Simulation studies of paper machine basis weight control

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Abstract: This report presents some simulation results of basis weight control in paper machine. In particular, the dilution actuator width, actuator response width and the effect of scanner measurement uncertainty are studied. Also different controller configurations in machine direction control are tested.

Basis weight is one of the most important quality parameters in paper manufacturing. The control problem is two-dimensional, since variations occur both across the paper web (cross-direction, CD) and along the production line (machine direction, MD). In addition, the basis weight is measured from the end of the line and the actuators are at the beginning of line. This means long measurement delay, which makes the problem more difficult.

The simulations are performed using the simulator originally developed in Tampere University of Technology. The control performance is evaluated using the criteria of 2σ standard deviation, spectral properties, and variance reduction percentages of disturbances.

CD control performance decreases with wider CD actuator widths. Simulations suggested that better CD control performance was achieved using wider actuator response widths than it was identified earlier in a mill. Increased scanner measurement uncertainty decreased the CD control performance, since the increased measurement uncertainty provides worse CD estimates. MD control performance is related to the control interval applied and, of course, the tuning of the controller. Predictive controller simulated here was found to be practical if different control intervals are applied.

Keywords: paper machine, web forming, cross direction control, machine direction control

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APPENDIX
1 INTRODUCTION

The studies reported here are a part of QVision project, which aims to measure paper web properties of paper machine in high resolution, for example to enable better elimination of paper web disturbances. Simulations in this report show how the actuator settings of the headbox effect on paper web quality in cross direction. The effect of different control strategies on paper quality is studied in machine direction. First factor is the effect of CD actuator width on simulated paper quality. Then the effect of the actuator response width, which depends on machine speed and head box construction, on paper quality is studied by keeping the actuator width constant and studying the effect of the actuator response width on paper quality. Also the performance of the CD control with dynamically changing CD profile disturbances is evaluated. In addition, the control performance is studied in different cases (varying scanner measurement uncertainty and a simulated wire section problem). The MD control simulations include testing different controllers and control intervals.

The simulation studies utilise the simulator originally developed in Tampere University of Technology [8,9]. Authors have made following additions:

- Smart distribution of the actuators when the actuator width (i.e. actuator spacing) is changed.
- A possibility to change the actuator response according to the actuator width.
- The usage of dilution actuator control model with the base, which differs from the simulated response model, i.e. mismatch for more realistic simulation.
- Measurement delays from CD actuators to scanner measurement.
- MD control development. PI controller tuning and development of novel model predictive controller (MPC).
- Profile estimations based on exponential filtering and scan averages.

Chapter 2 gives a brief introduction to the basis weight control problem in paper machine. For more details, see e.g. [11]. In Chapter 3, the criteria for the evaluation of the control performance are given. The simulated cases are shortly introduced in Chapter 4 and the simulation results can be found from Chapter 5. Finally, Chapter 6 summarizes the main findings.
2 BASIS WEIGHT CONTROL

2.1 Variations in paper machine

Basis weight is probably the most important quality parameter in paper manufacturing. The control problem is two-dimensional, since variations occur both across the paper web (cross-direction, CD) and along the production line (machine direction, MD). Additionally, there are diagonal waves i.e. variations that cannot be classified to CD or MD variations. In addition, a large part of the variation takes place at too high frequencies for control. This part of the total variations is called residual variation. Figure 1 demonstrates the variations in basis weight.

![Variations in a paper machine](image)

Figure 1. Variations in a paper machine.

2.2 Control

Separate control systems are used for the machine-direction and cross-direction. Basis weight variation in MD is controlled by adjusting the amount of pulp flowing into the headbox. Variation in CD is controlled with numerous actuators in different CD locations either by adjusting the pulp flow (slice lip headbox) or by adjusting the consistency of pulp flow (dilution headbox) distributed to the wire. The MD control takes care of the setpoint value of the basis weight and the CD control tries to distribute the pulp evenly to
the wire while preserving the setpoint i.e. the mean value in CD. The control problem is illustrated in Figure 2.

