Constrained Model Predictive Control For Cross Directional Applications-Some Practical Examples

A. Bellette, R. Vyse, J. Backstrom, T. Steele

The implementation of constrained Model Predictive Control to paper machine cross directional (CD) processes presents numerous technical challenges. The ability to optimize all the CD actuators to produce the most uniform CD profiles provides the economic incentive to implement these schemes. This paper will review some of the technical challenges, but will focus on the recent implementation of Cross-Directional MPC on several paper machines and off-machine supercalenders. Of specific interest will be outlining the improvements seen relative to what could be achieved using optimized "conventional" control schemes.

INTRODUCTION

The implementation of constrained Model Predictive Control to paper machine cross directional (CD) processes presents numerous technical challenges, but with some strong possible advantages. A few early academic studies have shown promising results [7], [8]. A review of customer needs have indicated the following challenges with their existing CD controls.

1. The CD controls, especially the advanced features, were difficult for operators to understand and use.

2. Difficulty utilising linerboard headbox actuators for both dry-weight and moisture profile control.

3. Difficulty co-ordinating multiple actuators controlling one sheet property. Most notably, co-ordinating multiple slice/dilution actuators for weight control and co-ordinating steam boxes and rewet showers for moisture control.

4. Speed increases and/or grade changes sometimes resulted in long transition periods before achieving steady state.

5. Actuator constraints (physical limitations) were handled in an ad-hoc way, resulting in sub-optimal performance when the process requires CD actuators to operate at their constraints.

6. Difficulty controlling the paper near the edges of the sheet due to the complexity of modelling different CD actuator responses for both the middle and edges of the sheet.

Challenge number 1 was addressed with the introduction of IntelliMap 3.0, a user friendly advanced tuning tool that allows the user to tune all components of a traditional CD control system, guaranteeing optimal trade-off between robustness and performance [9]. We also developed easy rules of thumb for evaluating CD controllabili--ty [10]. The next version of IntelliMap will extend its support of user friendly tuning to CD-MPC.

The remaining challenges are addressed by the new CD-MPC controller, and are discussed in the following sections.

WHAT IS CD-MPC AND HOW IS IT DIFFERENT FROM TRADITIONAL CD CONTROL?

CD-MPC is a multivariable model predictive controller used for optimal co-ordination of multiple CD actuator beams controlling multiple sheet properties. It uses a model of each actuator's effect on each sheet property and takes the physical limitations of the actuator explicitly into account when calculating new optimal actuator setpoints. This directly addresses challenges 2, 3 and 5 listed in the previous section as well as the more general problem of co-ordinating any number of CD actuator beams for minimising the CD variation in any number of sheet properties.

CD-MPC is a predictive controller and after each measurement scan it calculates optimal setpoints that will minimise *future predicted* variation in the sheet properties. This, together with gain and speed retune features, addresses challenge number 4 from the previous section.

CD-MPC uses a model with six parameters to describe the effect of each CD actuator in a CD actuator beam on each sheet property. It uses a time constant and a time delay to describe the *dynamic* response and a gain, width, divergence and attenuation to describe the *spatial* response. This allows each CD actuator in a CD actuator beam to have a unique process model, and directly addresses challenge number 6 listed in the previous section.

Traditional CD controllers can be divided into two different groups:

1. Each CD actuator in a CD actuator beam has its own dynamic controller focused on minimising the CD error for one sheet property for a particular CD zone. The spatial coupling between actuators in the same CD actuator beam is co-ordinated through spatial filtering of both the measurement and the calculated actuator setpoints [4]. It can be shown that this co-ordination strategy leads to optimal co-ordination of the spatial coupling [6] in the absence of active constraints.

2. One static CD controller per actuator beam, which explicitly handles the coupling between CD actuators when calculating near-optimal setpoints for minimising the variation in one sheet property. This controller also takes physical limitation on the actuators explicitly into account [3]. Note that this controller is static and ignores the process dynamics, resulting in no ability to reduce the residual CD variation [10].

