without maximum steam flow limitation, but all the valves induce pressure loss as a function of steam flow and pressure.

### Controllers in the Simulation Model

It is possible to utilise also standard PID controllers in the APMS-platform. Because of possible data-transfer delays all the low-level control loops are simulated in the simulator instead of the connected DCS. Also because one purpose of using APMS-platform was to get as realistic responses as possible compared to a real paper-machine the simulator includes all the standard controllers for steam pressures, pressure differences and condensate tank levels. All the standard controllers needed in the short circulation are in use also. The only external control actions in these simulations were the speed set-point, slice-opening set-point and the head-box pressure set-point.

### Configuration of the Simulation Cases

The simulation cases in this chapter are divided in two classes:

1. Pure drying section response.
2. The whole response from short circulation to the end of the drying section.

In pure drying section response cases the effective starting point in simulations was the beginning of the drying section. Either constant mass-flows including both dry matter and water or mass-flow changes were implemented by forcing the press-section output to follow the required mass-flow by nip-pressure control. In these cases all the other variable values from the short circulation except the stock temperature can be neglected. The simulation cases in sections 5.2.1 and 5.2.2 belong in this class.

When the whole response is considered the short circulation is included in simulations. The filler flow controller had a small constant set-point, the thick stock flow controller set-point was also kept constant but using a suitable value to achieve the required basis-weight at the machine speed in test in question. The retention aid controller on the other hand has a high set-point to keep the retention value also high. The simulation cases in sections 5.2.3, 5.2.4 and 5.2.5 belong in the whole response class.

## 5.1.1 Remarks about APMS Simulation Principles

### Web Moisture after Press Section

The press model in APMS is described in [Lap03], from where equations (21) and (22) are translated and duplicated here to see how the press behaves as a function of machine speed.

The web moisture equation [Lap03]/(21):

$$\frac{z}{z_0} = \left(1 + \frac{k_{FLT} A_s n z_0^n I}{\nu W^2}\right)^{-1/n} \tag{5.1}$$

where:

| | |
|---|---|
| $z$ | web moisture ratio after nip $[kgH_2O/kgD.C.]$ |
| $z_0$ | web moisture ratio before nip $[kgH_2O/kgD.C.]$ |
| $I$ | press impulse [(kN/m)/(m/s)] |
| $n$ | compressibility factor [1] |
| $A_s$ | specific permeability [g/m] |
| $W$ | dry basis weight [kg/m$^2$] |
| $\nu$ | kinematic viscosity of water [m$^2$/s] |
| $k_{FLT}$ | a factor depending on the number of water removal felts in the press nip [1] |

The value of $k_{FLT}$ is one for one felt case and four in the case of two felts.

The press impulse is calculated as [Lap03]/(22):

$$I = \frac{p_{LL}}{u} \tag{5.2}$$

where:

| | |
|---|---|
| $p_{LL}$ | press line pressure [kN/m] |
| $u$ | machine speed [m/s] |

When combining all of the constant factors together in $k_{CMB}$ the press can be expressed in the form:

$$z = z_0 \cdot \left(1 + k_{CMB} \cdot \frac{z_0^n \cdot p_{LL}}{W^2 \cdot u}\right)^{-1/n} \tag{5.3}$$

As can be seen in the model form that there is no distinction between separate dry stock components e.g. filler and different kind of fibre. The present measurement technology allows moisture measurement almost immediately after press section, which could make it easier to parametrise the model by estimating the combination factor $k_{CMB}$. The moisture ratio before nip can not be measured yet which is still a problem for this estimation.

### Evaporation Speed Dependency

As described in e.g. [Lap03, Kar84] the evaporation rate from paper to air depends on speed by the coefficient

$$\alpha_F = 5.3 \cdot s^{0.46} \tag{5.4}$$

where:

$s$ = machine speed $[m/s]$ and

$\alpha_F$ = convective heat transfer coefficient from paper to air $[W/m^2/°C]$.

The author mentions that the equation is valid for certain type of dryers and should be verified for practical machines. The coefficient (5.4) affects the amount of evaporating water e.g. in the following way ([Lap03]/(Eq. 28):

$$\frac{\dot{m}_{ev}}{A} = \alpha_F C \ln \frac{p_{tot} - p_{va}}{p_{tot} - p_v} \tag{5.5}$$

where:

$\dot{m}_{ev}$ = mass-flow of the evaporated water [kg/s]

$A$ = area of the paper from where the evaporation takes place $[m^2]$

$C$ = coefficient; $7.04 \cdot 10^{-4}$ $[kgH_2O\,°C/W/s]$

$p_{tot}$ = air pressure in the hood $[Pa]$

$p_{va}$ = partial pressure of the steam in the air $[Pa]$

$p_v$ = partial pressure of the steam on the evaporating surface $[Pa]$

From practical point of view concerning process modelling the equations above (5.4) and (5.5) do not tell directly the resulting speed impact. It would be useful to know which one is stronger, speed impact on drying time or impact on evaporation because of different air to paper speed difference.

In addition to the previous dependencies the evaporation depends also on stock composition. As mentioned in [Lap03] there are certain features in the stock that has been observed in practise that help the drying; big proportion of chemical pulp, high filler content, usage of fibres that have been dried already once in a cellulose drying machine. Also the refining energy used in the stock affects drying.

According to the author systematic information about different stock behaviour is missing. Also it is unclear if the mixtures of different stock behave like a weighted sum of the components or can there exist some non-linear effects in the behaviour. The stock composition dependency is included in Equation (5.5) with the so called sorption isotherms [Lap03, Hei93]

$$p_v = \varphi \cdot p_0 \tag{5.6}$$

$$\varphi = 1 - \exp\left(-\left(C_1 \cdot z^{C_2} + C_3 \cdot T_p \cdot z^{C_4}\right)\right) \tag{5.7}$$

where

$p_0$ = partial pressure of the steam on the paper surface $[Pa]$

$T_p$ = paper temperature $[^\circ C]$

$z$ = web moisture ratio $[kgH_2O/kgD.C.]$

$C_1, C_2, C_3, C_4$ = paper composition dependent coefficients.

A set of numerical values for coefficients $C_1 \ldots C_4$ are given in [Hei93], but using a general term “wood material”. The estimation of the coefficients is not discussed there.

## 5.2 Simulation Cases

The purpose of pure drying section response simulation cases is to study the basic behaviour of the drying section. It is possible to gather separate information of the pure drying section responses and possibly use that for constructing more accurate drying section models for control purposes. Until lately the measurement technology has not been available to find out the separate drying section part of the responses, i.e. the real water mass-flow into the drying section has not been measurable on-line. Also if the actual speed response in the total evaporation is needed for accurate moisture control the paper-machine drive system might limit in practise the possible machine-speed step rising time. The simulation cases presented in sections 5.2.1 and 5.2.2 belong in this class.

The rest of cases are closely related to grade changes. The cases include also short-circulation and press-section. These cases could explain what happens during some typical changes when the whole machine is included but without closed-loop quality control. The simulations are supposed to help to get information for disturbance compensation construction and possible ways of making changes in a way that causes disturbances as small as possible.

## 5.2.1 Water Mass-flow Change

Water mass-flow into the drying section changes as a consequence of either water feed change to the press-section or change in press-section conditions. As mentioned in [Lap03] the press model includes dry basis-weight as one of the affecting variables in press, which results in a change in water mass-flow in the input of drying section when the dry basis-weight changes at the wire. The wire section dry basis-weight can change because of the changes in the head-box area (handled in the following sections) or normal flow changes like thick stock, filler or retention aid flow. One source of change at this point is also the change in furnish composition. Does it change the press behaviour and that way the water mass-flow input to drying section or does it change the drying properties of the web in the drying section? This effect has been observed in practise but it seems that this has not been studied in the literature. The presented simulation does not include the evaporation dependency on the furnish composition.

### Simulation

In principle it is possible to change the water mass-flow into the drying section in a real machine e.g. by changing the nip line-pressure but naturally this would cause a disturbance in the moisture at the reel. One problem is to predict how big this possible moisture change would be if such a test would have been done. Most of the mass-flow and drying group temperature measurements are not available in any production machine except the on-line measurement of post-press moisture in a few machines.

The interesting item in this test is the dynamic response of pure water mass-flow change. Is it similar to the water-mass-flow change caused by some other reason which also changes the water mass-flow? Drying does not depend only on pure input water mass-flow but also on the dry-basis weight of the web. Which one is dominating, the water mass-flow change as such or dry basis-weight?

The following simulation is a step response test in which the water mass-flow into the drying section has been changed as a step. The dry mass-flow was forced to stay constant during simulation. Both of these mass-flows were controlled using the method described in Section 5.1. The drying section steam pressure controllers had constant set-points. The short circulation is insignificant in this test.

Figure 5.1 shows the responses of basic values. Water mass-flow progress along the drying section is shown in figures 5.2 and 5.3.

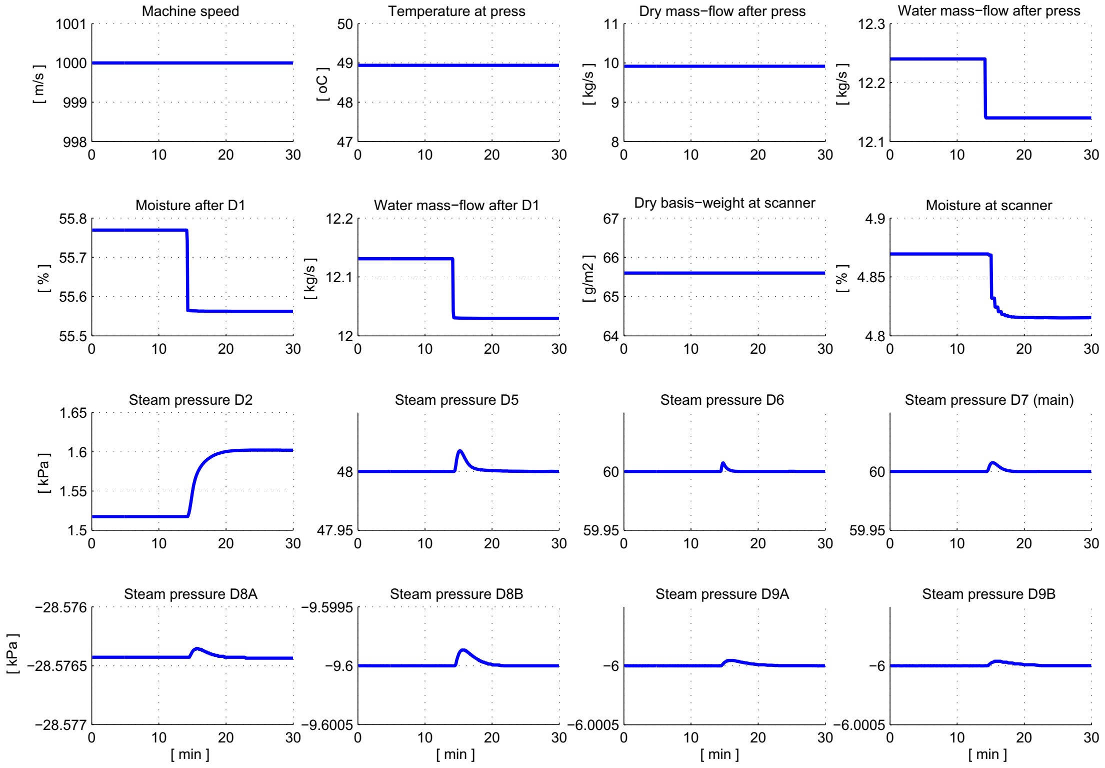

**Figure 5.1:** Water mass-flow change - basic values.

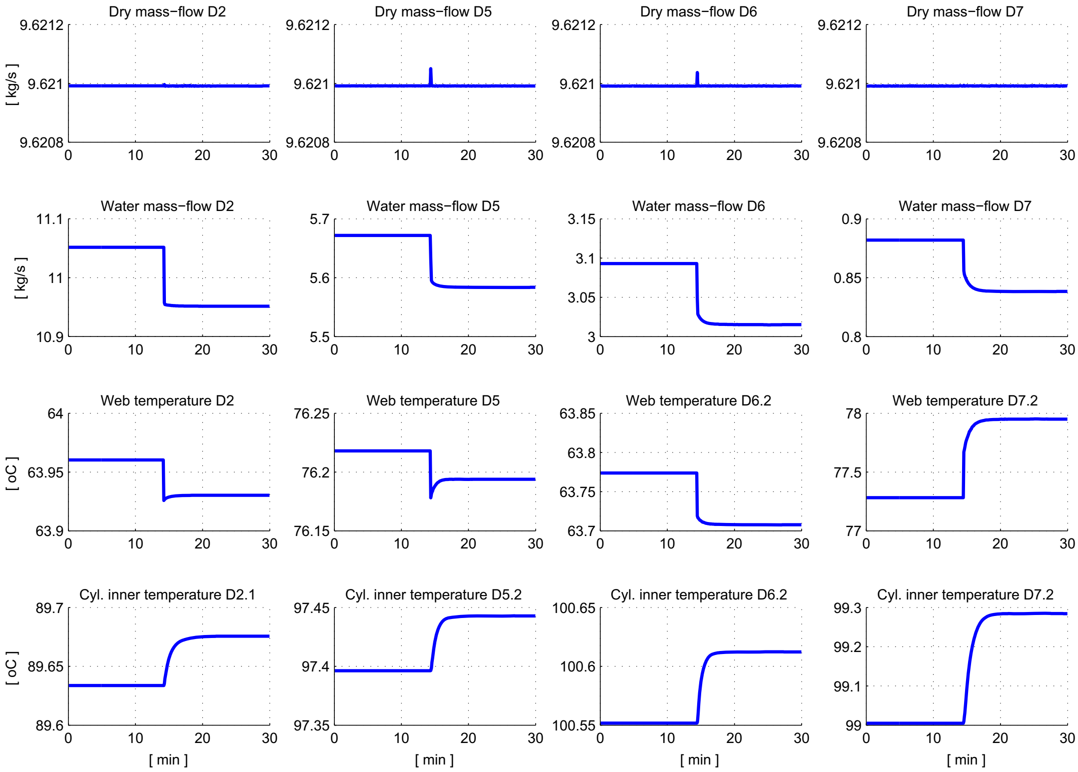

**Figure 5.2:** Water mass-flow change - mass flows and temperatures 1.

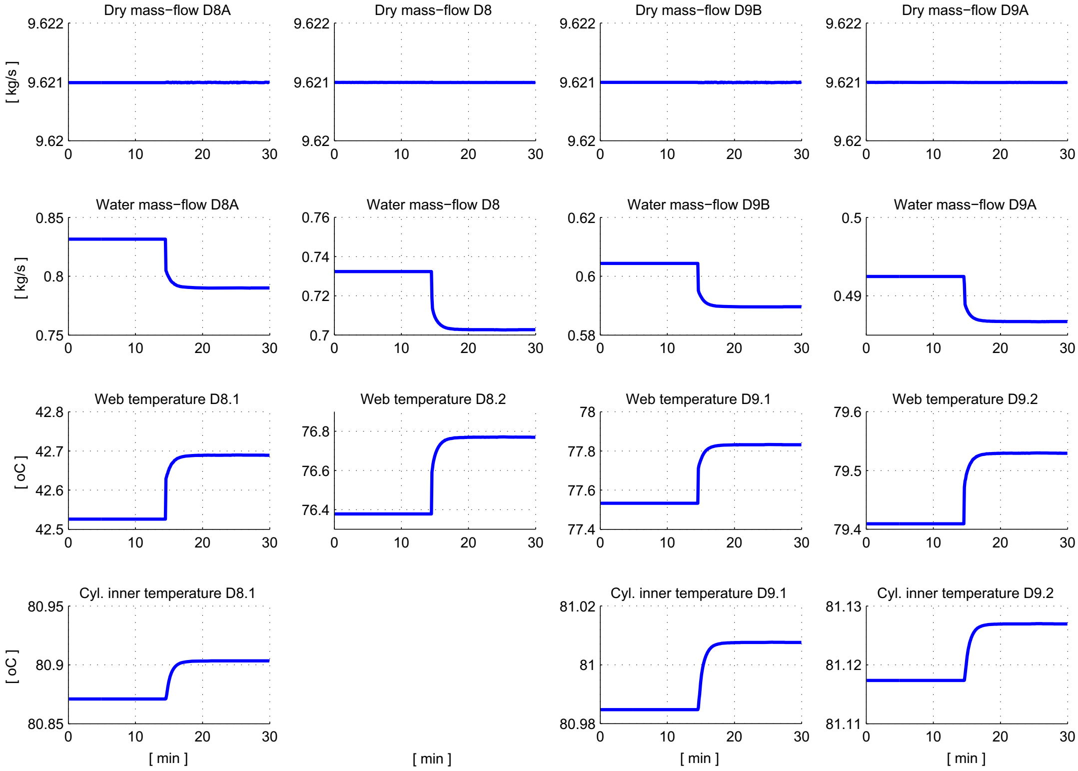

**Figure 5.3:** Water mass-flow change - final mass-flows and temperatures 2.

**Comments**

There is a quite radical change in the water mass-flow between the drying group 6 and 7, roughly from the level 3.1 kg/s to 0.9 kg/s. Also the change in the web temperature turns to the opposite direction compared to the earlier groups. The reason is the main evaporation that takes place in this drying model in the drying group 7.

As expected the response has similarities to steam pressure step change. It can be assumed that the dynamics is somewhat similar to the steam pressure change dynamics because in both cases the actual dynamic phenomenon is the heat-transfer balance. The difference that should be seen is that the step in mass-flow starts from the beginning of the drying section continuing to the end of that. The steam-pressure change rather takes place all over the drying section at the same time. In this way a certain amount of extra delay should be a seen in the water mass-flow change responses.

The water mass-flow change after D2 is from 11.05 kg/s to 10.95 kg/s which results to -0.1 kg/s and after group D8 from 0.73 kg/s to 0.7 kg/s which results to -0.03 kg/s. The ratio between the change in the input water mass-flow of the drying section and the output water mass-flow is roughly 3. The same ratio is calculated also in Section 5.2.4 for a different kind of change where there was also a temporary dry basis-weight change present.

Dry mass-flow values are presented only because standard trend lay-out used. They do not contain any additional information in this test.

### 5.2.2 Speed Change in The Drying Section

During a grade change one commanding variable is the machine speed. When both dry and water mass-flows fed into the drying section are kept constant and then the machine speed is varied at the same time show the pure speed induced effect on drying. This is supposed show the result of acceleration in actually a distributed delay and distribution[1] line but also the change in the interaction between the air and moving web in the evaporation.

It is almost impossible to change the machine speed but keep both the water mass-flow and the dry mass-flow constant at the same time on a practical machine. The only possibility is to make trials with a simulator. Two most interesting phenomena are the acceleration induced effect on water mass-flow and the water mass-flow level change because of speed-affected change in the evaporation. The simplest idea of handling the water mass-flow acceleration effect is to use the similar way of thinking as for dry mass-flow later in Chapter 7.

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[1] Evaporation is distributed in principal along the whole drying section.

### Simulation

This simulation is ramp test in which the machine-speed was changed as a ramp. The dry mass-flow was forced to stay constant during simulation. The water mass-flow from the press-section was also kept constant (12.14 kg/s). Both of these mass-flows were controlled using the method described in Section 5.1. The drying section steam pressure controllers had constant set-points. The short circulation is insignificant also in this test.