![Diagram of improved basis weight estimation for improved basis weight control](image)

**Figure 2. Estimation and control of basis weight variations [1].**

CD actuators response is wider than the actuator hence the response affects also the adjacent actuators. These interactions are taken into account by defining the control actions that minimise the observed CD variation for the whole width of the paper i.e. setpoint values for each actuator are calculated simultaneously. Usually only a part of the calculated control action is performed to ensure stability. MD control is performed usually with PI-controllers or model predictive controller (MPC).

### 2.3 Measurements

Control actions are based on the profile estimates which are calculated from the measurements provided by the scanning sensor. These measurements can be taken only from sufficiently dry paper web at the end of the production line. This causes a long delay between the actuators and measurements. Additionally, since the sensor travels back and forth across the paper web at speed from 0 to 1 m/s, while the paper web moves fast in other direction, the measurement path forms a zig-zag-pattern (see Figure 3). The horizontal parts in the path correspond to the fact that the scanner stays some seconds at the paper edge before changing the direction.
Figure 3. Measurement path caused by the movement of the paper web and the traversing scanner.

Only a small amount of the paper web is actually measured, e.g. 0.2 % [2] or 0.001 % [3]. The movement of the sensor and the paper web means that the measurements contain mixed information of CD and MD variations. Some MD variation may be aliased into the CD profile due to the periodic nature of the variations and the sensor path.

The measurement frequency of the scanner can be up to 4000 Hz. Scanner measurements are usually averaged in e.g. 1 cm data boxes, which are then used in calculating the profiles. The CD profile estimates are conventionally generated using exponential filtering i.e. the estimate in each CD position is a weighted average of data boxes. The MD profile is estimated from the average of a single scan. It means that the new MD profile information is available when a single scan is completed. Depending on the speed of the scanner and the width of the paper web, it takes up to 50 seconds to perform a scan. Due to exponential filtering, changes in CD profile are detected even slower than MD changes. More sophisticated methods use Kalman filtering to give profile estimates at each time instant. This improves the dynamic bandwidth of the measurement significantly.
3 PERFORMANCE CRITERIA

The most typical criterion for evaluating the control performance is $2\sigma$ i.e. twice the standard deviation of the measurements. The criterion describes the average deviation from the mean value. The $2\sigma$ value means that 95% of measured values deviate less than $2\sigma$ value from the average value. It is also the criterion constantly observed in paper manufacturing process. In these simulation studies, the $2\sigma$, and other criteria, are calculated from the actual data, not from the profile estimates.

The control performance is evaluated separately in machine direction and cross direction. The following criteria $C_i$ are used (the acronym in parentheses):

- **$2\sigma$ standard deviation in CD ($2\sigma$ CD):**

  $$C_1 = 2 \sqrt{\frac{\sum_{i=1}^{M} (\bar{x} - x_i)^2}{M - 1}}$$  

  where $\bar{x}$ is the average of data points $x_i$, $M$ is the number of data points in CD, $x_i$ are calculated from:

  $$x_i = \frac{\sum_{k=1}^{N} x_k}{N}$$  

  where $N$ is the number of data points in MD.

- **$2\sigma$ standard deviation in MD ($2\sigma$ MD)**

  $$C_2 = 2 \sqrt{\frac{\sum_{i=1}^{N} (\bar{x} - x_i)^2}{N - 1}}$$  

  where $\bar{x}$ is the average of data points $x_i$, $N$ is the number of data points in MD, $x_i$ are calculated:

  $$x_i = \frac{\sum_{k=1}^{M} x_k}{M}$$  

  where $M$ is the number of data points in CD.
With simulated data, it is possible to compare the controlled and the uncontrolled paper webs. Hence, the reduction of variance is also used as a performance criterion. The criterion gives the percentage of the removed disturbances in simulation. The whole finite amount of data in simulation at its full resolution is used to perform the calculations.