Neither of these schemes was designed to handle the situation where one CD actuator affects several sheet properties. This is handled in an ad-hoc fashion, with some form of error splitting used to co-ordinate several CD actuator beams to minimise the CD variation in one sheet property. Conversely, some form of error blending is used when one wishes to minimise the sheet variation in several sheet properties utilising only one CD

* *Honeywell ACS Industry Solutions Vancouver Operations Pulp, Paper & Printing 500 Brooksbank Avenue North Vancouver, B.C. Canada V7L 3S4*

actuator beam. This ad-hoc approach typically results in difficulties in obtaining good co-ordination and overall performance, something that was also raised as a customer challenge in the previous section.

CD-MPC takes the best features from the two traditional CD controllers; taking both the spatial and dynamic process model into account, and explicit handling of actuator constraints. It also extends the scope of control from one CD actuator beam controlling one sheet property to multiple CD actuator beams controlling multiple sheet properties. This eliminates the need for ad-hoc co-ordination of actuator beams.

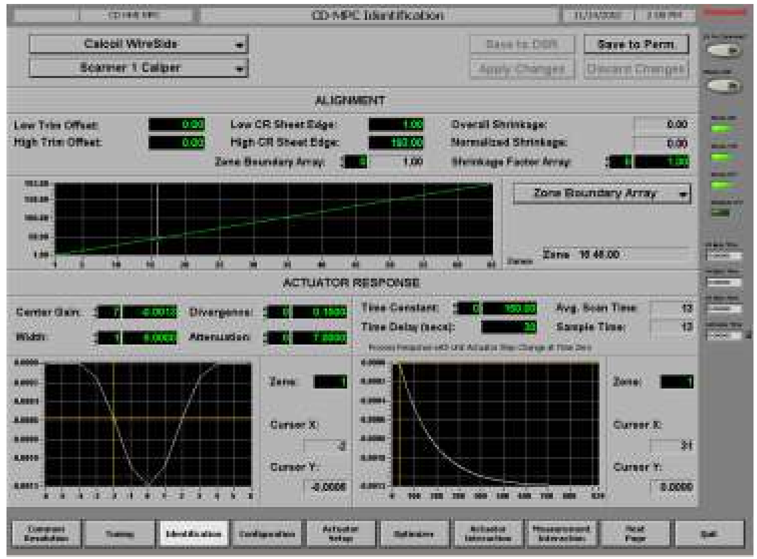

Figure 1: CD-MPC identification display.

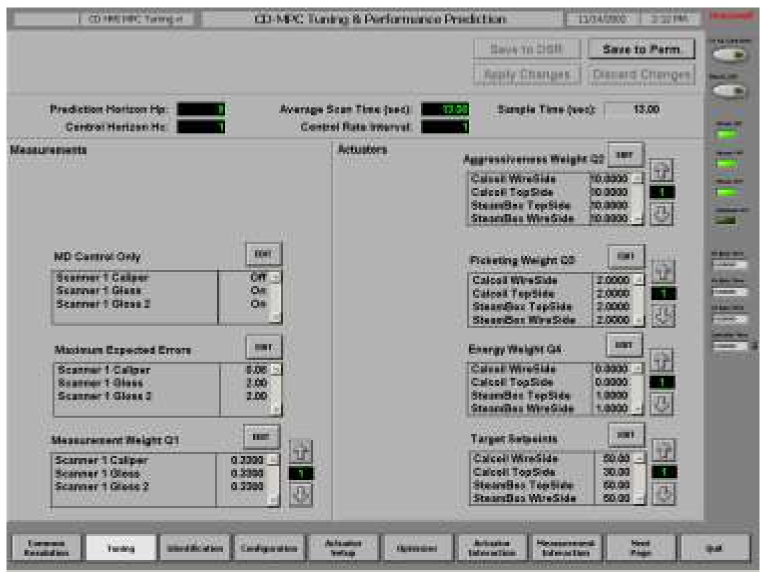

Figure 2: CD-MPC tuning display.

PRESENTING CD-MPC TO THE USER

CD-MPC is a very complex CD control solution, which will typically be operated by users with limited understanding of advanced control. It is therefore very important to create an application that is easy to use and hides the complexity of the controller.