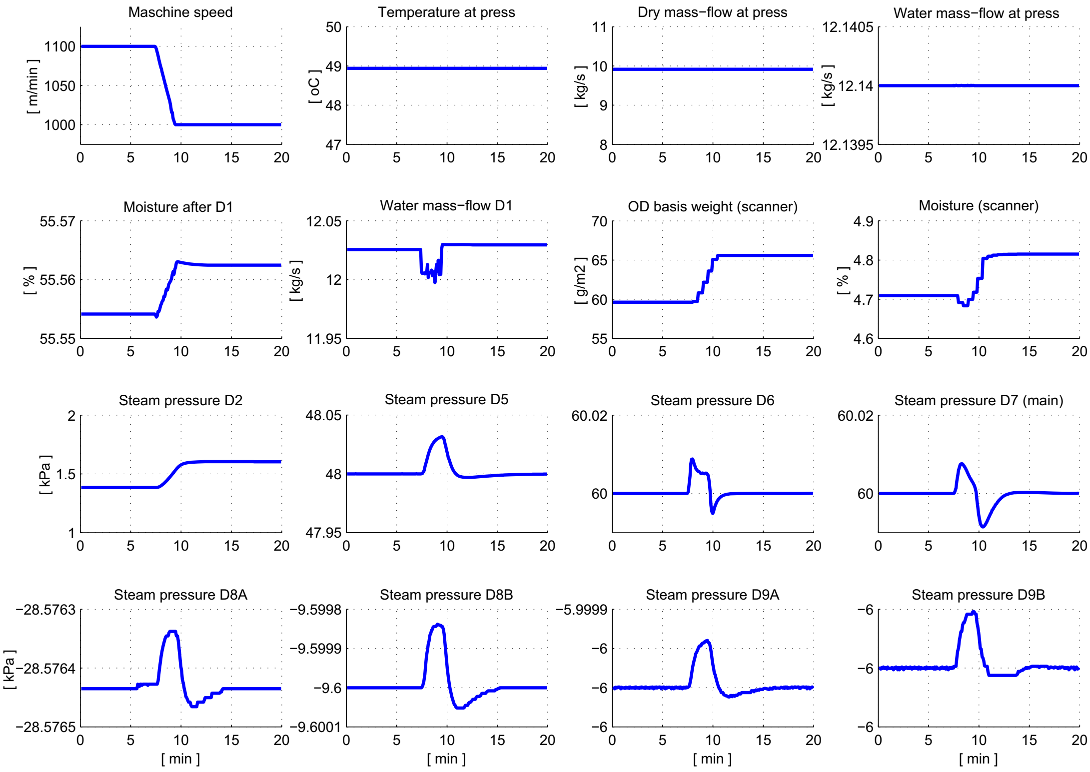

**Figure 5.4:** Speed change - basic values.

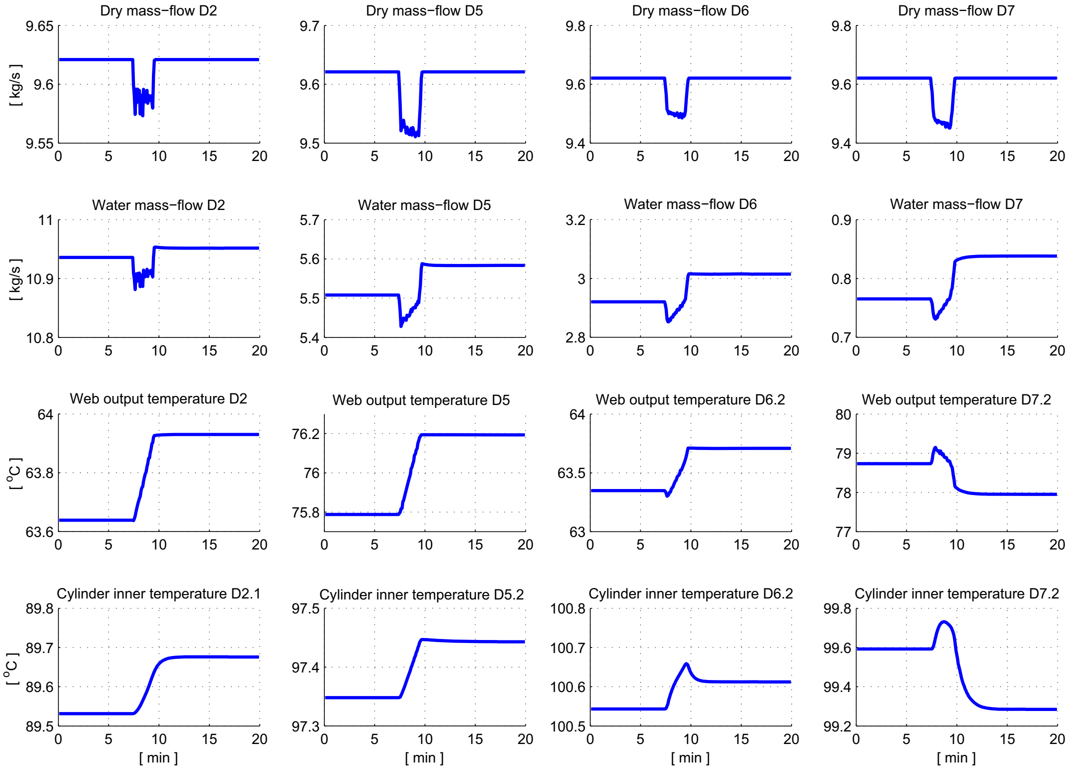

**Figure 5.5:** Speed change - mass flows and temperatures 1.

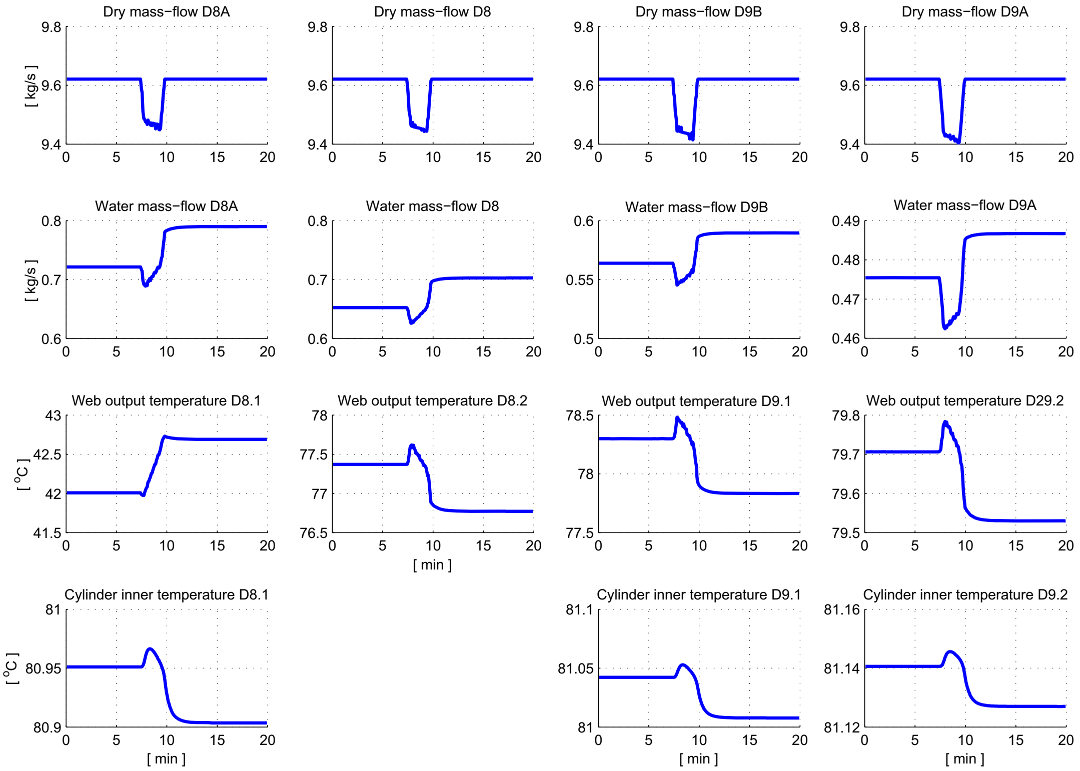

**Figure 5.6:** Speed change - final mass-flows and temperatures 2.

### Comments

Figure 5.4 shows a 100 m/min change with the acceleration rate 50 m/min$^2$. The dry mass-flow acceleration effect can be seen clearly in figures 5.5 and 5.6. The water mass-flow progress along the drying section can be seen in figures 5.5 and 5.6. As can be expected the water mass-flow in section 1 changes only very little. Only a small acceleration effect can be seen in water mass flow both in the beginning and the end of the speed ramp. The speed level change generates evaporation level change and acceleration change can also be seen nicely in later sections as well as the steam system and drying mass thermal capacity dynamics generated smoothing in the response by comparing the water mass-flow e.g. after drying group 5 and group 8. The level change could be inversely relative to the speed change because of the changing drying time in the drying section. However the simulation shows that this is not exactly true. The explanation is the constant steam pressure, which actually means constant drying cylinder inner temperatures. This will lead to a new operating point where the constant pressure compensates the moisture change a certain amount.

As in the dry mass-flow it is possible to distinguish first in the water mass-flow the area where the main effect comes from the pure acceleration. The next phase shows the change in the evaporation rate because of speed level change. The final heat-transfer stabilisation to a new operating point happens in the third phase. It can be seen that in a typical paper machine (with a short drying section delay ~40 s) the acceleration effect for water mass-flow is comparable to the dry mass-flow effect. By calculating the water mass-flow ratio and dry mass-flow ratio we get the (rough) numerical values after group 7 and 9A given in Table 5.1 (Note: In the table DMF = Dry Mass-Flow and WMF = Water Mass-Flow). Numerically strength of the effect could be maximum 4.5 % of the water mass-flow after group 7 giving 0.15 % absolute moisture short term error at 3 % absolute moisture level. But as can be seen the final acceleration effect is still stronger in water mass-flow than in dry mass-flow and it could be speculated if it is actually possible to distinguish accurately the pure acceleration area at all. E.g. the web temperature starts to increase also at the same time as the expected acceleration effect starts which tells that the acceleration can not be seen separately at all in the water mass-flow.

**Table 5.1:** Comparison of water and dry mass-flow ratios by acceleration.

| Group | DMF-a) | DMF-b) | WMF -a) | WMF-b) | Dry ratio | Water ratio |
|---|---|---|---|---|---|---|
| 7 | 9.62 | 9.47 | 0.765 | 0.732 | 1.016 | 1.045 |
| 9A | 9.62 | 9.43 | 0.4755 | 0.462 | 1.02 | 1.029 |

### 5.2.3 Speed Change in the Whole Machine

This simulation resembles typical effects during a speed change when the slice opening is kept constant, but speed is changing. The difference compared to a normal speed change is that the thick stock flow has been kept constant, which affects the dry basis-weight. The simulation will show the effect of head-box flow change without the change in thick stock flow thus showing the basic head-box flow change generated disturbances both in dry and water mass-flows.

#### Simulation

This simulation is ramp test in which the machine-speed was changed as a ramp. The whole short circulation is included. The normal operation of press section is included giving the possible non-linearity from there.

Figure 5.7 shows the characteristics of speed change.

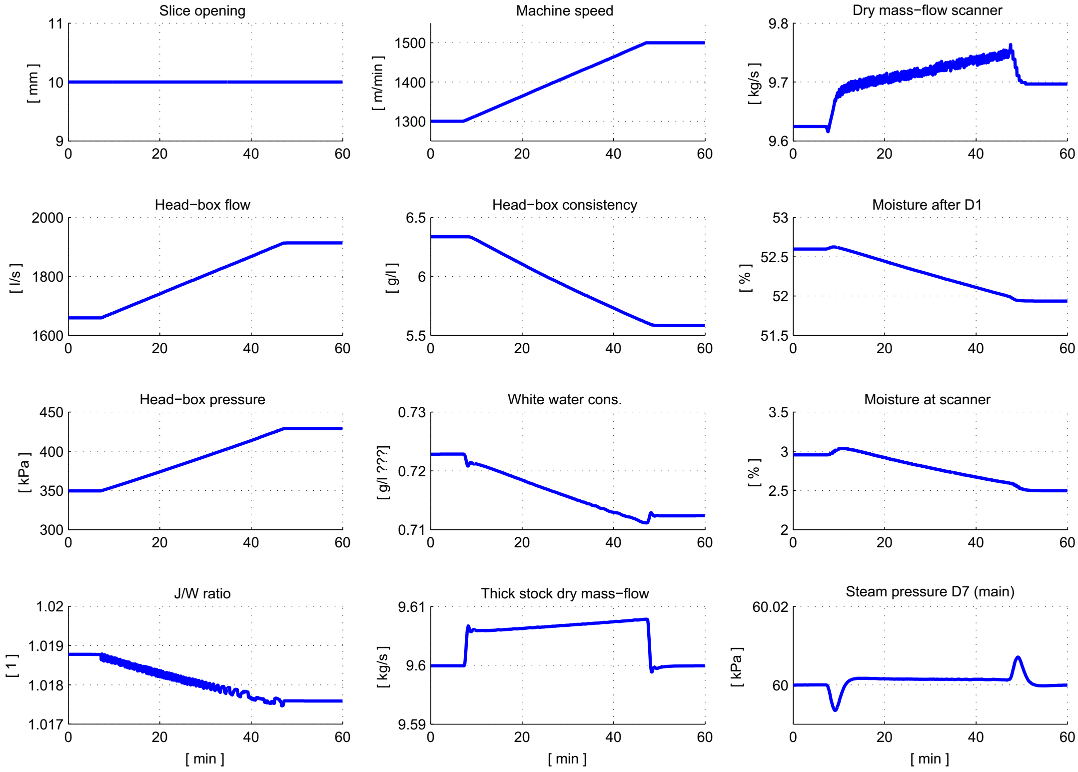

**Figure 5.7:** Speed change - basic values.

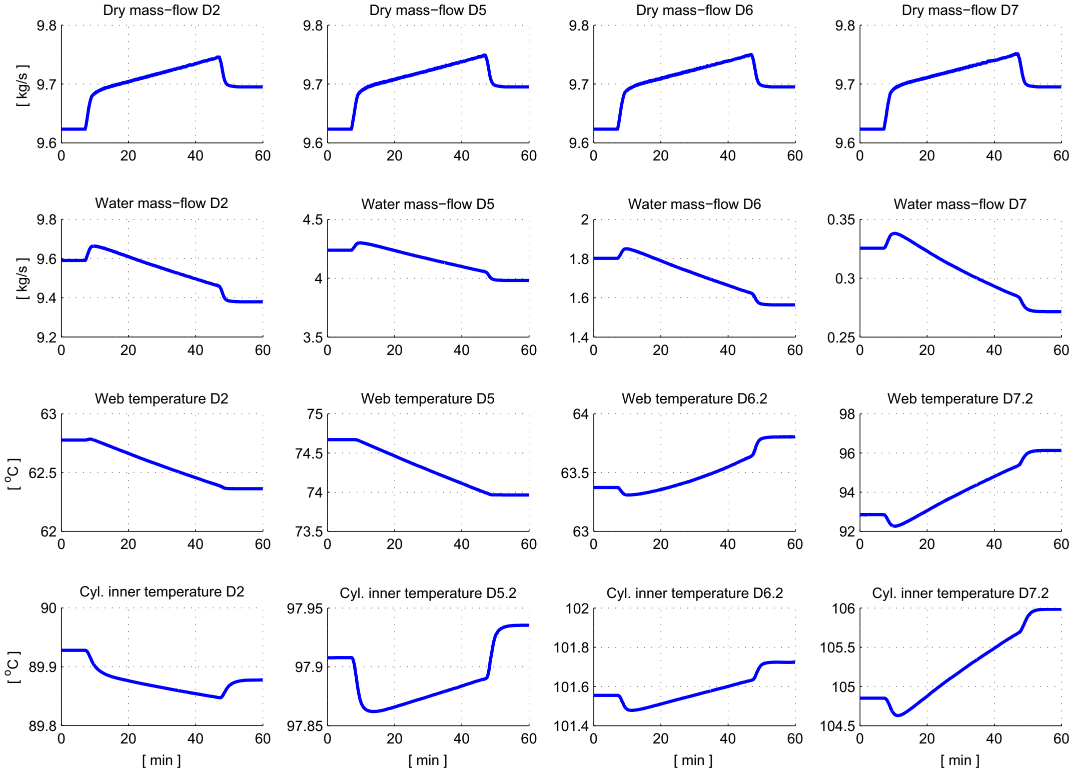

**Figure 5.8:** Speed change - mass flows and temperatures 1.

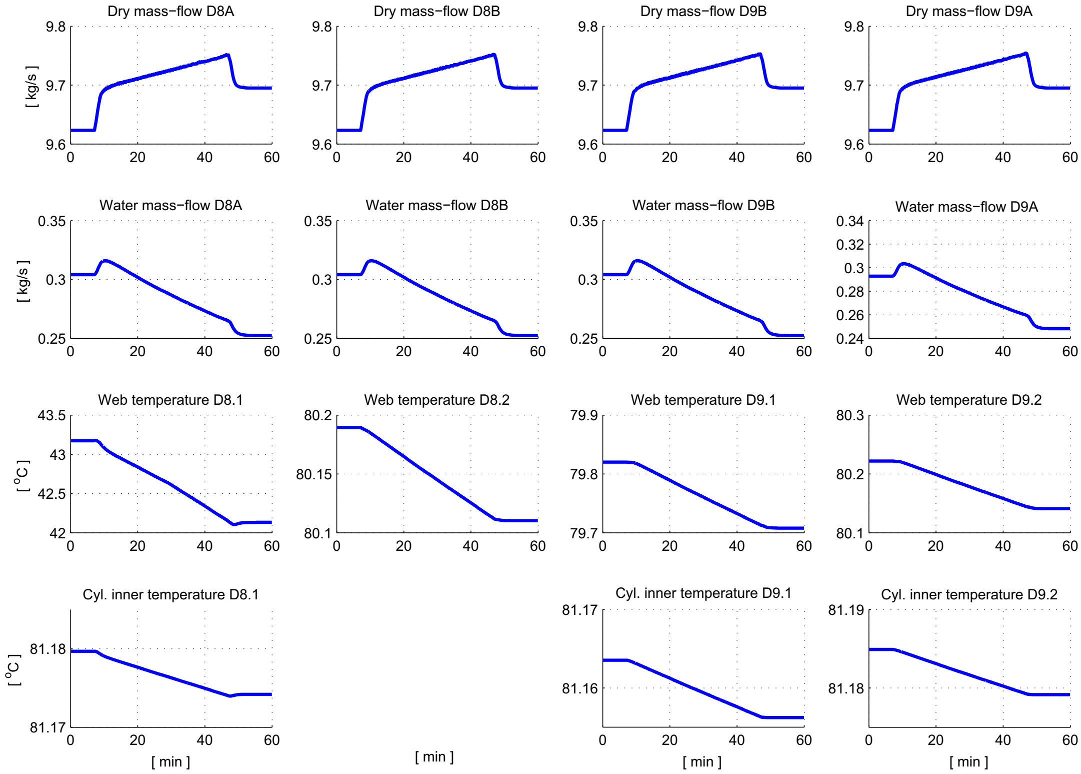

**Figure 5.9:** Speed change - mass flows and temperatures 2.

### Comments

Figures 5.8 and 5.9 show the mass-flow and temperature responses to the speed ramp. It is noticeable that even with a low acceleration the head-box flow change induced a mass-flow change (see later in Chapter 8), seen e.g. at the output of the group 2. There is a small decrease in the J/W level which is probably a result of the simplified head-box pressure set-point calculation. Even though the thick stock flow controller had a constant set-point a change in the actual measurement can be seen during the head-box flow change, which is a consequence of pressure changes in the mixing point in the wire pit. There is also a change in the final dry mass-flow level which should not appear in principle because the thick stock flow is kept constant. This change is a result of small retention change in the short circulation changing the reject mass-flow out of the screens.