- reduction of variance in CD [%] (CD var reduction)

\[
C_3 = 100 - \frac{M - 1}{\sum_{i=1}^{M} (\bar{x} - x_i)^2} * 100
\]

(5)

where \(x\) are the controlled paper web points values and \(z\) the values of uncontrolled paper web.

- reduction of variance in MD [%] (MD var reduction)

\[
C_4 = 100 - \frac{N - 1}{\sum_{i=1}^{N} (\bar{z} - z_i)^2} * 100
\]

(6)

Power spectrum gives information on the nature of the variations. The data is transformed into spectrum data with Matlab function “fft”, fast Fourier transform. Here the spectrum has been used as a visual inspection tool showing how different components of simulated variations have been attenuated by the control actions. Figure 4 illustrates the typical power spectra of uncontrolled paper web and controlled paper web in machine direction and in cross direction. Also, the sum of spectrum values and variance of spectrum values are used as performance criteria (CD spectrum sum, CD spectrum variance).
Figure 4. MD and CD power spectra for input disturbances and controlled paper web. The simulated disturbances in CD spectrum reach the peak values of around five.

From the MD spectrum, it can be seen that the input disturbances have frequencies around 0.001 and 0.002 Hz, where the higher frequency component has also higher amplitude. The controller has attenuated these components quite nicely. From the CD spectrum, it is visible that the main disturbance components with wavelengths around 0.01 and 0.02 1/cm have been efficiently damped by the control actions.
4 SIMULATION STUDIES

4.1 Simulated disturbances

The input disturbances are sine waves of form:

\[ d = A \cdot \sin(2\pi \cdot f \cdot x) \]  

(7)

where A is the amplitude of the variation and f is its frequency. x is the length of the simulation (MD) or width of the simulated paper web (CD). The amplitudes and frequencies of simulated variations are listed in Table 1. In addition, simulator generates also zero-mean residual variation with a variance of 0.1. In CD simulation studies in Chapters 5.1, 5.2 and 5.3 MD, disturbances are not simulated and MD control is turned off. Likewise, the CD components and CD control are not included in MD simulations in Chapter 5.6. The simulation in Chapter 5.4 and 5.5 contains different disturbance scenarios.

<table>
<thead>
<tr>
<th>CD component 1</th>
<th>CD component 2</th>
<th>CD component 3</th>
<th>MD component 1</th>
<th>MD component 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 0.8</td>
<td>0.7</td>
<td>0.3</td>
<td>0.7</td>
<td>0.5</td>
</tr>
<tr>
<td>f 0.1</td>
<td>0.04</td>
<td>0.0025</td>
<td>0.0017</td>
<td>0.001</td>
</tr>
</tbody>
</table>

The simulated disturbances demonstrate both the fast variations that most likely cannot be removed by the control systems and slower variations that are somewhat controllable.

4.2 Definitions in simulations

**CD actuator width** (act width [cm]) is the ratio of paper web width and the number of actuators. **The response width** (resp width) describes the width of CD actuator response in cross direction (CD). The actuator response width is 100 mm at 50 % amplitude of response [7]. The response width parameter 4 cm results in similar response as in [7].

In result tables, the following properties are presented to display settings used in simulations:

- **First centre** means the place of the first CD actuator response peak at the paper web (at left side). The place of the first centre is calculated on the basis of the actuator width.
- **CD control on** means whether the CD control is enabled (=1) or disabled (=0).
- **MD control** means which type of control is used in simulation. 1 means the pre-computed GPC and 2 the PI controller.
- **Saato** means which measurements are the bases of estimates in simulations. 1 means the scanner measurement based on Kalman filter and 4 the scanner measurement based on exponential filtering.

- **Delta u MD** means how often control actions in CD are performed.

- **Delta u CD** means how often control actions in MD are performed.

- **Alfa** describes how much of calculated CD control action is adopted.

- **N** means the length of the paper web in MD (s).