The majority of the configuration parameters that go into CD-MPC are those that describe the model between each CD actuator and each sheet property. This multivariable model is obtained from a new version of the advanced CD identification and tuning tool, IntelliMap [5],[9]. IntelliMap transfers the multivariable process model to CD-MPC over the local area network (LAN). Figure 1 shows the CD-MPC Identification display. Note that there is one pull-down menu for the CD actuator beams, and one pull-down menu for the sheet properties. Each of the six model parameters have array editors, which allow the user to easily set up different models for different actuators across the sheet.

Once the multivariable process model has been transferred from IntelliMap, the user needs to define the CD-MPC tuning parameters. All tuning parameters associated with CD-MPC fit on one display, which is shown in Figure 2. There are four main types of tuning parameters:

1. A tuning weight, Q_1, which allows the user to specify the relative importance of the controlled sheet properties. For example, the caliper profile could be given more importance than the gloss profile in a supercalendering application.

2. A tuning weight, Q_2, which is used for specifying the dynamic aggressiveness of the controller. The controller can be dynamically detuned by increasing Q_2.

3. A tuning weight Q_3, which allows the user to specify the spatial aggressivene--ss of the controller. The controller is spatially detuned by increasing Q_3. By selecting Q_3 appropriately, one is guara--nteed to prevent actuator picketing from building up over time.

4. Finally, there is a tuning weight Q_4, which allows the user to specify the desired actuator setpoint profiles and the costs associated with deviating from them. This tuning weight is typically used when there is a preferred actuator setpoint average or shape for an actuator beam. A common example would be to use this weight to minimise the average level of rewetting by a rewet shower in the dryer section.

Note that for each tuning weight there is an array editor associated with the corresponding measurement or actuator beam. This allows the user to apply different weightings to different measurement zones and actuators across the sheet width.

IntelliMap allows the user to evaluate and validate the tuning numbers through closed loop simulation (based on the identified process model) before applying them to the real paper machine. Once the user is happy with the predicted break recoveries and steady state profiles, he/she can transfer the tuning parameters to CD-MPC from IntelliMap, over the LAN.

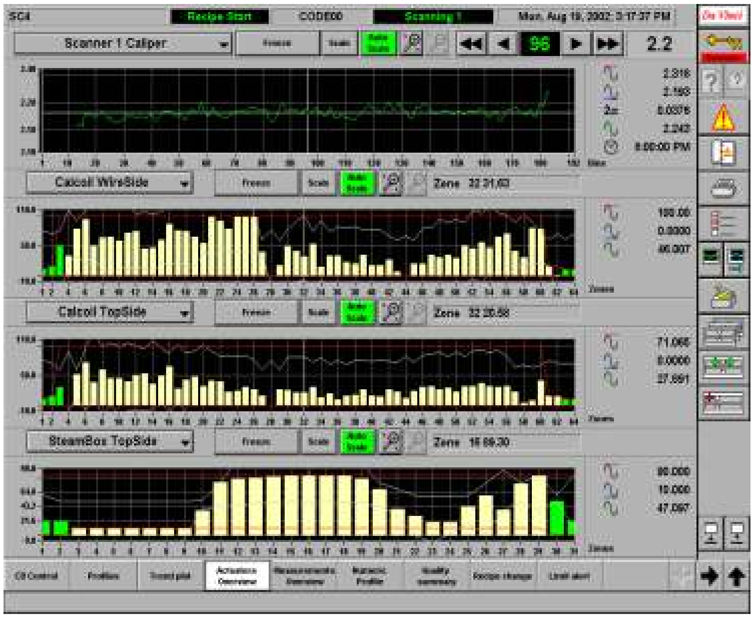

Figure 3: CD Actuator interaction overview display.