## 5.2.4 Pure Slice Lip Opening Change

Slice lip opening change is one of the strongest short-term disturbance generators on a paper machine, see e.g [MC99]. The following tests confirm the earlier observations and give information of the phenomenon for compensation purposes. The head-box pressure set-point is calculated directly from the machine speed and J/W set-points.

Head-box pressure controller gives the set-point to the fan-pump speed. The control configuration is described in the following.

### J/W Control Principle

In principle the J/W calculation calculates the required jet-speed from the present machine speed and J/W set-points by taking the account head-box geometry and the measurements. Then using these inputs it calculates the required head-box total pressure for the required jet-speed. This pressure is used as set-point at the head-box pressure controller whose output is connected as a set-point to the fan-pump speed control. Then finally pump speed creates the head-box flow which in turn sets the head-box pressure.

The presented simulation utilises the most simple pressure calculation equation, which does not take into account any specialities of the head-box internal geometry but works well enough for disturbance test simulations.This is based on the standard Bernoulli equation

$$P = \rho \cdot g \cdot h + \frac{1}{2} \cdot \rho \cdot S^2 \tag{5.8}$$

which is simplified to the following by taking to account that for water $\rho = 1\ [kg/dm^3]$:

$$P = \frac{1}{2} \cdot S^2 + bias \tag{5.9}$$

A suitable value for the *bias* term has been found by trial and error. The criteria for the *bias* was to have a sufficiently small error in the measured J/W inside the operating range that was used in simulations. The head-box was a hydraulic one in this simulator and thus did not include level control or measurement.

The control loop structure presented in Figure 5.10 is in principle like a cascade, but in practise there is more a question about measurement transformation than about real cascade control. The structure could also be a real cascade but because the jet-speed calculation is based on head-box pressure measurement it wouldn't give any further benefit. (Note: In [KNK06] the disturbances seen in the slice-opening change simulation example were probably too big compared to practical paper machine cases when the head-box pressure controller has been tuned carefully. The simulation system was using in the example case the original cascade structure consisting of two PID-controllers instead of the structure described here.)

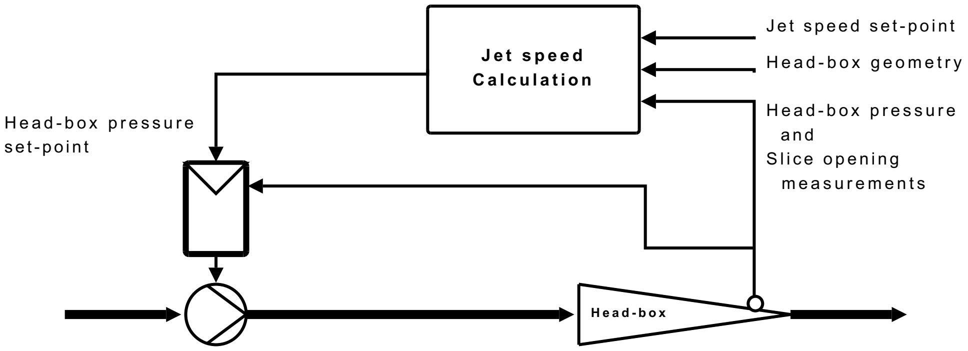

Figure 5.10: Jet/wire control principle

### Simulation

During the simulation the set-points of these flow-controllers; thick stock, filler and retention aid were kept constant. The main steam-pressure set-point was also constant as well as the J/W set-point. The test signal was a ramp in the slice opening. This kind of test could be done on a real machine by thus disturbing the production and actually such happens quite often at production machines. Some examples exist where this has happened by manual slice opening change. The tests give information how the J/W-control in cascade with the head-box pressure control reacts to the change. What happens to the mass-flows from the wire and what is the effect on evaporation.

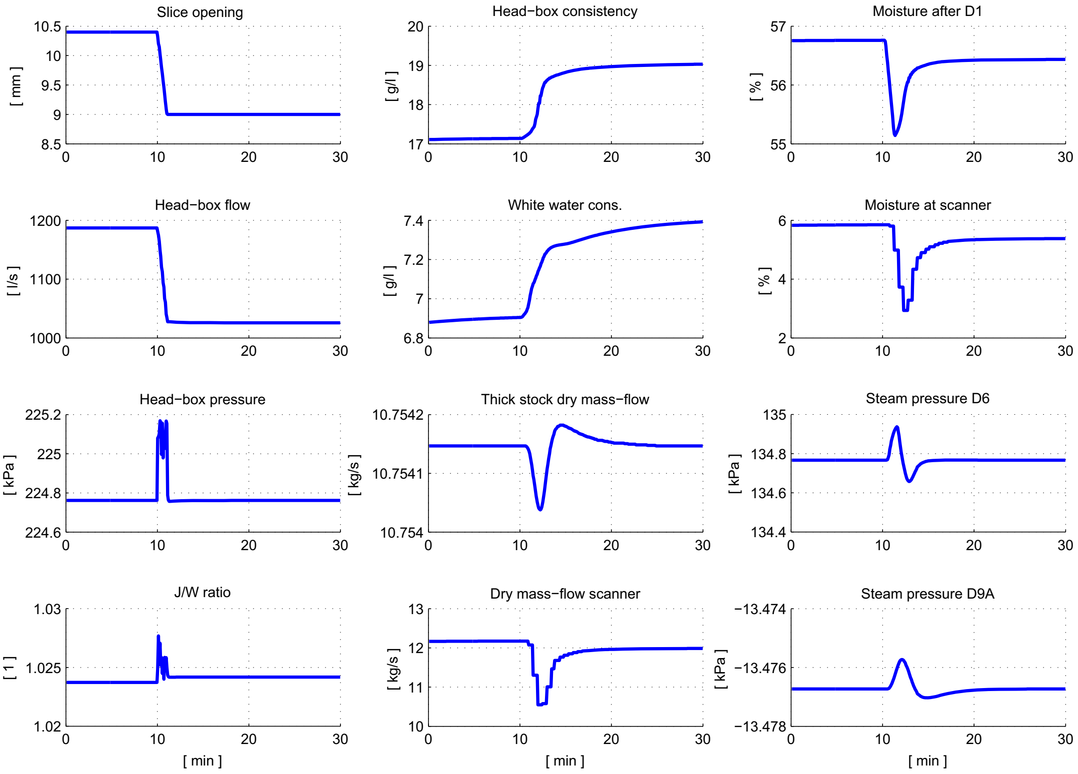

**Figure 5.11:** Slice change - basic values.

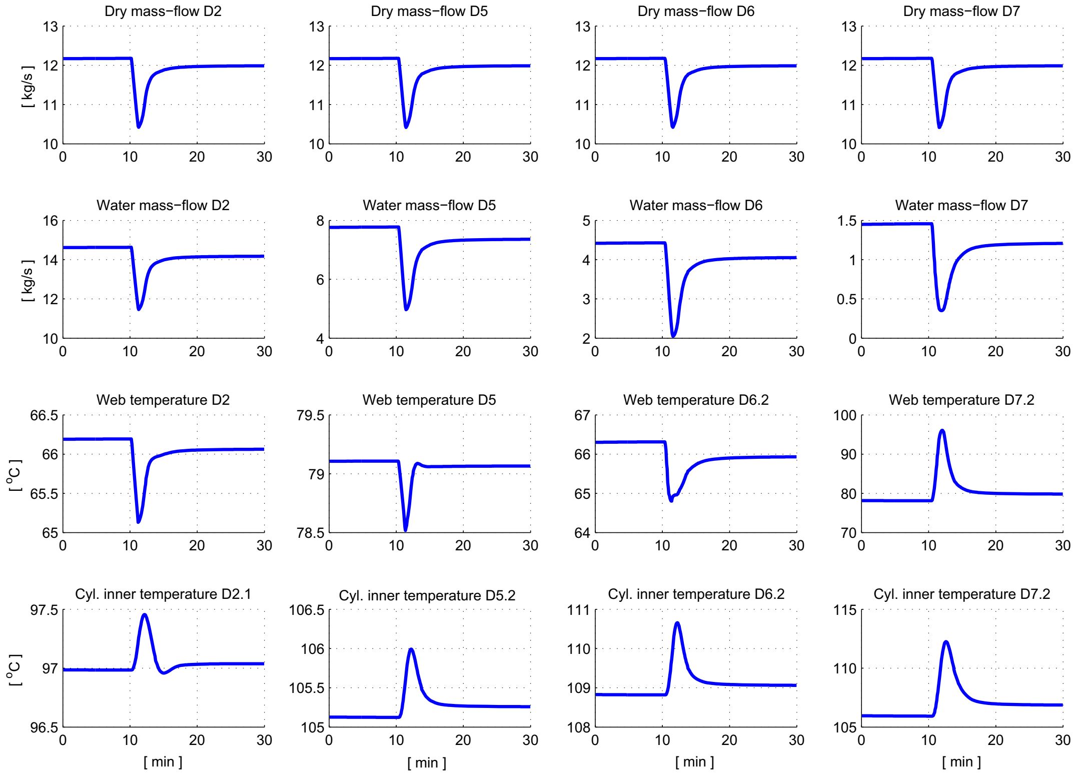

**Figure 5.12:** Slice change - mass flows and temperatures 1.

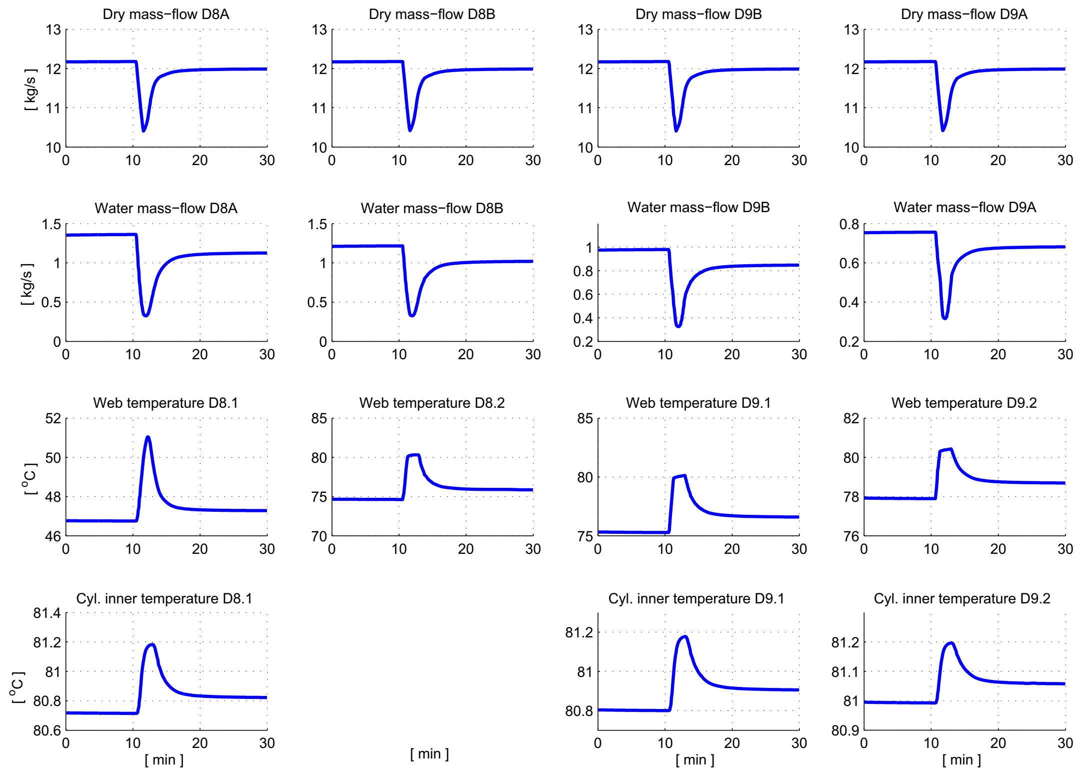

**Figure 5.13:** Slice change- mass flows and temperatures 2.

## Comments

Figure 5.11 shows a rapid one minute change in slice opening. The J/W and head-box pressure controller co-operation can be seen as very fast actions. This kind of change generates quite a huge temporary spike-like disturbance both in the dry and water mass-flows whose end levels in the end of the drying section are almost the same as in the beginning of the test. There is anyway a small change in the retention conditions at the wire which generates also a level change in both final dry and water mass-flows [Kos04] by the changes in the cleaner reject dry mass-flow. There is a large change in head-box consistency and flow (these are natural consequences).

Figures 5.12 and 5.13 show how the mass-flows and temperatures behave in drying groups during slice opening. The water mass-flow disturbance shape follows the dry mass flow change. The water mass-flow change peak at D2 is from 14.6 kg/s to 11.5 kg/s which results to -3.1 kg/s and after group D8 from 1.22 kg/s to 0.32 kg/s which results to -0.9 kg/s. The ratio between the change in the input water mass-flow of the drying section and the output water mass-flow is roughly 3.4. The ratio is quite near the ratio in Section 5.2.1 even though the change size is totally different and the nature of the change, permanent v.s temporary, is quite different. An important result is also that in this test the dry basis-weight changed but in the earlier test the change was pure mass-flow change.

### Production Machine Case

The same phenomena as seen on the simulations can be seen also on a production machine. Figure 5.14 shows an example of a manual GC case from a 3-layer board machine when there are slice opening changes during the GC. The transfer functions which were in use in the quality controller are listed in Appendix A.2 in Table A.3. In this case layer 2 was the main layer and the slice opening of that layer was changed manually. The slice is operated by push-pull buttons beside the wire running the position actuator open/close respectively. The opening control is based on visual water-line observation of the operator. The basis-weight control was not active except the speed dependent direct thick stock flow control. The moisture control was active and the biggest disturbances can be seen in moisture. It is not so easy to differentiate the slice-change generated part of the disturbance from the figures from the thick stock change generated part but because they happen long enough after each-other the distinction is possible. The order of events: 1) the change in thick stock flow, 2) the change in slice 2 opening, 3) the response in scanner measurement from thick stock flow and then finally the response 4) from the slice opening change.

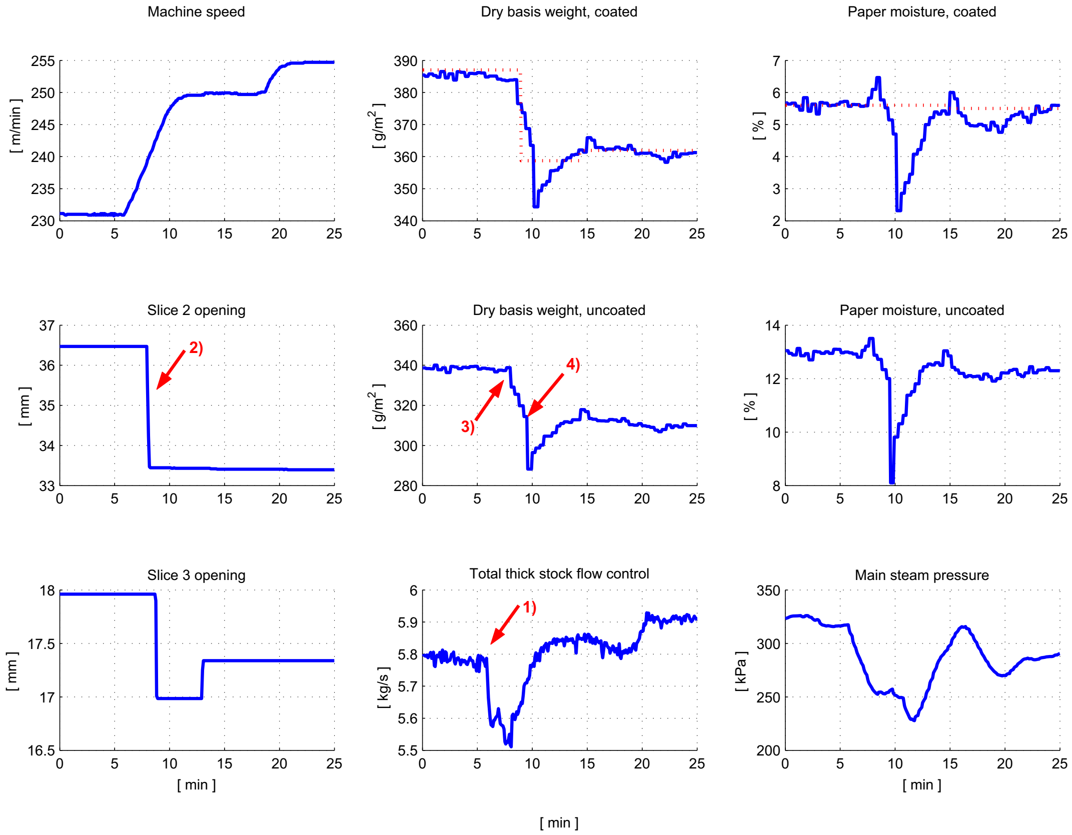

**Figure 5.14:** Slice change at the production machine.

### 5.2.5 Simultaneous Speed Change and Slice Lip Opening

If the slice opening is included in the GC it is typical that the slice opening and machine speed change simultaneously. Then the machine speed is the commander and the slice opening follows. In practise the slice opening can have a slight advance in timing v.s. speed but the ramp time from the starting point to the end followsthe speed ramp. There is not often any change in J/W set-point. In question of GC also other MVs change at the same time.

#### Simulation

During the test the thick stock flow had a constant set-point and the filler flow controller had a very a low constant set-point. The retention aid flow controller and the steam pressure controllers had also constant set-points. J/W calculation gave a set-point to the head-box pressure controller. The test signal was a ramp both in slice opening and machine speed with similar timing.

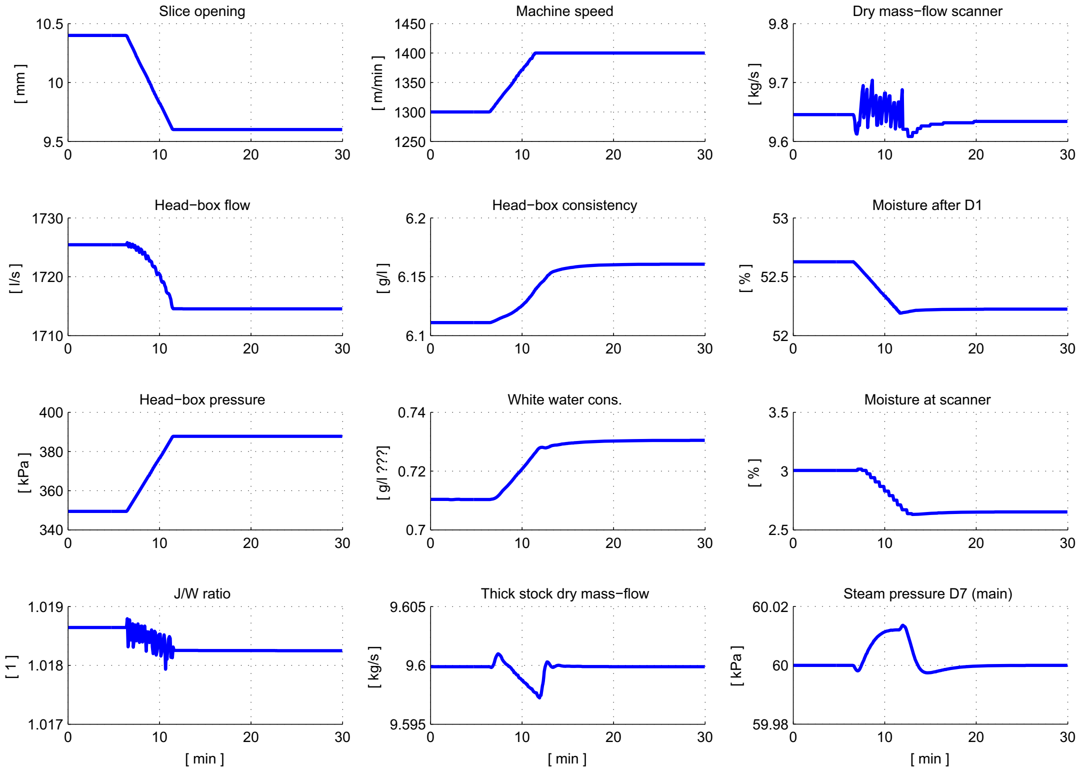

Figure 5.15: Simultaneous slice and speed change - basic values.