- **M** the width of the paper web in CD (cm).
5 RESULTS

5.1 Effect of CD actuator width

This simulation case illustrates the effect of CD actuator spacing (act width [cm]) in the dilution headbox. The simulation results using Kalman filter-based estimation are presented in Table 2. The results using exponential filtering are presented in Table 3. The actuator response width (resp width) is constant 4 cm, which results the width of 10 cm at 50% amplitude of response, which was earlier identified in a mill [7].

<table>
<thead>
<tr>
<th>act width</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
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<tbody>
<tr>
<td>resp width</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>first centre</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>7</td>
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<tr>
<td>CD control on</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>delta u CD</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>N</td>
<td>1000</td>
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<td>1000</td>
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<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>M</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
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<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
</tr>
</tbody>
</table>

Table 3. Simulation results as a function of CD actuator width using exponential filtering.

<table>
<thead>
<tr>
<th>act width</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
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<tbody>
<tr>
<td>resp width</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>first centre</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>CD control on</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>saato</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>alfa</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>N</td>
<td>1000</td>
<td>1000</td>
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<td>1000</td>
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<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>M</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
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<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
</tr>
</tbody>
</table>

All CD performance criteria suggest that CD control performance decreases with wider CD actuator widths. The simulated variations have the wavelengths of 10, 25 and 400 cm. Only disturbances wider than two times of the actuator width can be controlled [4,5,6]. The results support the theory, since only the actuator widths 4 and 5 cm can reduce the most frequent disturbance with 10 cm wavelength. According to theory [4, 5,
the actuator widths 13 – 15 cm can only reduce the disturbance of 400 cm wavelength disturbance. The results in Table 3 using exponential filtering as an estimation method are slightly better than in Table 2 using Kalman filter.

Narrower actuator widths allow the elimination of disturbances with shorter wavelengths. On the other hand, paper web shrinking or wandering cause problems and the problem is emphasized with narrower actuator widths. In simulations, shrinking and wandering were not considered.

5.2 Effect of CD actuator response width

In the dilution headbox, the width of the actuator response is constant. The following simulations are performed to study whether the response width is optimal or could additional improvement be achievable if the actuator response would be narrower or wider. The effect of the CD actuator response width was studied by keeping the actuator width constant at 10 cm and changing the width of actuator response (resp_width). To study only the effect of the actuator response width, the mismatch between the actuator response and control response was removed i.e. the simulated response and control response model are congruent. The results are presented in Table 4.

Table 4. Simulation results as a function of the CD actuator response width using exponential filtering.

<table>
<thead>
<tr>
<th>resp_width</th>
<th>act width</th>
<th>2σ CD</th>
<th>2σ MD</th>
<th>CD spectrum sum</th>
<th>CD spectrum variance</th>
<th>CD var reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>1.32</td>
<td>0.23</td>
<td>109.73</td>
<td>15.18</td>
<td>28.34</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>1.19</td>
<td>0.36</td>
<td>86.28</td>
<td>12.76</td>
<td>42.38</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>1.23</td>
<td>0.38</td>
<td>88.32</td>
<td>17.41</td>
<td>38.99</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>1.24</td>
<td>0.23</td>
<td>96.20</td>
<td>25.72</td>
<td>41.44</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>1.20</td>
<td>0.21</td>
<td>90.18</td>
<td>25.41</td>
<td>43.38</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>1.18</td>
<td>0.21</td>
<td>87.16</td>
<td>25.27</td>
<td>45.53</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>1.16</td>
<td>0.20</td>
<td>83.64</td>
<td>24.75</td>
<td>46.93</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>1.13</td>
<td>0.19</td>
<td>80.41</td>
<td>23.09</td>
<td>47.21</td>
</tr>
<tr>
<td>9</td>
<td>10</td>
<td>1.14</td>
<td>0.20</td>
<td>80.76</td>
<td>23.62</td>
<td>47.01</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>1.15</td>
<td>0.20</td>
<td>81.25</td>
<td>23.63</td>
<td>47.39</td>
</tr>
</tbody>
</table>