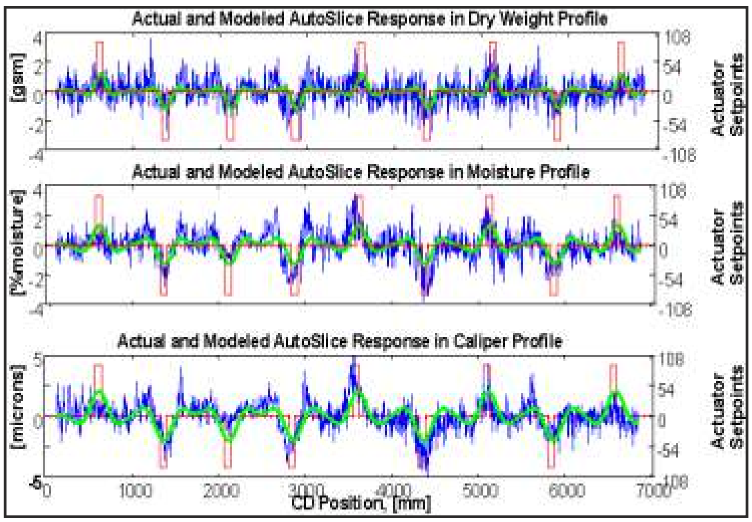

Figure 4: Multivariable identification results on a Canadian newsprint machine, showing the effect of headbox slice actuators on dry-weight, moisture and caliper.

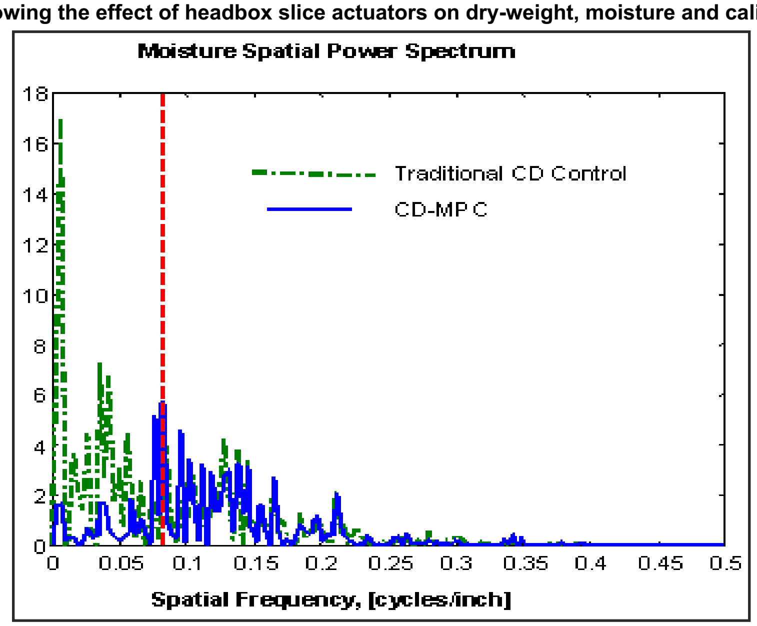

Figure 5: CD moisture power spectrum for traditional control versus CD-MPC on a U.S. linerboard machine.

A display similar to the CD-MPC Tuning display is available for entering in the physical limitations of the actuators. Default values are specified at system build time and typically do not need to be changed.

There are also several process overview and process interaction displays that provide the user with better insight into the multivariable nature of the process. One such overview display is shown in Figure 3.

Acknowledging that this is a completely new concept in CD control, and that it may be a bit intimidating to some users, it is possible to switch between CD-MPC control and traditional control on-line, at any time. This allows each user to learn, and familiarise themselves with CD-MPC at their own pace.

WHEN AND WHY TO CONSIDER CD-MPC?

CD-MPC should always be considered when there is more than one CD actuator beam affecting a sheet property, or if there is only one CD actuator beam but it affects multiple sheet properties. CD-MPC should also be considered if the CD actuators are operating at, or near, their constraints (e.g. being saturated).

The stronger the process coupling, and the closer the actuators are to their limits, the greater the benefits will be from utilising CD-MPC instead of a traditional CD controller. The authors can be contacted to perform a CD-MPC benefit analysis on any particular process.

Actual mill results for four typical papermaking processes are discussed in the following sections.