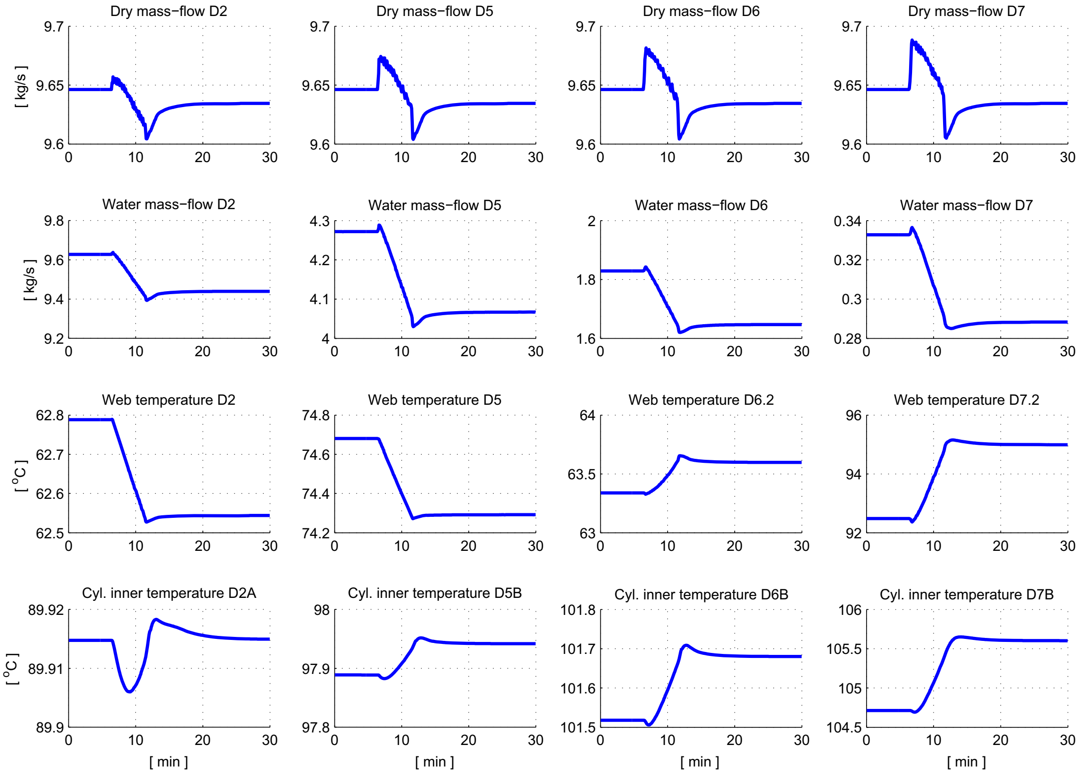

**Figure 5.16:** Slice and speed change - mass flows and temperatures 1.

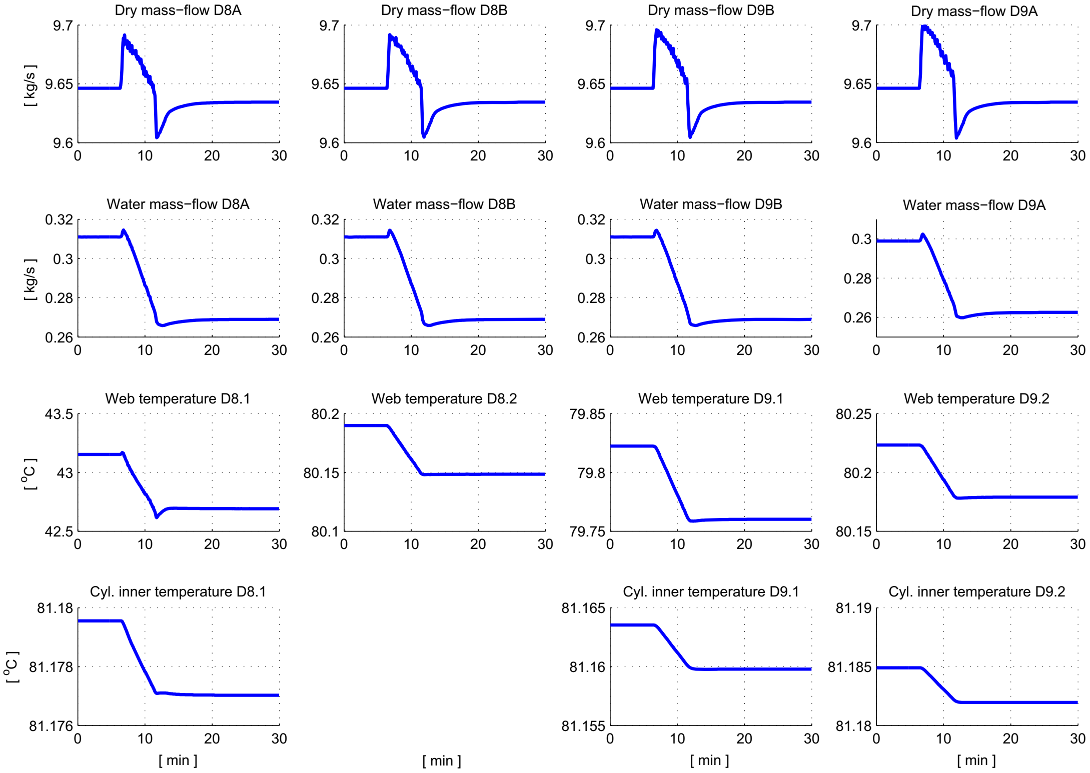

**Figure 5.17:** Slice and speed change - mass flows and temperatures 2.

### Comments

Figure 5.15 shows the basic responses of simultaneous slice and speed change. Figures 5.16 and 5.17 show the water mass-flow response to the simultaneous slice opening and speed ramps.

All the same components that are seen in the water mass-flow response can be seen also in the dry mass-flow where the final level is a consequence of outflow from screens because of retention change changing the internal mass-flows in the short circulation.

As can be seen from the figures, the dry mass-flow response has some amount of acceleration effect. By using these kind of ramps the slice opening disturbance can be almost eliminated, which is natural because of the explanation in the following section. When it is possible to include the slice opening change in the way simulated here during the GC the behaviour of all paper quality controls will be much smoother compared to the case where the slice change would be done manually as a step. One reason is that the total peak to peak change in head-box flow is smaller this way but even if the change is relatively large even without the inclusion of the head-box flow change compensation described in Chapter 8 the behaviour is more acceptable. By comparing both of the mass-flow disturbances at D2 to the simulation case in the previous section, it can be seen that the disturbance from the head-box flow change is either smaller or at the same level as there but here the acceleration level is higher. The only problem in practise is the final level of slice opening which is often based on the operator visual observation from the process. E.g. the water line location in the case of a board-machine is the determining factor of the slice opening.

### The Process Effects Cancellation Possibilities

The effects described earlier can be partly taken into account during a grade change as DV input predictions to the optimising controller or (local) feed-forward compensators. As can be seen that one of the strongest disturbing effects is the J/W+slice opening combined change. In many cases the slice opening is adjusted to keep the head-box total flow inside the optimal range.The flow can be calculated simply

$$F_H = J \cdot S_W \cdot W_H \cdot H \tag{5.10}$$

If the factor $J \cdot S_W \cdot H$ is kept constant, i.e. the head-box flow would stay constant there should not happen any disturbance in principle. If there is a timing difference in the actual speed and slice opening ramps, then this term is not constant anymore and the J/W-controller sees a different J/W-ratio requiring actions from the head-box pressure controller. The resulting J/W is smaller or bigger than the set-point if the slice opening ramp timing has lag or lead in it accordingly.

### Case from a Production Machine

Figure 5.18 shows an example of a GC case from a 3-layer board machine when possibility to a smoother slice change was tested on that machine. The machine and the process models in the paper quality controller were the same as in Section 5.2.4. In this case layer 2 was the main layer and the slice opening of that layer was changed manually to approximately follow the speed change ramp. The result ramp in slice opening in this test case was surprisingly good thanks to the careful operator. The slice was operated by push-pull buttons beside the wire running the position actuator open/close respectively. Even though the results from changing the slice opening as a ramp were encouraging at that machine it was not possible to implement reliable slice opening control because of technical difficulties.

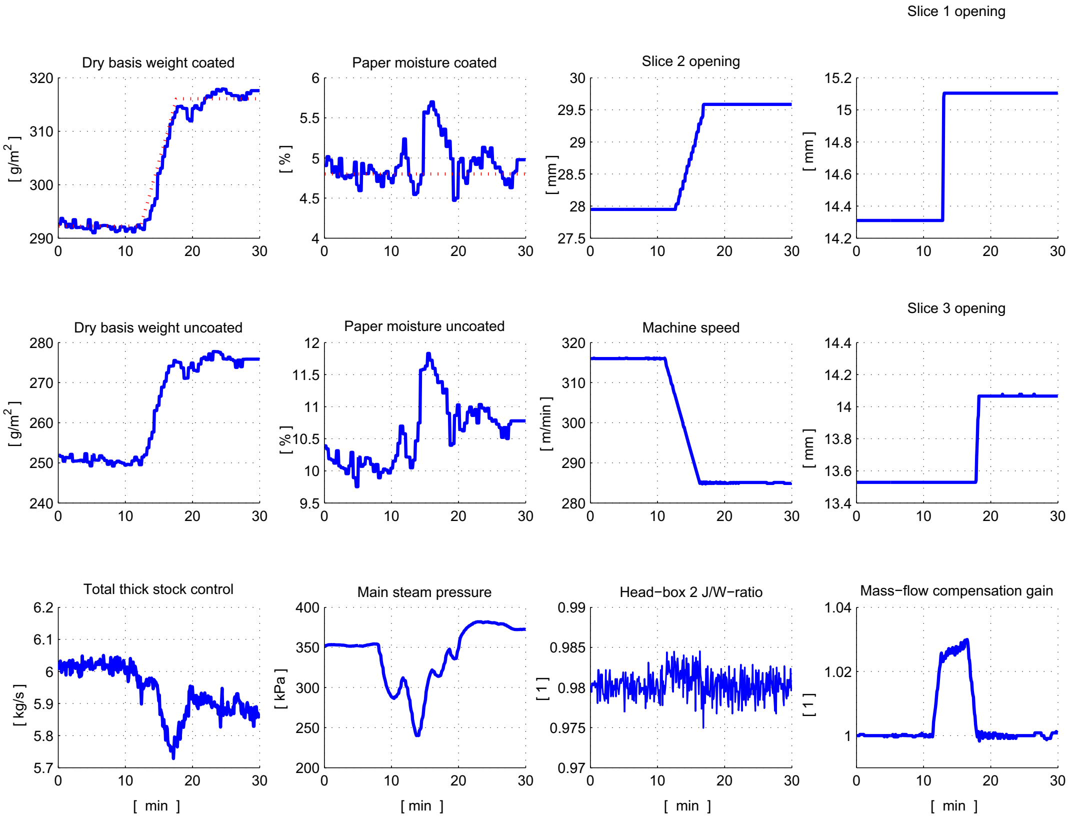

**Figure 5.18:** Slice and speed at the production machine.

# Chapter 6

# Closed Loop Grade Change

## 6.1 Basic Paper Quality Measurements

Measured paper quality variables are: dry basis weight (called also often as oven dry basis weight) which tells the amount of non-water matter per unit area [g/m$^2$], (pure) basis weight which includes total mass for the paper including water, water basis weight which tells the amount of water per unit area [g/m$^2$] (rarely used in practise as a customer unit). Moisture tells the percentage of water compared to the basis weight [%]. Filler content measurement which is normally called paper ash, indicates the percentage of inorganic fillers compared to the dry matter [%].

Then there are additional operating parameters that are useful; draw, the ratio between sheet speed at reel v.s. at the wire, web width at reel [m] and web width after wire [m]. CD-shrinkage is the ratio between web width at reel v.s. web width after wire and elongation in MD-direction, which is similar to the CD-shrinkage. The side-bands that are cut out of the paper have to be taken into account when calculating the CD-shrinkage. Measured draw is related closely to the elongation.

Note that in a stable control situation the shrinkage and elongation compensate each other almost totally from the paper dry mass-flow MD control point of view because the amount of mass-flow going into the drying section must also come out at the reel.

## 6.2 Wet-end Measurements

Typical short circulation related variables are thick stock flow [l/s], thick stock consistency [%] or [g/l] and thick stock ash content [%] which measures the proportion of filler of the dry content of the thick stock. The filler related variables are filler flow [l/s], filler density [kg/l] (measured rarely on-line) and retention aid flow [l/s].

Retention aid concentration at the feeding point could be a useful measurement also because this variation can impact the paper ash variation remarkably. It is normally not measurable. The actual retention aid is always a diluted mixture of water and retention aid whose volumetric flow is measured and controlled. The expected concentration of the diluted retention aid is assumed to stay constant.

### 6.2.1 Transformation to Mass-flows

The **thick stock** dry mass-flow $Q_{d\_T}$ $[kg/s]$ can be calculated as

$$Q_{d\_T} = C_T \cdot F_T \cdot 0.001 \tag{6.1}$$

Here standard assumption is that the specific weight of dry matter of the stock is the same as that of water. This is not exactly true especially if the stock contains a lot of recycling filler from the long circulation or from broke. This could be seen as gain parameter increase from the theoretical one to a bigger value in thick stock to paper dry mass-flow transfer function.

The **filler** dry mass-flow $Q_{a\_F}$ $[kg/s]$ can be calculated similarly as

$$Q_{a\_F} = C_{a\_F} \cdot F_{a\_F} \cdot 0.001 \tag{6.2}$$

Here the it is assumed is that the laboratory measured consistency value (as mass proportion) is available and the mixing of filler and water keeps constant. The specific weight of the filler is not needed and it is indirectly included in the consistency. Another way to calculate the filler mass-flow utilising the density measurement if it is available by using dry filler and water density values $D_a$ and $D_w$:

$$V \cdot D = V_a \cdot D_a + V_w \cdot D_w \tag{6.3}$$

$$V = V_a + V_w \tag{6.4}$$

where

| | |
|---|---|
| $V$ | total volume of mixture |
| $V_a$ | filler volume of mixture |
| $V_w$ | water volume of mixture |
| $D$ | measured mixture specific weight |

| | |
|---|---|
| $D_a$ | filler specific weight $[kg/l]$ |
| $D_w$ | water specific weight $[kg/l]$ |

From (6.3) and (6.4) it follows that

$$\frac{V_w}{V} = 1 - \frac{V_a}{V} \tag{6.5}$$

$$\frac{V_w}{V} \cdot D_w = D - \frac{V_a}{V} \cdot D_a \tag{6.6}$$

and combining (6.5)and (6.6) we get

$$p_a = \frac{V_a}{V} = \frac{\left(\frac{D}{D_a} - 1\right)}{(D-1)} \tag{6.7}$$

and then the final filler mass-flow as

$$Q_{a\_F} = p_a \cdot D_a \cdot F_F \tag{6.8}$$

(The unit of $p_a$ is here [1] instead of [%].)

**Sheet width** at reel $W_R$ $[m]$ is

$$W_R = W_W \cdot \sigma \tag{6.9}$$

where $\sigma$ is total CD-shrinkage along the drying section [1].

**Speed** at reel $S_R$ $[m/\mathrm{s}]$:

$$S_R = S_W \cdot \delta \tag{6.10}$$

where $\delta$ is total draw (or elongation) along the drying section [1].

The **total dry mass-flow** at reel $Q_{d\_T}$ $[kg/s]$ can be calculated from these as

$$Q_{d\_R} = S_R \cdot W_R \cdot \ B_{d\_R} \cdot 0.001 \tag{6.11}$$

The filler portion of the total dry mass-flow, **ash mass-flow** at reel $Q_{a\_R}$ $[kg/s]$:

$$Q_{a\_R} = Q_{d\_R} \cdot \ p_{a\_R} \cdot 0.01 \tag{6.12}$$

The **water mass-flow** at reel $Q_{w\_R1}$ $[kg/s]$ can be calculated as follows if the calculation is based on the normally available dry basis weight and moisture measurements

$$Q_{w\_R1} = Q_{d\_R} \cdot \frac{p_{w\_R}}{100 - p_{w\_R}} \tag{6.13}$$

where $p_{w\_R}$ is moisture (water proportion of **total**[1] basis weight) [%] because

$$Q_{w\_R1} = p_{w\_R} \cdot \ Q_R \cdot 0.01 \tag{6.14}$$

and

$$Q_R = \left(Q_{d\_R} + Q_{w\_R1}\right) \tag{6.15}$$

For convenience the following water mass flow $Q_{w\_R}$ expression is more suitable in practise $[g/s]$

$$Q_{w\_R} = Q_{w\_R1} \cdot 1000 \tag{6.16}$$

### 6.2.2 Mass-flow Usage

The above variable transformations are using the mass-flows divided in dry mass-flow, ash mass-flow and water mass-flow.

In principle it would make more sense to use fibre mass-flow instead of total mass-flow as one CV because now the ash portion is included actually twice in the variables above. The reason for this selection comes actually from the present scanning sensor technology. The present sensors give basically the following information from the paper web: (total) basis weight, water basis weight and ash proportion of dry content.

Now it is easy to calculate the total dry basis weight if the basis weight sensor and moisture sensor are functioning even if the ash sensor is broken. Because the required accuracy of dry basis weight of the paper is almost always more important than paper ash, the selected division will work to some extent even if the ash sensor is in service. During this time the filler dosage can be based on laboratory values and production rate. Unfortunately the moisture part can not be solved in this way. Both the basis weight and moisture sensors are required for both moisture and dry basis weight control.

---

[1] Note: It is typical in paper machine environment that the ash proportion is related to the dry basis weight whereas the moisture is given as the proportion of water from the total basis weight.

## 6.3 From MV-trajectories to CV-trajectories

When starting to construct the closed-loop GC-control for the paper machine utilising the above mentioned mass-flows the first question is “what kind of set-points in time should be used” for the controller. The main feature of the paper machine is that the wet-end is controlled mostly by mass-flows whereas the final measured dry-end end-product quality is affected also by machine speed. The binding equation (6.11) tells the relation. When machine is running at a stable operating point there is in principle no difference if the control is based either on the direct quality measurements or mass-flows. Each quality variable $X$ handled here could be substituted by the corresponding mass-flow value by a simple multiplication:

$$X = k \cdot Y \tag{6.17}$$

The situation changes if the speed change is included. The simplest case of this is when only speed is changed. All the quality variable set-points are supposed to be kept constant. What should be used as set-points for the closed-loop quality controller if there is no change in the quality variable set-point? Still the production rate changes and clearly all manipulated variables should change according to this. There is a suggestion in [MRC00] of a method how this could be done. The system is a hybrid system of open-loop MV-ramps added with model based quality control which activates if the real measurement differs too much from the model predicted one.

Method described here is based on using mass-flows both as final measurements and set-points instead of the direct quality value measurements. This gives the benefit that the machine speed is involved in both the measurements and set-points, thus taking into account also production rate change cases.

The other benefit is that the direct machine speed is removed from the control equations. Another necessary feature is the future target ( = set-point ) trajectory which is a natural part of the predictive control.