According to Table 4, the results are mainly at the same magnitude for all actuator response widths, except the narrowest ones. Actuator response width 8 cm results in the smallest 2σ CD standard deviation and the smallest CD spectrum sum, though the wider actuator response widths result in better CD variance reduction. Figure 4 illustrates the CD actuator response width 8 cm (red line). Blue line illustrates the actuator response width of 10 cm at 50 % response amplitude, which is identified in a mill [7]. The blue line corresponds the actuator response width (resp_width) of 4 cm. Simulations therefore suggest that, in this case, better CD control performance is achieved using wider actuator response widths than it was identified in the mill.
Figure 4. Blue line describes the response width of 10 cm at 50 % response amplitude, which was identified in a mill [7]. According to simulation results, better results are obtained using wider CD actuator response widths. Red line describes the actuator response width 8 cm.

5.3 Effect of scanner measurement uncertainty

The effect of scanner measurement uncertainty (sigma_mitt_0) was studied on paper web quality, Table 5.

<table>
<thead>
<tr>
<th>sigma_mitt_0</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>12</th>
<th>14</th>
<th>16</th>
<th>18</th>
<th>20</th>
<th>22</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>2σ CD</td>
<td>1.18</td>
<td>1.21</td>
<td>1.17</td>
<td>1.25</td>
<td>1.26</td>
<td>1.28</td>
<td>1.31</td>
<td>1.40</td>
<td>1.30</td>
<td>1.39</td>
<td>1.34</td>
<td>1.42</td>
</tr>
<tr>
<td>2σ MD</td>
<td>0.20</td>
<td>0.19</td>
<td>0.20</td>
<td>0.19</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
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<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>CD spectrum sum</td>
<td>94.39</td>
<td>99.32</td>
<td>103.79</td>
<td>118.31</td>
<td>126.72</td>
<td>139.05</td>
<td>143.51</td>
<td>156.13</td>
<td>142.68</td>
<td>143.44</td>
<td>166.85</td>
<td>184.89</td>
</tr>
<tr>
<td>CD var reduction</td>
<td>42.76</td>
<td>39.95</td>
<td>43.27</td>
<td>35.91</td>
<td>36.69</td>
<td>32.47</td>
<td>31.24</td>
<td>20.68</td>
<td>31.55</td>
<td>21.39</td>
<td>27.36</td>
<td>19.98</td>
</tr>
<tr>
<td>act width</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
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<tr>
<td>resp width</td>
<td>4</td>
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<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
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<td>4</td>
</tr>
<tr>
<td>first centre</td>
<td>3</td>
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Increase in the scanner measurement uncertainty naturally decreases the control performance, since the uncertainty reflects to the estimates. CD control has managed to
reduce variation in CD in all cases even with high sigma_mitt_0 values. The CD profile is estimated using exponential filtering, which seems to eliminate the effect of increased measurement uncertainty.

5.4 Simulation of wire section problem

Figure 5 illustrates simulation of disturbance in the wire section, where the basis weight at CD locations 200 - 230 cm is decreased by 1 unit. The actuator width is 10 cm and only residual noise and simulated wire section disturbance are used in cross direction (CD).

![Figure 5. The simulation of wire section problem, where the basis weight is decreased by one unit in CD locations 200 – 230 cm. The picture on right illustrates the effect of CD control at MD row 1000.](image)

The CD control has managed to eliminate the wire section disturbance. In this case, the disturbance width (30 cm) is three times wider than actuator width (10 cm). According to earlier studies, the wavelengths twice wider than the actuator spacing can be removed [4,5].

5.5 Simulation of unstable CD disturbance

In earlier simulations, the incoming CD variations were normal waves with constant wavelengths and amplitudes. Here the control performance of the linear steady-state optimal controller was tested against dynamically changing, or unstable, CD variations. The simulated variations were the two controllable wavelengths in Table 1 with the amplitude changing in time. The amplitudes in Table 1 define the boundaries for the changing amplitude. The time behaviour follows also a normal wave, but the phase is different for the both variation components. The actuator settings were act_width=6, resp_width=4.