THE COUPLING FROM HEAD BOX SLICE ACTUATORS ON A NEWSPRINT MACHINE

It is common knowledge that the CD moisture and CD caliper profiles usually correlate, to some extent, with the CD dry-weight profile. A typical newsprint machine uses a slice or dilution CD actuator beam for CD dry-weight control, a steam shower and/or a rewet shower for CD moisture control and induction heating actuators for CD caliper control. Possible effects that the headbox actuators might have on moisture and caliper are ignored. A

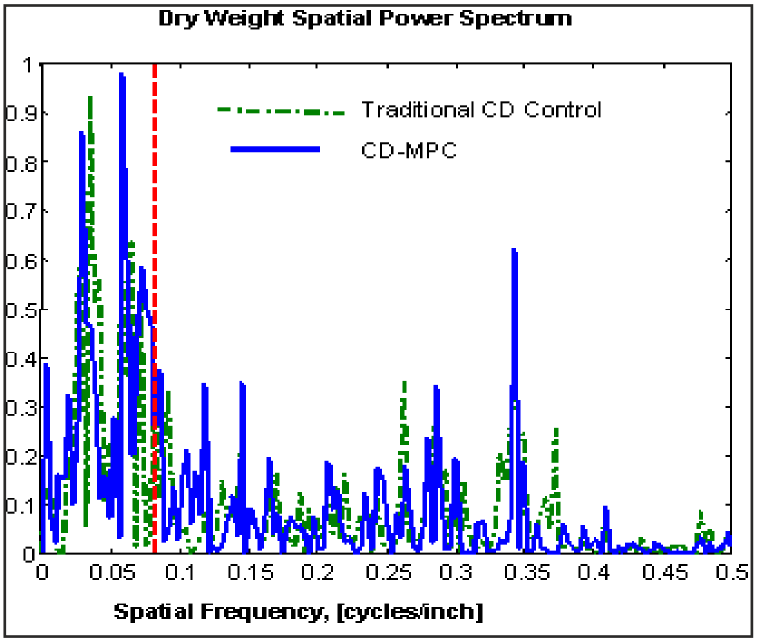

Figure 6: CD dry-weight power spectrum for traditional control versus CD-MPC on a U.S. linerboard machine.

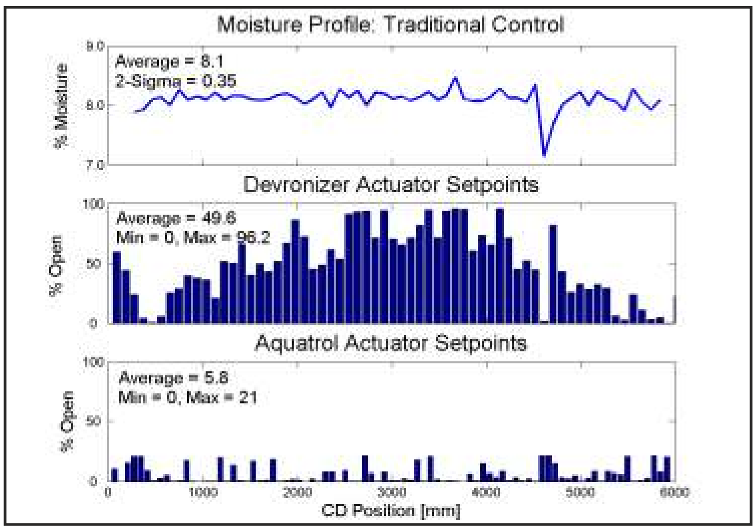

Figure 7: Co-ordinated moisture control on a Canadian newsprint machine using a traditional CD controller.

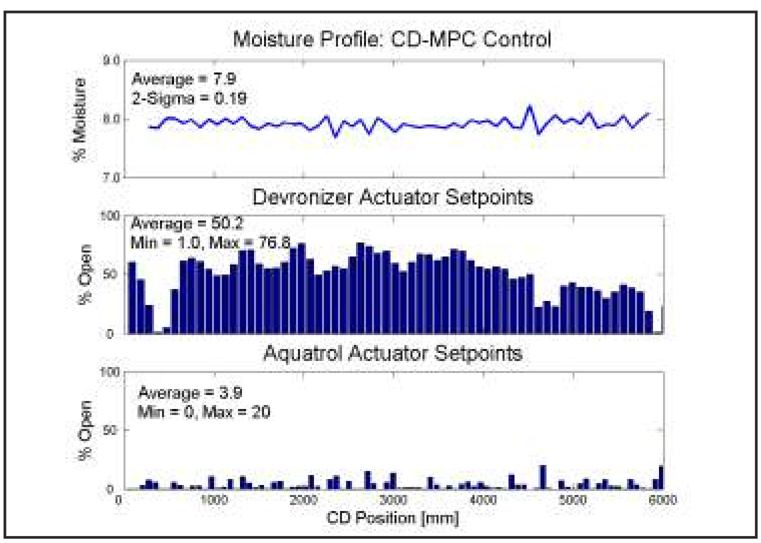

Figure 8: Co-ordinated moisture control on a Canadian newsprint machine using CD-MPC.