At paper machines it is normal that in grade changes the speed change and timing for the change is known beforehand. Then as in the traditional MV-ramp based GC it is natural to take the speed change as the predetermined baseline for all of the other operations. When the control is based on mass-flows there are two basic possibilities for calculating the timing and shape of the future trajectories:

1. Calculate from linearly changing dry basis-weight, ash and moisture the required non-linear mass-flow target trajectories or
2. Use linear mass-flow trajectories whose starting and end-points are calculated from the quality set-points and machine speed values at those points

In both cases the simplest timing is to tie both ends with corresponding time points of the speed change. The following illustrations of both cases assume that the trajectories are calculated directly using the mass-flow calculation equations at the reel of the machine without taking to account the items discussed later in Chapter 7. The speed change is from 1400 m/min to 1300 m/min between 400 s and 700 s. The change starting and end points are shown as red dashed vertical lines in each figure.

### From Linearly Changing Quality Targets to Mass-flows -Case 1

When the timing of the quality value ramps is tied to the timing of the machine speed change ramp, the result target mass-flow trajectories are depicted in Figure 6.1.

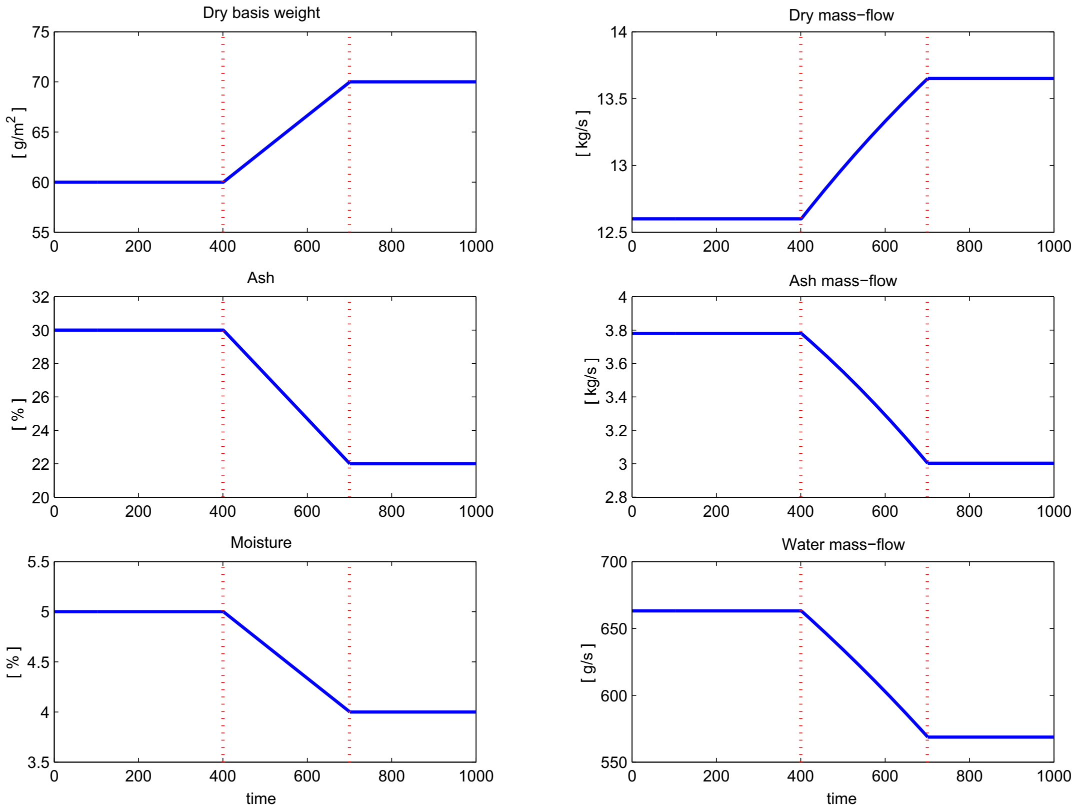

**Figure 6.1:** Mass-flows by linear quality ramps - basic.

The mass-flow values are determined by using the equations (6.11), (6.12) and (6.14). The quality trajectories are linear approximations in time between two end-points whose values are calculated using these same equations. The grade targets specify the starting and end point values of the quality trajectories. The target curve seen by the controller calculated in this way can have a rather complicated form if certain time-shifts in the target are used. The same problem appears also if the dry mass-flow changes to another direction than e.g. ash mass-flow. Figure 6.2 depicts a case when quality ramps have been shifted in relation to machine speed.

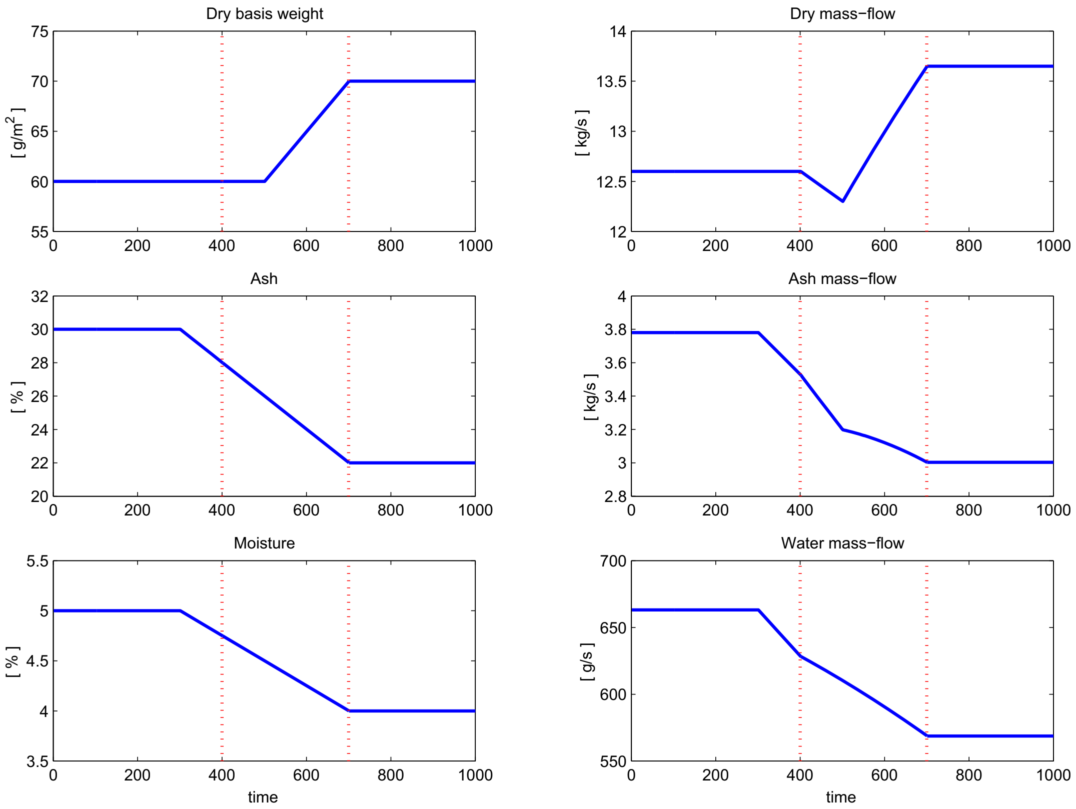

**Figure 6.2:** Mass-flows by linear quality ramps - shifted.

### From Quality Targets to Linearly Changing Mass-flows - Case 2

When the timing of the mass-flow ramps is tied to the timing of the machine speed change ramp, the result as quality values are depicted in Figure 6.3 assuming that the quality measurements follow the target trajectories:

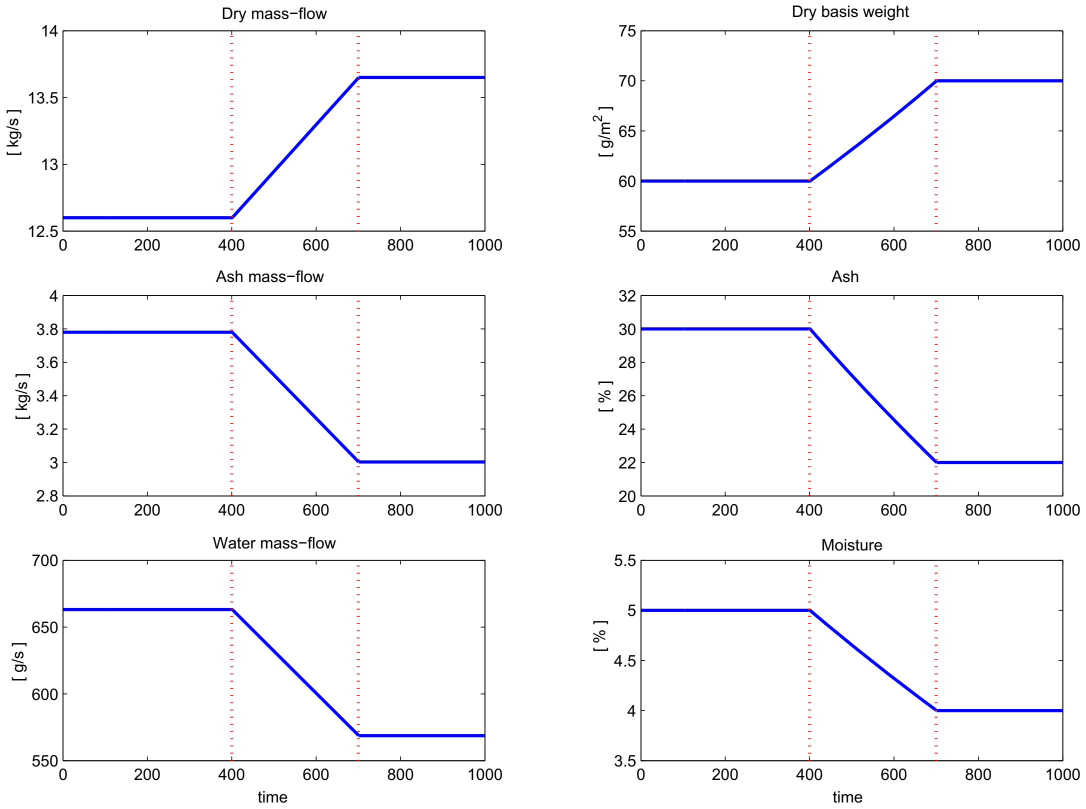

**Figure 6.3:** Quality values by linear mass-flows - basic.

The quality values are determined by using the equations (6.11), (6.12) and (6.14). The mass-flow trajectories are linear approximations in time between two end-points whose values are calculated using these same equations. The grade targets specify the starting and end point quality values from where the mass-flow value trajectories are calculated. The target curve seen by the controller calculated in this way can also have a rather complicated form if certain time-shifts in the target are used. The same happens also in the case if the dry mass-flow changes to another direction than e.g. ash mass-flow. Figure 6.4 depicts the latter case.

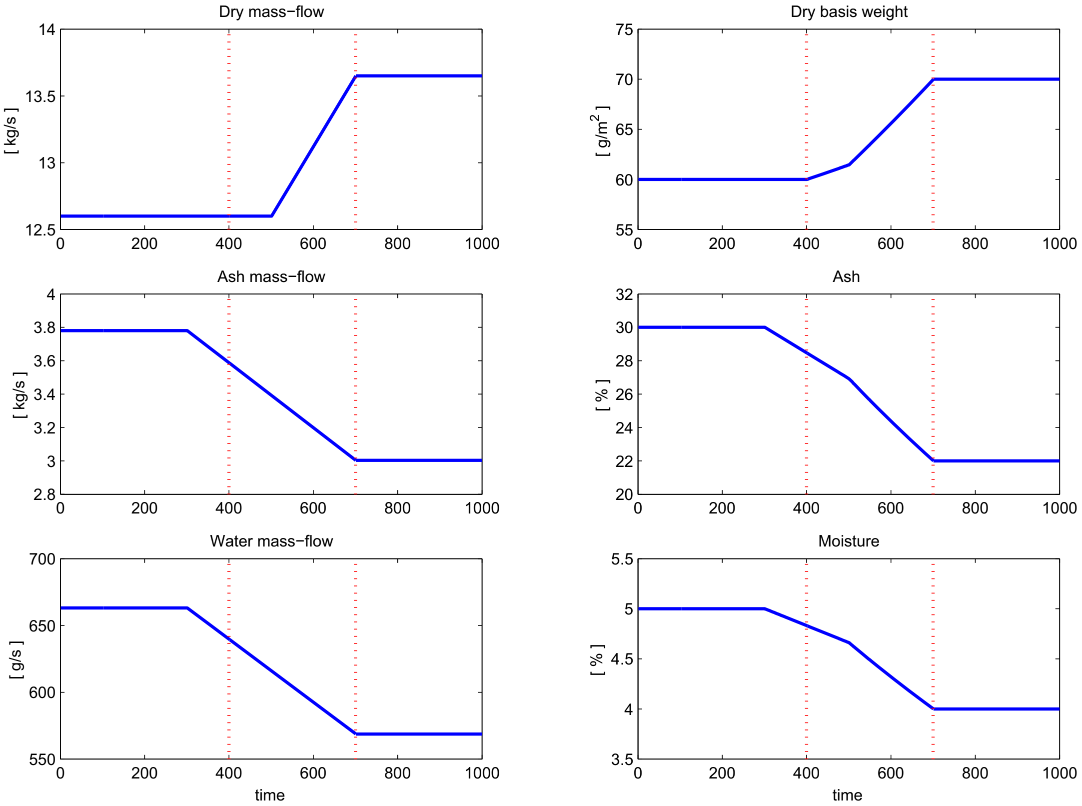

**Figure 6.4:** Quality values by linear mass-flows - shifted.

### Conclusion

As it can be seen from the previous illustrations, both methods can result in complicated target trajectory forms if there is a suitable timing shift between the target variables (either as mass-flow or direct quality) and speed. These can not be controlled by practical controller tuning and actuators. The simpler method, Case1 in Section 6.3 is chosen to be utilised because in practise the ramp-time area behaviour of the grade change is not very important as long as the measured values are near enough the targets during the time before and after the ramp.

## 6.3.1 Trajectory Timing Principles

Despite of the change from the open-loop control MV-trajectories to the closed-loop control CV-trajectories the process delays and time constants have to be taken into account. This means that the principles shown in Figure 4.1 are implicitly valid also for the closed loop case by requiring enough advance time for the controller to take into account the process dynamics. But this is not enough, because in the open-loop case the reference point, when considering the timing between the machine speed and a certain quality variable, is the head-box. For the closed-loop case the reference point is the measuring scanner and thus the drying section delay has to be added in the beginning of the target trajectories to guarantee that there is enough time reserved for the predictive control actions.

In the case of a paper machine the starting point of the grade change is based on production schedule which determines accurately the actual GC starting point in time in advance. Note that here the mass-flow measurement and speed related item described later in Chapter 7 is not yet considered.

### 6.3.2 Related Horizon Tuning Issues vs. Target Trajectory Timing

In e.g. [Mac02]control and prediction horizon issues are discussed. For example the book handles quite often the constant set-point case from disturbance elimination point of view or step-like changes in scalar set-points. The trajectory has been left inside the controller as a set-point smoothing filter. In some MPC-applications the prediction horizon is kept always constant length and the controller tuning is based only on weighting factors. In the case of a grade change the future time has clearly different areas with different importance which can be taken into account when horizons are chosen. There are two possible main classifications of the time area importance during the grade change. In large-scale changes the production during area I $\cdots$ II (ramp) in Figure 6.5 goes to broke and has only a little importance. In small-scale no-broke changes or speed-changes all areas are as important. By inspecting the figure and the form of the penalty function of MPC (6.18) it can be seen that probably the horizon parameter selection principles used for steady-state disturbance compensation are not the best for GC. First, the CV horizon area has equal importance in the function when the main interest during GC is the change itself. For steady-state operation the maximum prediction horizon is usually selected to be far-away in the stable area of the dynamic responses of the controlled variables. Then the relative weight of the stable area is too big compared to the change area in the horizon which is the main interest. Second, the usual rules for MV horizon selection during steady-state operation suggest small values for that. It can be understood that trying to control change in several controlled variables with interactions at the same time when the future target trajectory includes a change as a ramp with two corner points requires more freedom as a longer control horizon. To control successfully the whole change the action prediction needs the possibility to take into account the impact of the actions for the first corner point in the actions for the second and vice versa. In practise this requires at least as long a control horizon as the ramp time of the change.

Quite often the MPC literature shows the MPC weighting as constant diagonal matrices $\boldsymbol{R}_{m\times m}$ and $\boldsymbol{Q}_{c\times c}$. It is in principle a straightforward task to add time-weighting in a typical MPC penalty function, because almost all formulations include the horizon parts as in (6.18).

$$J = \sum_{i=p}^{h} \hat{\boldsymbol{\varepsilon}}(i)^T \cdot \boldsymbol{Q}_i \cdot \hat{\boldsymbol{\varepsilon}}(i) + \sum_{j=1}^{k} \Delta\hat{\boldsymbol{u}}^T(j) \cdot \boldsymbol{R}_j \cdot \Delta\hat{\boldsymbol{u}}(j) \tag{6.18}$$

where $m$ is MV dimension, $c$ CV dimension, $J$ penalty function, $i, j$ indices in the future time i.e. 0 for present, $p$ the prediction horizon minimum, $1 \leq p < N$, $h$ the prediction horizon maximum, $p < h \leq N$, $k$ control horizon, $1 \leq k < (h - p)$, $N$ model length, $\hat{\boldsymbol{\varepsilon}}(i)$ the error between the target trajectory and the CV prediction in the future, $c$ vector, $\boldsymbol{Q}_i$ weight factor matrices for predicted CV error, typically a constant square diagonal matrix along the whole horizon, $c \times c$, $\Delta\hat{\boldsymbol{u}}(j)$ predicted MV actions in the future, $m$ vector and $\boldsymbol{R}_j$ are weight factor matrices for predicted MV actions, typically a constant square diagonal matrix along the whole horizon, $m \times m$.

By adding time weighting for each variable using time weighting vectors

$$\boldsymbol{g}(i) = \begin{bmatrix} g_1 \\ g_2 \\ \vdots \\ g_n \end{bmatrix} \tag{6.19}$$

where

$n$ is dimension of MV or CV,

$i$ index in the future time i.e. 0 for present, $i = 1 \ldots N$

$\boldsymbol{g}(i)$ time weighting factors[2] for, $\underline{0} \leq \boldsymbol{g}(i) \leq \underline{1}$

Now each result weighting matrix can be expressed as

$$\boldsymbol{W}(i) = diag\left(\boldsymbol{g}(i)\right) \cdot \boldsymbol{W}_0 \tag{6.20}$$

where $\boldsymbol{W}_0$ is the nominal weighting matrix ether $\boldsymbol{Q}_0$ or $\boldsymbol{R}_0$ , typically in use during stable operation.

The time-weighting could be added both in the CV-weights and MV-weights. For CV-weights the reason is natural because of the earlier performance requirements but for the MV-side the reason could be certain specific process restrictions. In this special case (grade change with a clear area of broke) the timing requirements are a result of the product quality requirements before and after the change and in that

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[2] The prediction horizon $p, h$ could be also seen as a special case of time weighting.