Figure 6 shows that the disturbances are efficiently damped with both estimation methods. Performance criteria show that the results are now better with Kalman filter. Reduction in CD variation for the exponential filtering and Kalman filter was 72% and
84%, respectively. Unstable CD disturbance does not seem to have a significant effect on control behaviour. This was expected with the current robust controller settings (only 10% of control action is performed at each control interval) and the control interval is, of course, longer than the dead-time between actuators and measurements. Most likely, more variation could be damped with more aggressive tuning or shorter control interval.

![CD power spectral density](image)

Figure 6. CD power spectrums for input disturbances and controlled paper, when control actions are based on different estimation methods.

5.6 MD simulations

In MD simulations, the results for the two different controllers as a function of MD control interval are presented. The results for the PI controller are presented in Table 6 and the results for the pre-computed Generalised Predictive Controller (GPC) in Table 7. GPC is constructed as explained in [10] using a first order plus delay model, see also Appendix. Notice that the simulated MD response follows a second order model. The simulated paper web width is 400 cm i.e. the time consumed by a single scan is 8 seconds. Hence, control intervals of the scan time and multiple of scan times are studied with a traditional estimating mode. The smaller control intervals are performed with the estimates provided by Kalman filter. The control performance is only evaluated according to disturbance rejection properties. Setpoint following and stability in setpoint changes are not taken into account when tuning the controllers.
The PI controller was tuned using a gain term \( P \) equal to one and the integration term five times the control interval. This tuning gives great results with the control interval of 8 seconds. However, the MD control performance decreases with increased MD control interval. It is obvious that the controller should be tuned more carefully when changing the control interval. Simulations with the constant tuning parameters produced unstable control performance. For the shorter control intervals, the PI controller fails in control, because all simulations have negative MD variance reduction value meaning that control has actually increased variation.

The pre-computed GPC can be tuned with a single tuning parameter \( \lambda \), which is set here to the constant value of one. Since the model in the controller is based on sampling time one, the best control performance is achieved with the smallest control interval. The MD control performance decreases with the increased MD control interval, but the degradation is not as clear as with PI controller. Another option to use the GPC is to identify the process model with the sampling time determined by the control interval. The tests not presented here, however, showed that the tuning parameters must also be altered when the control interval changes.
6 SUMMARY AND CONCLUSIONS

CD control performance decreases with wider CD actuator widths. The rule of thumb is that only disturbances with wavelengths twice wider than the actuator spacing can be removed [4, 5, 6]. The simulated results support this theory. Narrower actuator widths allow the elimination of disturbances with shorter wavelengths. On the other hand, paper web shrinking or wandering cause problems and the problem is emphasized with narrower actuator widths. In simulations, shrinking or wandering was not considered.

Simulations suggest that better CD control performance is achieved using wider actuator response widths than it was identified earlier in a mill [7]. Although the analysis is incomplete, the results suggest that there would be additional improvement achievable with different design of the dilution actuators and headbox construction. Naturally, wider response is also achieved by decreasing the speed of the machine, which, however, is not an acceptable option in most cases.

Increased uncertainty in the scanner measurement decreases the CD control performance. The result is expected, since in some point the capability of the estimation method to filter out the noise is exceeded and the increased measurement uncertainty provides worse CD estimates. With the controller settings used in simulations, unstable CD variations do not harm the control performance significantly. However, most likely a more aggressive control strategy would remove more variations, but the robustness may become an issue.

MD control performance with different control intervals decreases as the interval increases. The degradation is more profound with PI controller than with pre-defined Generalised Predictive Controller. With careful tuning the performance of the PI controller may be better than with the GPC, but the stability is easily lost. GPC can be applied with different control intervals without re-tuning, still achieving a good control performance in each case.