bump test identification result from a Canadian newsprint machine is shown in Figure 4. As can be seen, the headbox slice actuators had an equally strong effect on moisture and caliper as they had on dry-weight. Clearly, one ends up with sub-optimal performance by not considering this strong coupling from the headbox slice actuators.

CO-ORDINATED WEIGHT AND MOISTURE CONTROL ON A LINERBOARD MACHINE

A U.S. customer producing linerboard had problems with their CD moisture profile. The existing moisture actuators on the machine were saturated and out of range. The customer had both the top and bottom headboxes equipped with AutoSlice actuators for automated CD weight control. However, the top head box actuators were not under automatic control due to the large negative impact that they had on the moisture profile. Our first Alpha version of CD-MPC was installed on this machine, and provided co-ordinated weight and moisture control using the top headbox slice actuators. The CD power spectrums for dry-weight and moisture are shown in Figure 5 and Figure 6. In this case, CD-MPC maintained the low CD dry-weight variation, while drastically reducing the CD moisture variation compared to what was obtained with traditional CD control. The CD control of this process is discussed in more detail in [2].

CO-ORDINATED MOISTURE CONTROL ON A NEWSPRINT MACHINE

Many newsprint machines today have both a steam shower in the press section and a rewet shower in the dryer section for CD moisture control. Under traditional CD control these two actuator beams are co-ordinated with some form of error splitting strategy, as discussed earlier. It is typically desira--ble to minimise the overall amount of rewetting in the dryer section. This avoids production problems such as sheet blackening, and prevents undesirable tension and shrinkage phe--nomenon in the finished paper product. A comparison of using CD-MPC and traditional CD control for co-ordinating a steam shower and a rewet shower on a Canadian newsprint machine is shown in Figure 7 and Figure 8. In this case the co-ordination strategy for the traditional controller had been set up by experts and

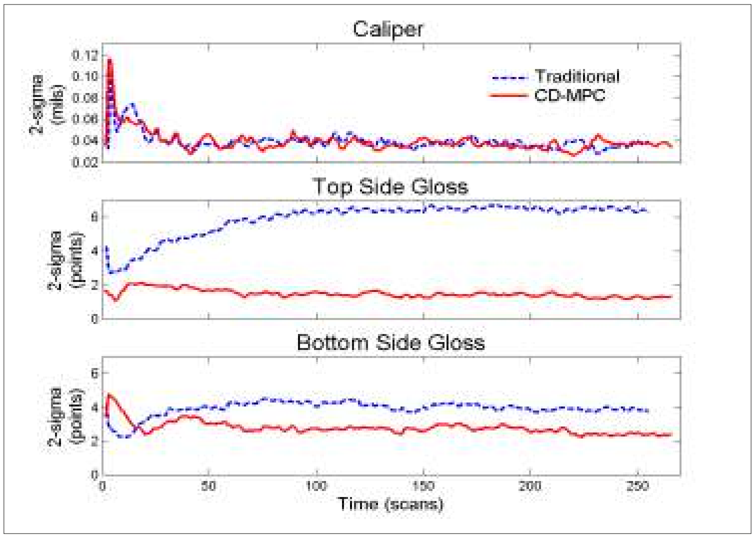

Figure 9: Supercalender CD 2-sigma trends for co-ordinated gloss and caliper control using traditional CD control and CD-MPC.

performed rather well, i.e. it provided a low CD moisture variation and a low level of overall rewetting by the Aquatrol rewet shower. Even so, the CD-MPC reduced the CD moisture variation by 46%, and at the same time reduced the Aquatrol's average rewetting by 33%.