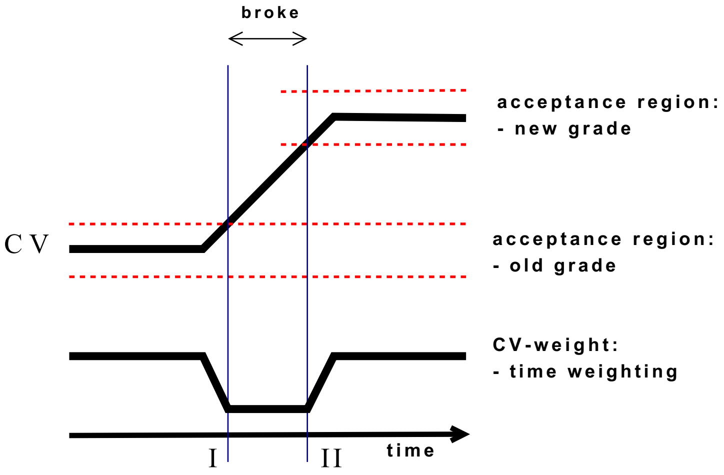

**Figure 6.5:** CV weight time weighting.

way predetermined.Figure 6.5 shows the principle of a possible way to utilise time weighting. It can be immediately seen that this possibility adds complexity in the tuning if free selection of the weighting is allowed and why it is not used in practical implementations.

### 6.3.3 GC Controller Structure

The proposed GC controller consisted of a multivariable predictive controller basically utilising the algorithm described in [Tia95] (the algorithm in the actual control product included also constraint handling utilising quadratic optimisation). Mass-flow trajectory calculations utilise the previously described transformations (6.11) - (6.16) between the present grade target values and new grade targets. Target trajectory timing is described in Section 6.3.1. Each target trajectory is shifted during GC one execution time shift in the trajectory for one control execution. Mass-flow transformations are used (naturally) for both directions, from measured quality values to transformed measurements and from control output mass-flows to actual flows. Logic is added for tuning changes in different operating conditions, normal (stable) situation, break and the actual grade change. For a start-up situation tuning displays are added which including also both CV- and MV-predictions in addition to the standard history trends.

The proposed method has been implemented in the Metso Automation control product IQWetendMD, which consists of two separate controllers:

- Wet end controller without any DVs, controlling:
  - thick stock flow [kg/s], filler flow [kg/s] and retention aid flow [l/s] as MVs

  - dry mass-flow [kg/s] and ash mass-flow [kg/s] at the reel and white water consistency [g/l] as CVs

- Dry end controller with DV-prediction inputs:
  - using DVs from the wet-end controller, thick stock flow future prediction, filler flow future prediction and retention aid flow future prediction
  - the drying section main steam pressure [kPa] as an MV
  - the water mass-flow [kg/s] at the reel as a CV

Often in predictive control text-books the viewpoint is from such industries where the target trajectories are used only passively i.e. the external targets are scalars for each CV instead of future target vectors. The target trajectory itself is used mostly for controller internal set-point change smoothing called as a reference trajectory. In this application the target trajectories are calculated externally according to the predetermined information from the speed and quality targets of the next grade. Another example of active target utilising in a totally different environment (ship steering) can be found in [Han96] (pp 131-134).

### 6.3.4 Practical GC Example at the Production Machine

There is a GC example from a production machine Figure 6.6. The GC was controlled using the principles and structure described above. The speed change was 1080 - 1280 m/min with the rate 10 m/min$^2$. The process models that were in use during this GC are given in Appendix A.1, tables A.1 and A.2.

Here is a list of phenomena to be noticed:

- Even though there is regular ash variation, the value stays almost all of the change time between typical acceptance range ± 0.5 %-units for normal operation.
- Dry basis-weight performance is also good.
- Moisture performance could be acceptable but several spikes can be seen there during the GC. It turned out after examination that the source of these spikes are the slice opening changes done during the GC. It is also noticeable that these changes show mostly in moisture but a little bit also in dry basis weight.

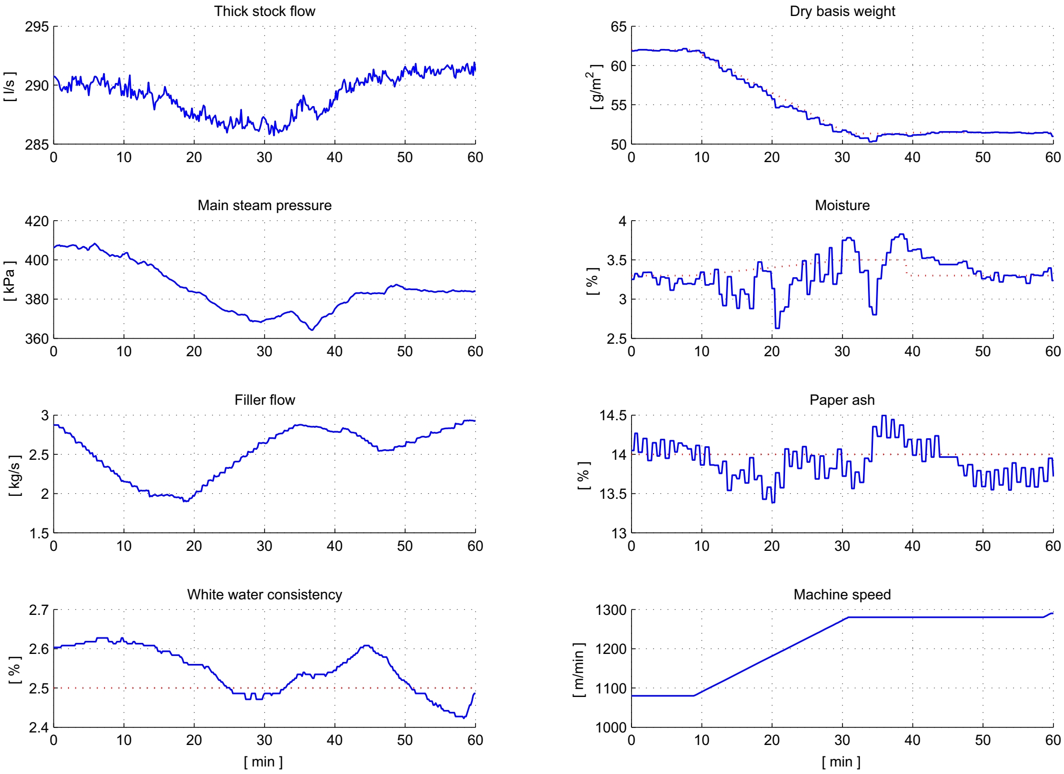

**Figure 6.6:** GC example.

## Comments on the Moisture Spikes

Figure 6.7 shows the manual slice opening changes during grade change, their effect in the J/W-ratio and effect in the moisture. Two of the strongest influence-points are shown with arrows in the J/W-ratio and the respective points in moisture. The disturbance can be seen also in dry basis weight but not as strong as in the moisture. The slice opening and machine speed generated head-box flow disturbance is handled more detailed in sections 5.2.2, 5.2.4, the disturbance and compensation in 8.4.2.

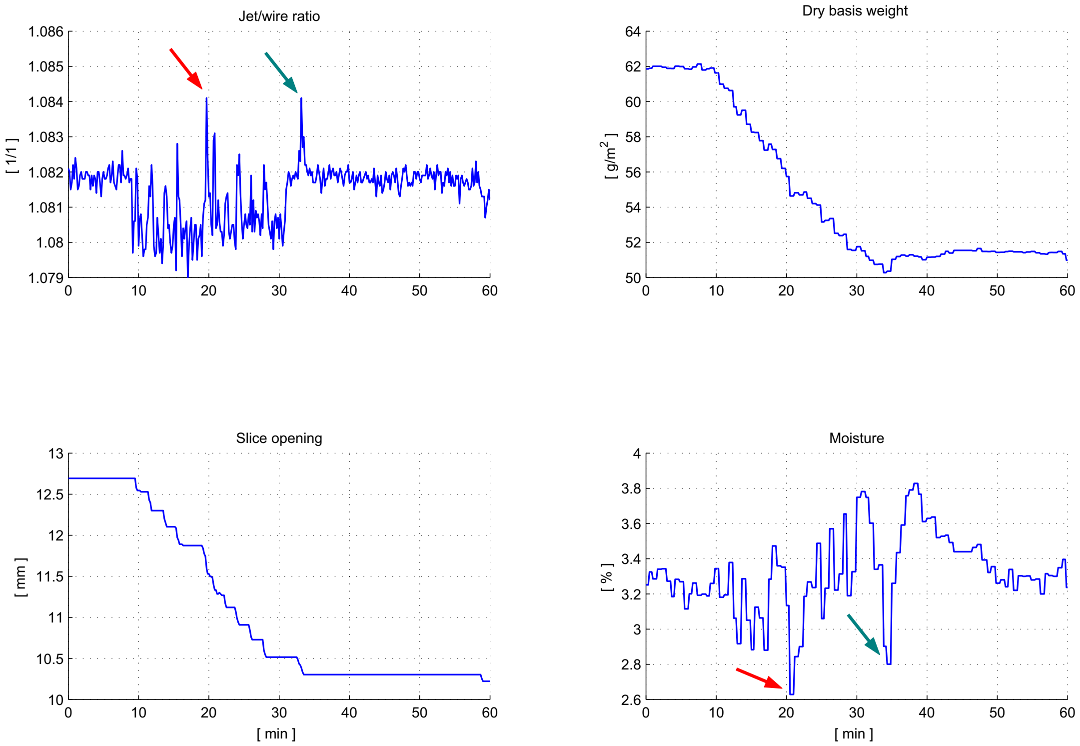

**Figure 6.7:** Slice opening changes.

### 6.3.5 Special Situations with Predictive Multivariable Controllers

#### MV Constraints

In the SISO-based control structure there is only a direct effect from a single MV to certain CV. If the MV in question hits the limit this does not change the behaviour of the other manipulated variables at all. In the MIMO-case the situation is different because the controller is using all the possible manipulated variables that have a dynamic model for a certain CV to correct the error in the predicted target value. This can be seen as one of the advantages of the MMPC. Sometimes this is a feature that should be avoided in practise. In the paper machine case if the controller has been constructed in a straightforward way the full-scale controller includes the following models in a way or another; thick stock flow to moisture and steam pressure to moisture.

When the steam pressure hits the constraint the MMPC will use the thick stock to correct the possible problem in moisture which will ruin the dry basis weight performance. This is a situation which is not allowed in a normal paper machine in most cases.

There are at least the following possibilities how to solve the situation:

- Divide one MMPC to two separate MMPCs or
- Use different models for prediction and control or
- Remove the interacting model temporarily from the MIMO model matrix during a special situation e.g. if the MV in question hits the hard limit.

Moisture is a special variable in the sense that there is only one-way coupling from wet-end variables thick stock flow, filler flow and retention aid flow to dry-end moisture but no coupling backwards from steam pressure to wet-end related variables dry basis weight, ash proportion or white water consistency. Now it is easy to separate the moisture part to a separate dry-end MMPC and use the predictions of the wet-end manipulated variables as a feed-forward in the dry-end controller.

The other possibility is to use different models during prediction and control action calculation means that all the models are in use when calculating the base prediction. After that when the actual control action part of the algorithm is executed, the gains of the coupling models are switched to pure zero, which makes them non-active from the penalty function point of view. The result is that the prediction is a full-scale including all the MVs but control actions use only those MVs that are allowed to use for a certain CV.

### Different Delays

Especially during GC there is one special situation when the MMPC can make unwanted actions because of the multivariable nature of it. Say e.g. there are two CVs C and D whose preferred MVs are respectively A and B. If the model B $\longrightarrow$ C has a shorter time delay than the main MV model A $\longrightarrow$ C and if the dynamic part of the (B,C)-model is included in the prediction horizon the only possible MV to be used for that part of the horizon in control is B. It is not easy to predict the controller behaviour in that kind of situation.

# Chapter 7

# Mass-flow Measurement and Speed Interaction

Mass-flow based measurements have certain advantages instead of the more obvious direct quality measurements. The transformed measurements make it possible to leave out the machine speed from the actual controller by importing the speed only indirectly there as mass-flow target trajectories. Then during constant speed there are no special problems when using mass-flow based measurements.

The grade change includes often also machine speed change. Especially the purpose of the so-called coordinated speed change is to change the machine speed, which actually is the production rate change. Both GC and coordinated speed change lead always to a situation where there is a contradiction between the mass-flow coming in the drying section and the mass-flow that comes out of it.

## 7.1 Speed Induced Disturbance

The difference in the mass-flow is determined by the dry end delay and the relative speed change rate. The input mass-flow at time $t$ can be calculated as

$$Q_{in}\left(t\right) = W_W\left(t\right) \cdot B_{d\_W}\left(t\right) \cdot S_W\left(t\right) \tag{7.1}$$

The corresponding mass-flow that comes out at the reel at time $\left(t + \tau_{d\_DE}\right)$ after the dry-end delay is

$$Q_{out}\left(t + \tau_{d\_DE}\right) = W_R\left(t + \tau_{d\_DE}\right) \cdot B_{d\_R}\left(t + \tau_{d\_DE}\right) \cdot S_R\left(t + \tau_{d\_DE}\right) \tag{7.2}$$

If we ignore the CD-shrinkage and MD-elongation effects (from the MD-controls point of they cancel each other in mass-flow calculations for dry matter) and notice that the dry basis weight which is formed at the forming section stays constant through the drying section, by setting

$$W_R\left(t+\tau_{d\_DE}\right) = W_W\left(t\right) \tag{7.3}$$

$$S_W\left(t\right) = S_R\left(t\right) \tag{7.4}$$

$$B_{d\_R}\left(t+\tau_{d\_DE}\right) = B_{d\_W}\left(t\right) \tag{7.5}$$

we get

$$Q_{out}\left(t+\tau_{d\_DE}\right) = W_W\left(t\right)\cdot B_{d\_W}\left(t\right)\cdot S_W\left(t\right)\left(t+\tau_{d\_DE}\right) \tag{7.6}$$

Measured mass-flow out of the drying section is equal to the mass-flow into the drying section only if $S\left(t+\tau_{d\_DE}\right) = S\left(t\right)$, i.e. there is no speed change.

The measurement problem of (7.1) and (7.6) could be possibly solved introducing a special form of target trajectory which takes into account the speed change effect along time. Another way to handle this is to compensate mass-flow measurement by the speed-ratio between the starting point of mass-flow path and the one at the reel. The idea is based on the following restructuring of the mass-flow process model. During stable situation the delay part of partial dry mass-flow process model can be concentrated in one unit, which form is normally used with the model based controllers. This is shown in Figure 7.1, where the transfer function $D_{TOT}$ represents all of the delays gathered together and $G_{TOT}$ represents the dynamic part of the response.

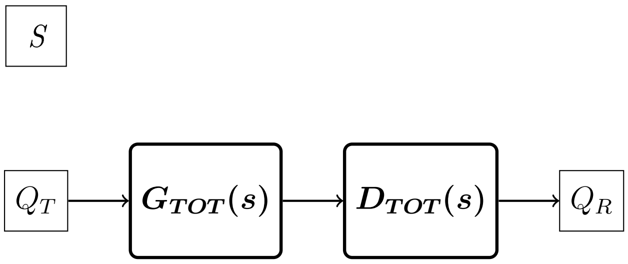

**Figure 7.1:** Constant speed situation.

The model can be divided in the following representation in Figure 7.2, which is equivalent to the one in Figure 7.1 during stable speed situation.

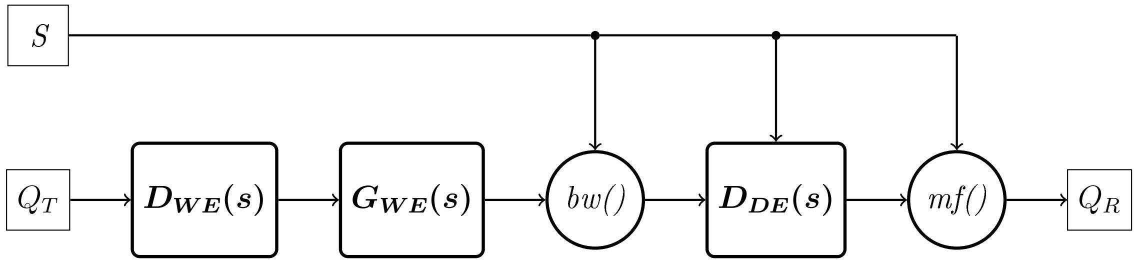

**Figure 7.2:** Equivalent structure

The total delay has been split in the wet-end part $D_{WE}$ and dry-end part $D_{DE}$. The block *bw( )* represents the mass-flow transformation to dry basis-weight and *mf( )* the transformation backwards to mass-flow:

$$bw(\,) = \frac{Q_d}{W \cdot S} \quad \text{and} \quad mf(\,) = W \cdot B_d \cdot S \tag{7.7}$$

From the controller point of view the same value of mass-flow that goes into the block $D_{DE}$ has the value that should come out of the block after the delay because the gain is unity. If the controller doesn't get any information about the speed change except possibly the mass-flow target value change the measurement has to be transformed to be invariant of the speed change. In the previous block diagram the measurement value that the controller expects can be calculated when the history of the speed values is stored and the active dry-end delay is known.

The basic formula that ties together the speed, the dry-end delay and the length of the drying section web is given as

$$L_{DS} = \int_{t_0}^{t_0+\tau_{d\_DE}} s(t)dt \tag{7.8}$$

By solving the value $\tau_{DE}$ in this the integral, which corresponds to the length of the web in the drying section, $L_{DS}$, the effective delay at a certain time $t$ is known. Figure 7.3 shows the compensation added in the process model.

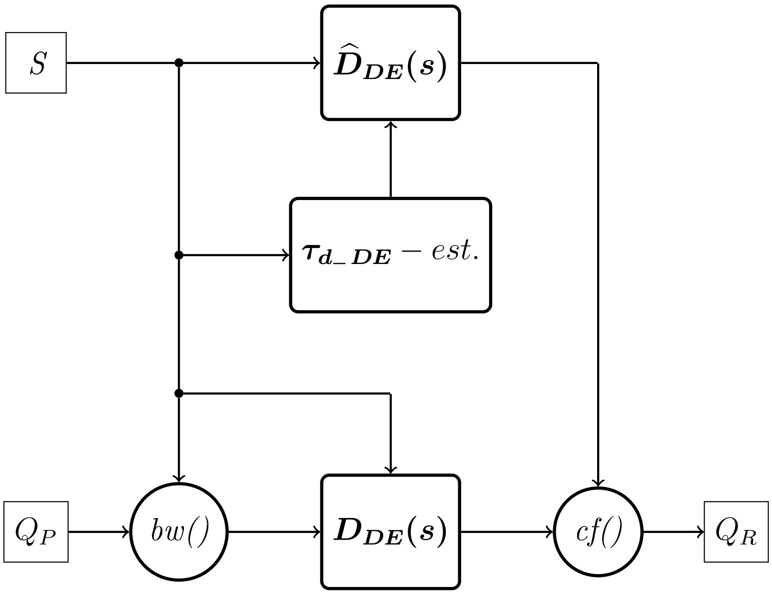

**Figure 7.3:** Compensated measurement.

The delay estimation utilises Equation (7.8). The block *cf( )* represents the final mass-flow measurement compensation (7.9)

$$cf(\,) = k_{comp} \cdot W \cdot B_d \cdot S \tag{7.9}$$

where $k_{comp}$ is the compensation gain.

By using the delay information from (7.8), the relation between the input- and output mass-flows (7.10) and their equations (7.1) and (7.6) the compensation gain for the dry mass-flow measurement can be calculated (7.11). Equation (7.12) shows the form that can be used for the present time instead of future time. After this compensation the measured mass-flow corresponds to the mass-flow that was present at the wire, when that point of the paper web left the wire section.

$$k_{comp}(t + \tau_{d\_DE}) \cdot Q_{out}\left(t + \tau_{d\_DE}\right) = Q_{in}\left(t\right) \tag{7.10}$$

$$k_{comp}(t + \tau_{d\_DE}) = \frac{S(t)}{S(t + \tau_{d\_DE})} \tag{7.11}$$

$$k_{comp}(t) = \frac{S(t - \tau_{d\_DE})}{S(t)} \tag{7.12}$$

### Compensation Case During GC

The required compensation gain depends on the drying section delay and relative speed change. Figure 5.18 in Section 5.2.2 shows in addition to the slice opening and speed change effects how the compensation gain changes during GC. The active gain effect for the control can be seen on both the total thick stock flow and main steam pressure as downward movements opposite to the upward movement in compensation gain.

## 7.2 Scanning Measurement

At speed change both the speed and the mass-flow in question can be assumed to change as a linear ramp in time during the scan period. The MD-measurement is an average of fast measurement samples from the scan period. The result is equivalent to a half point value between the end-points of the scan if the measurement change is linear in time, see Figure 7.4. If very precise performance is required the speed measurement should be handled in a similar way as the corresponding scanned quality measurement.

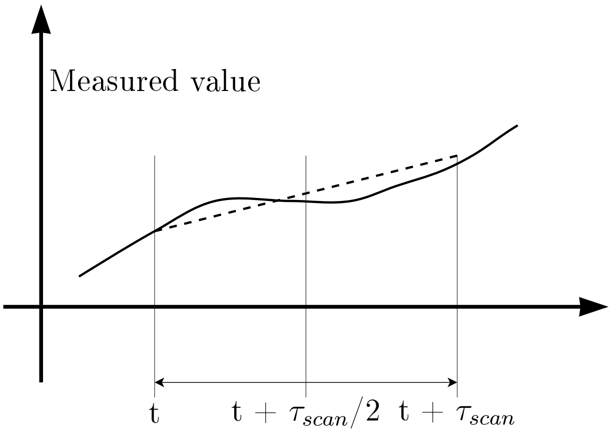

**Figure 7.4:** Linear change approximation.

One possibility would be to use a suitable first order low-pass filter, but a simpler way as the speed for the compensation is to add there scan-time related delay in the total delay (7.13). The value of middle point of a linear ramp during scanning period corresponds to the average of the values during the same time.

$$\tau_{comp} = \tau_{d\_DE} + \frac{\tau_{scan}}{2} \tag{7.13}$$

The scan-block for speed in Figure 7.5 reduces in this way to an additional delay in speed measurement.

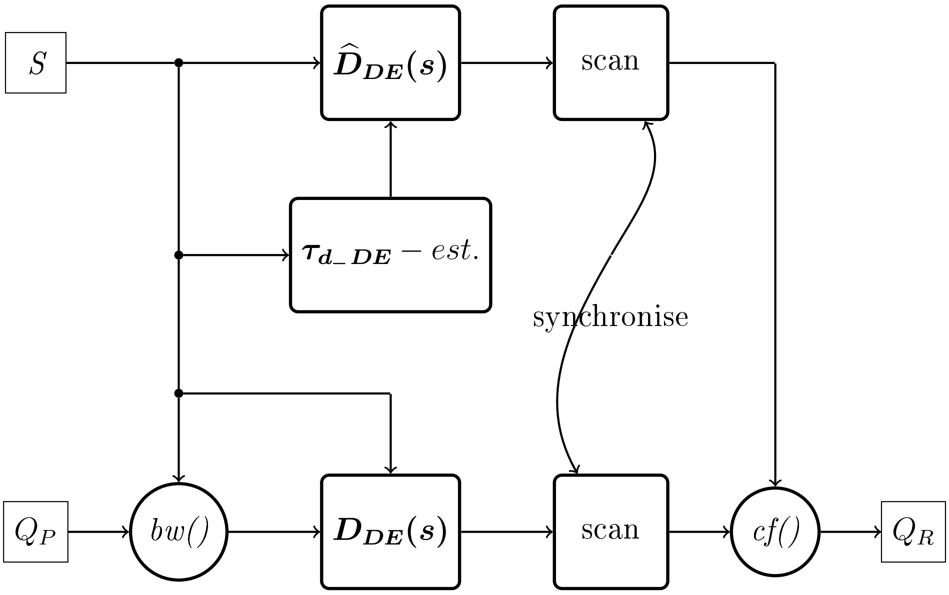

**Figure 7.5:** Compensation with synchronisation.

## 7.3 The Moisture

The proposed mass-flow compensation method is useful as such for any kind of dry material (fibres, fillers) whose basis weight portion does not change in the drying section which is a pure mass transfer between two points. The moisture is more complicated, because the actual mass-flow change changes also the evaporation conditions. Still the same principle is useful in compensation but only partly as it has been seen in Section 5.2.2.

# Chapter 8

# Head-box Flow Change

As we have seen already in simulations (5.2.3) and (5.2.4), either machine speed change through J/W-control or the slice lip opening change can cause a remarkable mass-flow disturbance from the head-box to the wire. This will be seen as a disturbance also in dry basis-weight and moisture. It is a most typical situation as the head-box flow changes during grade change. The mass-flow disturbance could be decreased by suitable head-box pressure manipulation, but this will cause an error in the J/W-ratio.

The calculation model of the the head-box mass-flow disturbance is derived in this chapter. This model is then used as a non-linear external prediction in model predictive controller. The compensation method utilises thick stock flow actions and their predictions given by the controller in an iterative manner to minimise the disturbance. The key idea is to manage the mass-flow during the predicted head-box flow change. The resulting controller doesn't disturb the J/W-control but can still compensate the mass-flow disturbance.

## 8.1 Static Mass-flows

Figure 8.1 depicts the main flows in short circulation.

For the disturbance calculation purposes it can be assumed that the reject flow from screens $F_S = 0$ (the flow is small) as well as the by-pass flow $F_B = 0$ (the by-pass flow is small and arrives back in the approach system). Most of the press section flow arrives also back in the white water but a small part of the flow continues to drying section. From the following calculation point of view $F_P = 0$. From these it follows also that $F_H = F_M$. The flow to long circulation $F_L$ can be assumed to be equal to the thick stock flow $F_T$ in a stable situation i.e. the amount flow that arrives in the short circulation has to leave from there also.

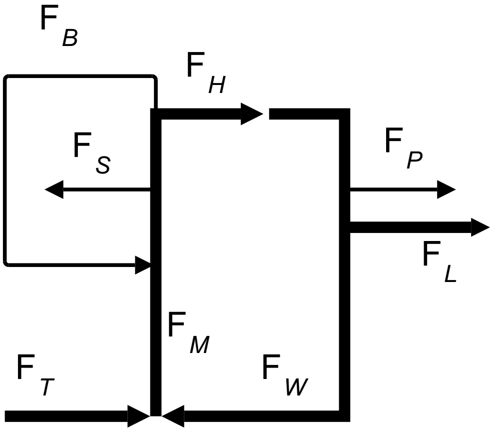

**Figure 8.1:** Short circulation flows.

The dry mass-flow output from the wire is determined by the mass-flow at the head-box and retention. The dry mass-flow is almost equal to the mass-flow at the reel because there is only negligible outflow of the fibres and fillers in the press section, where most removal is water.

$$Q_{d\_H} = \frac{Q_{d\_P}}{R_d} = \frac{Q_{d\_R}}{R_d} \tag{8.1}$$

$$Q_{d\_H} = B_{d\_H} \cdot S_H \cdot W_H = F_H \cdot C_H \tag{8.2}$$

also

$$Q_{d\_H} = B_{d\_H} \cdot S_H \cdot W_H = \frac{B_{d\_W} \cdot S_W \cdot W_W}{R_d} = \frac{Q_{d\_P}}{R_d} \tag{8.3}$$

As we can see, the basis weight depends on the machine speed. Assuming that the J/W-control is working properly, an ideal situation, the head-box jet-speed follows machine speed.

$$S_H = J \cdot S_W \tag{8.4}$$

The head-box flow depends on the wire speed (normally it is the same as machine speed), slice lip opening and web width. From (8.2) - (8.4) we get the head-box consistency making a practical assumption $W_H = W_W$, which is adequate for disturbance calculation, but not for static mass-balance. Therefore

$$C_H = \frac{B_{d\_W} \cdot S_W \cdot W_H}{F_H \cdot R_d \cdot J} \tag{8.5}$$

At the mixing point

$$F_H = F_T + F_W \tag{8.6}$$

$$C_M = \frac{F_T \cdot C_T + F_W \cdot C_W}{F_H} \tag{8.7}$$

When there are no changes, then

$$C_H = C_M \tag{8.8}$$

The white water consistency can be calculated from head-box mass-flow and retention:

$$C_W = \frac{F_H \cdot (1 - R_d) \cdot C_H}{F_H - F_T} \tag{8.9}$$

For simple speed changes (no slice opening changes or basis weight changes allowed), it is possible to formulate a direct calculation for thick stock flow compensation. The idea is to keep the mixing point consistency constant during the change. When (8.7) is valid, then the mass-flow change is proportional to the speed change and the basis weight stays also constant.

The required thick stock flow is then

$$F_T = \frac{F_H \cdot (C_H - C_w)}{C_T - C_W} \tag{8.10}$$

Because $F_H$ follows the machine speed by (8.14) and the consistencies $C_H$ and $C_W$ can be calculated either by using measured or assumed retention $R_d$. In practise a simplified implementation works well enough even if the values calculated in the beginning of the change for the consistencies $C_H$ and $C_W$ are kept constant.

## 8.2 Disturbance Prediction

The mass-flow at the head-box can be calculated by the present head-box flow and delayed consistency at the mixing point

$$Q_{d\_H}(t) = F_H(t) \cdot tf\,(C_M(t - t_H)) \tag{8.11}$$

where $tf\left(C_M(t)\right)$ is the mixing point consistency at the head-box after head-box approach piping pure dynamic response without the plug-flow part in it.[1].

E.g. the following simple transfer function is adequate in practise to describe the required dynamic part of the disturbance calculation in place of $tf\left(\right)$:

$$G(s) = \frac{1}{1 + s \cdot \tau_H} \tag{8.12}$$

If head-box flow change is small the mixing consistency after dynamics can be approximated as

$$tf\left(C_M(t - t_H)\right) \approx \frac{1}{F_H(t - t_H)} \cdot tf\left(F_T(t - t_H) \cdot C_T + F_W(t - t_H) \cdot C_W(t - t_H)\right) \tag{8.13}$$

The flow in the head-box is related to the geometry of head-box opening and machine speed because of the controlled J/W-ratio:

$$F_H = k_c \cdot S_H \cdot H \cdot W = k_c \cdot J \cdot S_W \cdot H \cdot W_H \tag{8.14}$$

The constraction coefficient $k_c$ value has been assumed to be 1 in the following equations. From (8.11) and (8.13) by taking into account that; $Q_T(t-t_H) = F_T(t-t_H) \cdot C_T(t-t_H)$, assuming $C_T(t) = C_T(t-t_H)$ and also that the thick stock flow does not affect the head-box flow this becomes

$$Q_{d\_H}(t) = \frac{F_H(t)}{F_H(t - t_H)} \cdot tf\left(Q_T(t - t_H) + F_W(t - t_H) \cdot C_W(t - t_H)\right) \tag{8.15}$$

Adding the dependencies from (8.14) we get

$$Q_{d\_H}(t) = \frac{J(t) \cdot S_W(t) \cdot H(t) \cdot W_H(t)}{J(t - t_H) \cdot S_W(t - t_H) \cdot H(t - t_H) \cdot W_H(t - t_H)}$$

$$\cdot tf\left(Q_T(t - t_H) + F_W(t - t_H) \cdot C_W(t - t_H)\right) \tag{8.16}$$

The following assumptions can be done in practise:

---

[1] The dynamics between the mixing point and the head-box actually consists of successive delays and first order responses in a real paper machine and in the simulation model.

$$J(t) = J(t - t_H) \tag{8.17}$$
$$W(t) = W_H(t - t_H) \tag{8.18}$$
$$C_T(t) = C_T(t - t_H) = C_T \tag{8.19}$$

Using these we get the simplified equation

$$Q_{d\_H}(t) = \frac{S_W(t)}{S_W(t - t_H)} \cdot \frac{H(t)}{H(t - t_H)} \cdot tf\left(Q_T(t - t_H) + F_W(t - t_H) \cdot C_W(t - t_H)\right) \tag{8.20}$$

This can now be expressed in prediction form

$$\widehat{Q}_{d\_H}(t) = \frac{\widehat{S}_W(t)}{\widehat{S}_W(t - t_H)} \cdot \frac{\widehat{H}(t)}{\widehat{H}(t - t_H)} \cdot tf\left(\widehat{Q}_T(t - t_H) + \widehat{F}_W(t - t_H) \cdot \widehat{C}_W(t - t_H)\right) \tag{8.21}$$

This can be further simplified by using the following assumptions after which the prediction consists only of predetermined parts and quality controller given action predictions and their history. When the retention is high then as a consequence the wire pit consistency is very low:

$$R_d \approx 1,\ C_W \approx 0 \tag{8.22}$$

then

$$\widehat{Q}_{d\_H}(t) = \frac{\widehat{S}_W(t)}{\widehat{S}_W(t - t_H)} \cdot \frac{\widehat{H}(t)}{\widehat{H}(t - t_H)} \cdot tf\left(\widehat{Q}_T(t - t_H)\right) \tag{8.23}$$

In a simpler form

$$\widehat{Q}_{d\_H}(t) = R_S(t) \cdot R_H(t) \cdot tf\left(\widehat{Q}_T(t - t_H)\right) \tag{8.24}$$

where

$$R_S(t) = \frac{\widehat{S}_W(t)}{\widehat{S}_W(t - t_H)} \text{ and } R_H(t) = \frac{\widehat{H}(t)}{\widehat{H}(t - t_H)} \tag{8.25}$$

| | |
|---|---|
| $R_S(t)$ | Delayed machine speed ratio, where the prediction is the machine speed controlled by the control system where timing is determined by the GC timing and known beforehand, $t = 1 \ldots N$. |
| $R_H(t)$ | Delayed slice opening ratio, where the prediction is the slice opening controlled by the control system where timing is determined by the GC timing and known beforehand, $t = 1 \ldots N$. |
| $tf\left(\widehat{Q}_T(t - t_H)\right)$ | Delayed thick stock mass-flow prediction fed through the transfer function (8.12). The prediction is the thick stock mass-flow prediction from the predictive paper quality controller, $t = 1 \ldots N$. |

For a more correct prediction it would be possible to use directly (8.21) by predicting head-box flow from machine speed and that way also flow to the wire pit. The consistency value could be kept constant using the calculated starting point value as the predicted consistency value. For high retention values the simple version (8.23) seems to be accurate enough for disturbance compensation purposes.

## 8.3 Handling Fillers

The filler handling for the head-box flow changes is more complicated because of much lower filler retention, filler feed both from the actual filler flow but also with the thick stock.

By using the principles of the Section 8.2, it possible to construct also a predictor for ash during head-box flow changes. There are anyhow problems in utilising this in practise. The thick stock flow ash consistency can vary a lot, but it is measured quite rarely. The filler retention is measured more often, which should be taken into account in the disturbance prediction. A proper common dynamic model for the head-box-flow-induced filler disturbance is not normally available. In practise some kind of combination of the filler to paper ash and thick stock to paper ash models should be considered. Normally there is no model of how pure fibres affect the dry mass-flow but the model includes the whole response of thick stock flow change including filler. When handling the fillers, the fibres should be taken into account also separately. The disturbance calculation is not as useful in the case of high ash paper machines compared to low ash machines, because both speed and slice changes are relatively small. On the other hand, the importance of the separate filler disturbance handling in low ash machines, is small.

## 8.4 Non-linear Disturbance for MPC

### 8.4.1 Disturbance Calculation

The head-box flow change, either caused by a change in slice lip opening or as a consequence of changing machine speed, can produce a big disturbance mainly in dry basis-weight and moisture. If the control system is traditional i.e. the ash proportion is controlled using direct ash percentage as a measurement, the disturbance in ash proportion could be small. The reason is that, when the head-box flow changes, the proportions of different components in the suspension do not change. When mass-flow based measurement is used, also the ash control is disturbed by causing unnecessary control actions. Still the filler mass-flow change as a disturbance affects the drying properties of paper disturbing moisture control in both cases.

The previous sections showed equations how to construct the disturbance prediction when the following predetermined values and predictions are known: machine speed, slice opening and thick stock flow or thick stock mass-flow. Also if white water consistency prediction is available (in the case of high ash content), it could be used in the disturbance prediction. The next step is to connect the prediction to the multivariable MPC.

### 8.4.2 Disturbance in MPC

As presented earlier the typical MPC penalty function is a starting point for the actual control actions calculation. The first step of most of the MPC control algorithms is to make the base deviation prediction $\hat{\boldsymbol{\varepsilon}}(i)$ using assumption $\Delta\hat{\boldsymbol{u}}(j) = 0,\ j = 1 \ldots N$ i.e. the open loop free response without control actions. An example of such a control algorithm is presented in [Tia95]. If the algorithm does the prediction explicitly then the actual control principle does not limit the methods of forming the base future prediction as a combination of the controller internal linear prediction with any externally calculated either linear or non-linear disturbance. Another requirement for the MPC to be utilised with the method proposed here is that the controller can give the MV action predictions out explicitly.

The basic error prediction from free response is given as

$$\hat{\boldsymbol{\varepsilon}}(i) = \hat{\boldsymbol{z}}(i) - \boldsymbol{r}(i),\ i = 1 \ldots N \tag{8.26}$$

where:

$\hat{\boldsymbol{\varepsilon}}(i)$ = error prediction between the target trajectory and the CV prediction in the future at time $i$,

$\hat{\boldsymbol{z}}(i)$ = process CV prediction in the future at time $i$ without future MV actions and

$\boldsymbol{r}(j)$ = reference trajectory in the future at time $i$.

This can be expressed in the following form when an external disturbance is included

$$\hat{\boldsymbol{z}}(i) = \hat{\boldsymbol{z}}_{\boldsymbol{u}}(i) + \hat{\boldsymbol{z}}_{\boldsymbol{d}}(i),\ i = 1 \dots N \tag{8.27}$$

where

$\hat{\boldsymbol{z}}(i)$ = base CV prediction in the future at time $i$ without the impact of predicted future MV actions,

$\widehat{\boldsymbol{z}_{\boldsymbol{u}}}(i)$ = process CV free response prediction in the future at time $i$ based on MV action history and

$\widehat{\boldsymbol{z}_{\boldsymbol{d}}}(i)$ = external disturbance prediction in the future at time $i$.

The disturbance compensation principle structure is depicted in Figure 8.2 including as an example the previously discussed future machine speed and slice opening target trajectories where

$[r(t+1)\dots r(t+N)]$ = CV target trajectory in the future at time $t=0$,

$y(t)$ = the present CV measurement value,

$[s(t+1)\dots s(t+N)]$ = machine speed target trajectory in the future at time $t=0$,

$[h(t+1)\dots h(t+N)]$ = slice opening target trajectory in the future at time $t$=0,

$\left[u\widehat{(t+1)}\dots u\widehat{(t+N)}\right]$ = MV prediction at time $t=0$ and

$\left[d\widehat{(t+1)}\dots d\widehat{(t+N)}\right]$ = external DV prediction at time $t=0$.