CO-ORDINATED GLOSS AND CALIPER CONTROL ON SUPER CALENDERS

Our last CD process example is from the recent start-up of CD-MPC on a Canadian supercalender. Super calendering is a highly coupled CD process in which steam showers, air-atomized rewet showers and Calcoil induction-heating actuators are used to control CD caliper and CD gloss. Typically, each actuator has a very strong effect on both gloss and caliper.

In order to reduce sheet two-sidedness, there is usually one actuator beam of each type applied to both the top side and the wire side of the sheet. In some cases, this causes bleed-through, which occurs when an actuator applied to one side of the sheet also affects the paper properties on the opposite side of the sheet.

Multivariable identification, analysis and CD control simulation of this Canadian supercalender process was discussed in [1]. This work also showed that stable control of this process could not be guaranteed with a traditional CD controller.

This supercalender is equipped with one profiling steam shower and one induction heating actuator beam for each side of the sheet. This requires that four CD actuator beams be co-ordinated to control three sheet properties; wire side gloss, caliper and top side gloss. As for most supercalender processes, the CD caliper has a higher relative importance than the CD gloss.

Multiple trials were conducted using both the CD-MPC and traditional controllers. CD profiles were collected for the entire length of the paper reels as they passed through the supercalender. Representative CD 2-sigma trends for caliper, top side gloss and wire side gloss are shown in Figure 9.

The traditional CD controller did a good job controlling CD caliper, the primary CD sheet property, but could not do so without compromising the CD gloss control. CD-MPC maintained the same low level of CD caliper variation as the traditional CD controller, but was able to simultaneously provide a CD 2-sigma reduction of 80% for topside gloss and 39% for wire side gloss. Based on these excellent results with CD-MPC, we are now in the process of starting up CD-MPC on another supercalender in this mill.

CONCLUSIONS

We have in this paper presented CD-MPC, the next generation multivariable CD controller. We have stressed the importance of providing interfaces and tools that make the controller easy to use for non-experts in CD control. Superior results compared with traditional CD control have been demonstrated for several different CD processes.

REFERENCES

[1] Backstrom J, Henderson B and Stewart G, “Identification and multivariable control of super calenders” *Control Systems 2002, June 2002*, Stockholm Sweden.

[2] Backstrom J.U, Gheorghe C, Stewart G.E, Vyse R.N “Constrained model predictive control for cross directional multi-array processes”. *Pulp & Paper Canada.* T128 102:5 (2001).

[3] Chen S.C, Wilhelm Jr. R.G “Optimal control of cross-machine direction of web profiles with constraints on the control effort” *Proc. of American Control Conf.* Seattle WA, June 1986.

[4] Heaven, E. M., Jonsson I. M., Kean. , M. A. , and Vyse, R. N.. “Recent advances in cross machine profile control using modern estimation and control technology” *Second IEEE conference on control applications, September 1993,* Vancouver, BC. pp 217-226

[5] Gorinevsky D., Heaven E.M., Gheorghe C, “High performance identification of cross-directional processes” *Control systems 1998.* Povoro Finland, September 1998.

[6] Gorinevsky D, Heaven M, Vyse R, ”Performance Analysis of Cross-Direction Process Control Using Multivariable and spectral models” *IEEE Transaction on Control Systems Technology,* vol. 8, No. 4, July 2000.

[7]Rao, Christopher V., Campbell, John C., and Rawlings., James B. “Efficient Implementation of Model Predictive Control for Sheet and Film Forming Processes”, *Proc. of American Control Conf. June 1997,* Albuquerque, New Mexico.

[8]Rigopoulos, A and Kayihan, F. “Model Predictive Control of CD profile disturbance models identified by adaptive PCA” *Proc. of American Control Conf. June 1997,* Albuquerque, New Mexico.

[9] G.E. Stewart, C. Gheorghe, and T. Steele. “IntelliMap 3: Two-Dimensional Loop Shaping for Cross-Directional Controller Tuning”, 88th Annual PAPTAC Meeting, pp. A95-99, Montréal, PQ, January 2002.

[10]G.E. Stewart, J.U. Backström, P. Baker, C. Gheorghe, and R.N. Vyse. “Controllability in Cross-Directional Processes: Practical Rules for Analysis and Design”, Pulp and Paper Canada Journal, 103(8), T208-214, August 2002.