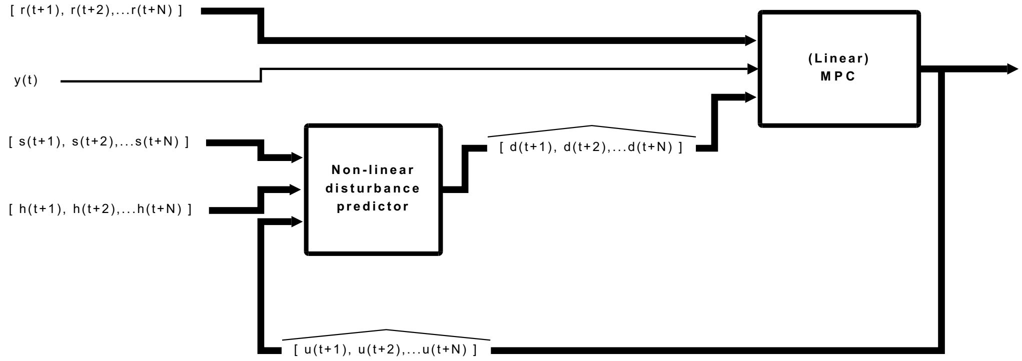

**Figure 8.2:** Disturbance compensation with MPC.

The disturbance cancellation algorithm for changes:

1. Assume relatively stable starting conditions in the process.
2. Introduce at time $t_0$ the predetermined disturbance trajectories, (time value)-points.
3. Calculate the external non-linear disturbance predictions based on the predetermined trajectories and the present MPC control action predictions (from the previous execution) using the result 8.24 for each future point in time.[2]
4. Execute the MPC algorithm with the external prediction included corrective action prediction to decrease the disturbance effect.
5. Shift the target trajectories one element forward.
6. Go back to 3.

As can be noticed the algorithm is based on successive executions of the DISTURBANCE CALCULATION $\Longrightarrow$ MPC -pair. To really decrease the disturbance this requires more than one execution cycle before those predetermined disturbances occur to get useful results. The reason is the iterative nature of the solution, which suggests new control action predictions to decrease the deviation and calculates new disturbance prediction.

In the case of totally non-linear MPC there might be possibilities to avoid certain part of the required execution cycles in advance, but the process delays have still to be taken into account in advance.

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[2] This iterative compensation structure is not limited to this special case but the disturbance can be anything that can be expressed by using either MV or CV predictions.

### 8.4.3 Disturbance Compensation Simulation

#### Principle

The simulation environment in the disturbance simulation was the same APMS simulator that was used in the response simulations in Chapter 5. This time also the paper quality controller was active controlling dry basis-weight and moisture. The head-box flow disturbance compensation prototype was using the principle described above but also the mass-flow measurement speed-compensation described in Chapter 7 was in use. The prototype was implemented as an addition to the standard IQWetendMD quality control package with grade change. The speed change control and the internal mass-flow target calculations were using the standard grade change package but in this case only for production rate change. The reason to investigate the behaviour by production rate change is to see more clearly the performance than in the case of a grade change including basis-weight change.

The disturbance prediction model was based on the ideas in Chapter 7. The dry mass-flow disturbance prediction was using the transfer functions $G_{WE}$ and $D_{WE}$ in the head-box flow dry mass-flow disturbance calculation according to Figure 7.2. The rest of the model $D_{DE}$ is straightforward, because there is no change in the dry basis-weight in the drying section but pure delay.

To utilise the idea in moisture disturbance the total dynamic part of the disturbance was taken from thick stock mass-flow to water (paper moisture) mass-flow transfer function. The only problem is that this dynamics should be separated in two parts: the mass-flow dynamics of the head-box flow change and the dynamics in the drying section. When the thick stock flow to paper water transfer function is available the dynamics should be seen as a series of those two dynamics from where the drying section part should be separated.

The practical problem in the simulation system process transfer functions given in Appendix B.1, Table B.1 is that the time constant in both the thick stock flow to dry mass-flow and water-mass-flow transfer functions is almost the same. This would mean that the time constant of the drying section part would be very small. It seems anyway that this could be realistic in real paper machines, because the response shapes observed after slice opening changes are very sharp also in moisture without almost any smoothing. In this simulation the small time constant value was not used in prediction but the time constant value was 50 s, which was shown also as weaker compensation performance in moisture than in dry basis-weight.

#### Results

Table 8.1 shows the disturbance peak values when simulating the speed-change generated disturbances. The table shows simulation results of cases P1 and P2 when the disturbance cancellation was passive and the cases A1 and A2 correspond to active cancellation. The speed-change test case is described by:

- Speed change 880 - 930 m/min (or vice versa)
- Speed change rate 10 m/$min^2$
- Dry basis weight set-point 81.6 g/$m^2$
- Moisture set-point 4 %

The controller was using the models in Table B.1.

**Table 8.1:** Peak values in simulation.

| Case: | P1 | P2 | A1 | A2 |
|---|---|---|---|---|
| OD peak-peak weight at wire | 81.2 - 83.6 | 80.8 - 83.3 | 81.6 - 82.6 | 81.9 - 82.6 |
| OD at wire pp range | 2.4 | 2.5 | 1.0 | 0.7 |
| Head-box consistency | 9.35 - 9.6 | 9.29 - 9.55 | 9.37 - 9.48 | 9.41 - 9.49 |
| HB cons. pp range | 0.25 | 0.26 | 0.11 | 0.08 |
| OD weight at scanner | 80.55 - 82.9 | 80.9 - 82.5 | 80.9 - 81.9 | 81.2 - 81.9 |
| OD at scanner pp range | 2.35 | 2.6 | 1.0 | 0.7 |
| Water mass-flow at D7 | 0.486 - 0.585 | 0.458 - 0.547 | 0.483 - 0.544 | 0.480 - 0.575 |
| Water mass-flow pp range | 0.099 | 0.089 | 0.061 | 0.095 |
| Moisture at scanner | 3.74 - 4.42 | 3.62 - 4.22 | 3.87 - 4.14 | 3.72 - 4.26 |
| Moisture pp range | 0.68 | 0.60 | 0.27 | 0.54 |
| Time constant factor | - | - | 0.5 | 1.0 |

As an example from the cases Figure 8.3 shows simulation without the head-box disturbance compensation, case P1. The second Figure 8.4 shows the active compensation case A2.

### Comments on Active Compensation Cases

Figure 8.4 shows the compensation case A2 where the dry basis weight disturbance is smaller. From the moisture point of view the other case A1 would be better because in the second case the moisture disturbance is almost as big as in the non-compensated case. The most likely reason to this is too long a time constant used in the drying section model for moisture discussed already in the beginning of this section.

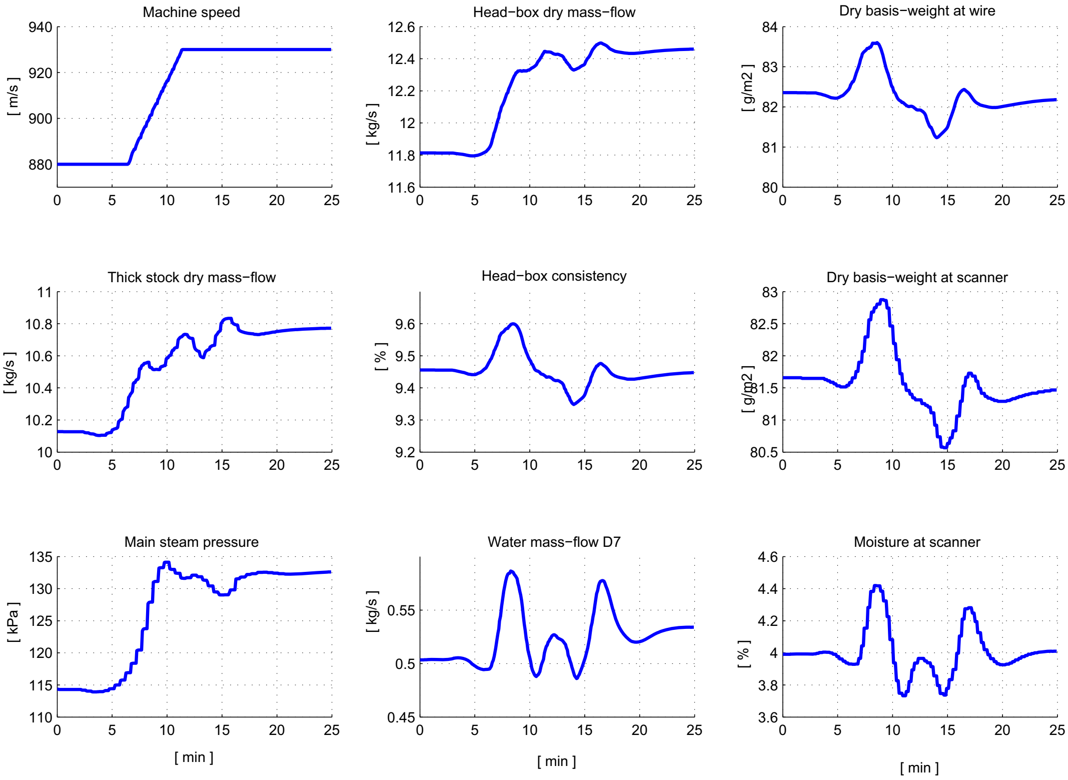

Figure 8.3: Without compensation - case P1

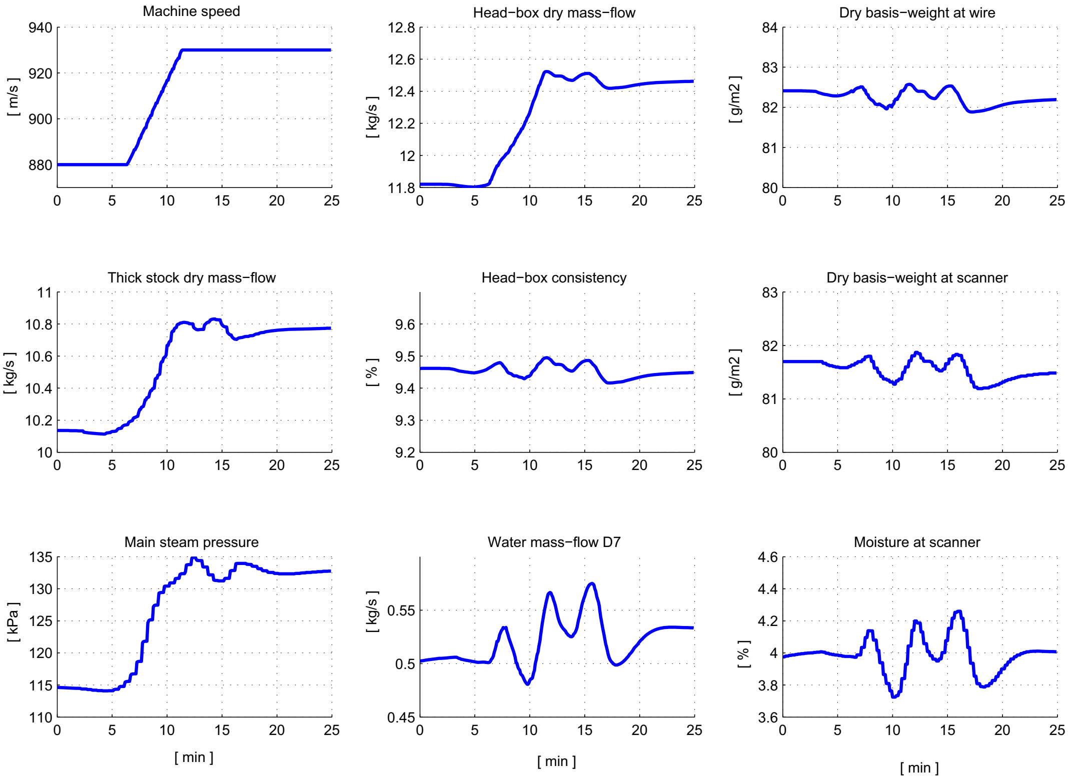

Figure 8.4: Compensation active- case A2.

# Chapter 9

# Conclusions

### Results

In this thesis, the closed-loop control of paper machine grade changes has been discussed. All of the principles and ideas about closed-loop control were based on the utilisation of a multivariable predictive controller. The examples from both simulations and production machines were using a certain type of model predictive controller but the principles should be general enough to be utilised with almost any kind of predictive controller.

The grade change in its simplest form could be just a set-point change of the quality variables. Even in that case better performance can be achieved by giving the set-point changes to the predictive controller in advance in the form of trajectories. The situation is more challenging if the grade change requires also either a machine speed change or a machine speed change with a production rate change. In this, case the operating point moves resulting in process dynamics change, but in more importantly it generates mass-flow disturbances in the process. The thesis includes analysis of these disturbances and proposes solutions how to minimise their effect in control performance during grade change.

Paper machine internal behaviour after a change in the manipulated variables was first explained in more detail than the typical black-box type models used during closed-loop control. That information is used as a basis for designing a compensation calculation method when mass-flow changes during machine speed or head-box flow changes.

Different type of grade change classes were described along with their partly contradicting requirements. Also, which kind of grade change is useful for which situation was explained.

Some of the problems of the open-loop control were demonstrated with simple simulation examples. One of the key points from control maintenance point of view is the model parameter accuracy. Model mismatch limits the performance of the pure open-loop control, one good reason for favouring closed-loop-based grade change management.

The internal behaviour of the drying section was also studied with several specially chosen test cases to show that the idea of using similar compensation calculation that was proposed for dry mass-flow for speed-changes is sound. This is however only a partial compensation but in the right direction. One of the important results of the simulations shows that the alignment of slice-opening change with the machine speed change results in smooth process behaviour to be utilised under closed-loop control. A case at a production machine where the slice opening was operated manually confirms the simulation result.

The multivariable model predictive-based closed-loop grade change controller principles were described. The controller includes mass-flow based future target trajectories whose present and target values were determined from the actual grade targets in typical paper quality units which were then transformed to internal mass-flow representation. Timing of the result trajectories were based on predetermined machine speed change ramp timing. Controller tuning parameter selection, prediction horizon mainly, was discussed.

Finally the usual disturbance in paper machine generated by the head-box flow change during either machine speed or slice opening change was studied. The derived non-linear disturbance prediction was utilised in a multivariable predictive controller which was able to compensate the disturbance by the thick stock mass-flow actions.

### Future research possibilities

During the previous two or three decades, there have been several articles on paper machine grade changes. So, is there anything left for further research?

When the measurement principles and accuracy are evolving, there is still something that could be done both at the wet-end and at the dry-end. There are some open areas at the wire section concerning the effect of changes in the vacuums for water-removal but also the effect in dry content removal and that way in the retention of fibres and fillers. After the wire section, the next question mark is the press. If the amount of water coming from the wire section is known more accurately and if better press models would be developed, the amount of water into the drying section would be known. For moisture disturbance prediction, this would be very useful. Utilising this information, the disturbance compensation would become easier. In principle it would be possible to use nip-press or -presses as active moisture control actuators.

The steam-cylinder-based drying section has still open issues making room for future research, maybe not so much from the model principle point of view but more from the practical control point of view. Drying models are DDE-models including hundreds of parameters in principle. The next step when trying to reach better control performance for the paper moisture control is the simplification of these models into a form that it is possible to get an accurate enough model for control purposes by a simple and practically implementable process test. The measurements in the drying section area represent another weak point except for the lately moisture measurement possibilities after the press section. In a typical steam-based drying section it is not possible to measure the energy balance very well. There is normally not enough instrumentation in the condensate area to do this reliably.

The problem of water mass-flow disturbance in the drying section generated by the machine speed change was solved only partially. If the drying section modelling procedure evolves to a form that can be implemented in practise, better disturbance handling methodology will be required. It may also be useful to derive filler disturbance model generated by the head-box flow in an implementable form if the changes in high-ash machines tend to speed-up.

One important area of research outside of the paper machine is impact of the stock composition and refining on both the wet-end but especially the drying section behaviour. This would require at least a thorough process study under different operating conditions individually in each machine. However, as the costs of any kind of process test and modelling in customer projects is a limiting factor, the only practically acceptable way to do this would be some kind of automatic or semi-automatic modelling. Automatic or partly automatic modelling utilising data from normally running machines would be the only useful option also in developing better drying section models.

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# Appendix A

# Production machines

## A.1 Production machine A

Here are some typical production values of the customer paper machine A. The machine produces LWC paper including an on-line sizing unit. The second drying section after the sizer is left out from the examples and also was not included in the application handled in this thesis. Some key values:

| | |
|---|---|
| Speed range | $1000 \cdots 1500$ m/min |
| Basis weight | $40 \cdots$ 90 g/m$^2$ |
| Ash | $12 \cdots$ 15 % |
| Web width | 8.7 m (at reel) |

The raw material is pure chemical pulp.

The transfer functions which were in used in the controller are presented in tables A.1 and A.2.

**Table A.1:** Process models of the machine A excluding moisture.

| $CV$ \ $MV$ | $Q_{d\_T}$ | $Q_{a\_T}$ | $F_A$ |
|---|---|---|---|
| $Q_{d\_R1}$ | $e^{-90s} \cdot \frac{1.1}{1+60s}$ | $e^{-165s} \cdot \frac{0.086}{1+285s}$ | $e^{-75s} \cdot \left(\frac{1}{1+95s} + \frac{-0.9}{1+850s}\right)$ |
| $Q_{a\_R1}$ | $e^{-80s} \cdot \frac{0.095}{1+200s}$ | $e^{-105s} \cdot \frac{0.055}{1+1050s}$ | $e^{-80s} \cdot \left(\frac{1}{1+90s} + \frac{-0.3}{1+1250s}\right)$ |
| $C_W$ | $e^{-10s} \cdot \frac{0.02}{1+300s}$, UR | $e^{-240s} \cdot \left(\frac{0.1}{1+420s} + \frac{0.18}{1+1300s}\right)$ | $e^{-215s} \cdot \left(\frac{-1.2}{1+300s} + \frac{-0.3}{1+1250s}\right)$ |

**Table A.2:** Moisture process models of the machine A.

| $MV$ \ $CV$ | $Q_{w\_R1}$ |
|---|---|
| $Q_{d\_T}$ | $e^{-90s} \cdot \frac{320}{1+60s}$ |
| $Q_{a\_F}$ | UR |
| $F_A$ | $e^{-100s} \cdot \left(\frac{230}{1+120s} + \frac{-240}{1+1500s}\right)$ |
| $P_D$ | $e^{-80s} \cdot \frac{-3.5}{1+65s}$ |

Note, the symbol UR in previous tables A.1 and A.2 means that the parameters in the model in question are unreliable and the controller does not use the model.

## A.2 Production machine B

Here are some typical production values of the customer paper machine B. The machine produces packaging board including an on-line coater. The board consists of three layers as well as three wire sections and head-boxes. The drying section after coater is controlled manually. Some key values:

| | |
|---|---|
| Speed range | $200 \cdots 400$ m/min |
| Basis weight | $200 \cdots 400$ g/m$^2$ |
| Coating | $30 \cdots 40$ g/m$^2$(proportion of the total basis weight) |
| Web width | 3.5 m (at reel) |

The raw material is mainly recycled fibre.

The transfer functions which were in used in the controller are presented in Table A.3.

**Table A.3:** Process models of the machine B.

| $CV$ \ $MV$ | $Q_{d\_T}$ | $P_D$ |
|---|---|---|
| $Q_{d\_R2}$ | $e^{-160s} \cdot \frac{1.15}{1+45s}$ | - |
| $Q_{w\_R1}$ | $e^{-150s} \cdot \frac{575}{1+60s}$ | $e^{-97s} \cdot \frac{-0.97}{1+120s}$ |
| $Q_{w\_R2}$ | $e^{-175s} \cdot \frac{575}{1+60s}$ | $e^{-106s} \cdot \frac{-.97}{1+120s}$ |

# Appendix B

# Control models used in APMS simulation

## B.1 APMS-models

The transfer functions which were used in the controller during closed-loop control simulations with APMS are presented in Table B.1. The controller included a full scale wet-end models but paper ash and white water consistency related parts were inactive during simulations, because both the filler and retention flows were kept in constant values.

**Table B.1:** Process models during APMS closed-loop simulations.

| $CV$ $MV$ | $Q_{d\_T}$ | $P_D$ |
|---|---|---|
| $Q_{d\_R}$ | $e^{-120s} \cdot \frac{0.95}{1+95s}$ | - |
| $Q_{w\_R}$ | $e^{-120s} \cdot \frac{200}{1+90s}$ | $e^{-65s} \cdot \frac{-7}{1+65s}$ |