The performance criteria used in these simulation studies contain some basic measures of control performance. The simulated data allows also evaluating the reduction of the overall variation. An effort to calculate some numerical values from spectrum data is also given. Since all measures give similar behaviour, it cannot be concluded if one is suited better than another. The behaviour of performance criteria should also be studied with the data from profile estimates.

Finally, the authors want to point out, that the results of the control performance are, of course, case sensitive and related to the simulated disturbance scenarios. Solid conclusions based on these results should not be made. For a more comprehensive control studies, different methods should be applied. The simulations here are more or less performed also to demonstrate the usability of the simulator as a research tool. The modular structure of the simulator allows also using mill data as an input.
7 REFERENCES


APPENDIX

A Generalized Predictive Controller, GPC [10]

Model Predictive Control (MPC) does not refer to a single control algorithm, but a family of algorithms that differ in terms of model applied and the in the way the control actions are calculated. They have the following step-wise procedure in common

- An explicit process model is used in predicting the future plant output over the prediction horizon.
- A sequence of the future manipulated variable is calculated optimally so that the predicted output is as close as possible to the desired future output.
- The first value in the sequence of manipulated variables is applied to the plant.

The following presentation is based on Reference [10] that introduces a procedure starting from the first order model and ending up with a predictive controller having pre-calculated control parameters that leave only one tuning parameter. The basic GPC algorithm is given e.g. in [A1].

GPC algorithm minimizes the following cost function

\[
J = E \left\{ \sum_{j=N_1}^{N_2} \left[ \hat{y}(t+j|t) - w(t+j) \right]^2 + \sum_{j=1}^{N_u} \lambda(j) \left[ \Delta u(t+j-1) \right]^2 \right\}
\]

and calculates the future control sequence so that the future plant output is forced close to the reference trajectory. Following denotations are in use; \( E \{ \cdot \} \) is the expectation operator, \( \hat{y}(t+j|t) \) is the optimum j-step prediction of the system output until time \( t \), \( N_1 \) and \( N_2 \) are the minimum and maximum costing horizons, \( N_u \) is the control horizon, \( \lambda(j) \) is the sequence of control weights, \( w(t+j) \) is the future reference trajectory and \( \Delta u(t+j-1) \) is the control signal trajectory.

GPC in [10] uses a first order plus delay model

\[
G(s) = \frac{K}{\tau s + 1} e^{-\tau_d s}
\]

\( K \) is the process gain, \( \tau \) is the time constant and \( \tau_d \) is the time delay. This model can be transformed into [10]

\[
y(t+1) = (1+a)y(t) - ay(t-1) + b\Delta u(t-d) + \varepsilon(t+1) \tag{A3}
\]

In (A3), \( a = e^{-\tau_d/T} \), \( b = K(1-a) \), \( d = \tau_d/T \) and \( \varepsilon \) is zero-mean white noise. Notice that the dead time is assumed to be an integer multiple of the sampling time. The minimum costing horizon must be greater that the dead time. In the following, \( N_1 = d+1 \) and \( N_2 = d+N_u \).
According to [10] the best expected value for the output is

$$\hat{y}(t + d + j \mid t) = (1 + a)\hat{y}(t + d + j - 1 \mid t) - a\hat{y}(t + d + j - 2 \mid t) + b\Delta u(t + j - 1)$$  \hspace{1cm} (A4)$$

assuming that two output estimates on the right-hand side are known. Minimizing (A1) gives the formula for the control increment

$$\Delta u(t) = l_{y1}\hat{y}(t + d \mid t) + l_{y2}\hat{y}(t + d - 1\mid(t) + l_{r1}r(t)$$  \hspace{1cm} (A5)$$

where $r(t)$ is the reference signal. The coefficients $l_i$ are functions of $a$, $b$ and $\lambda(t)$. Reference [10] gives detailed information on how to calculate control parameters in advance and how the algorithm is working.

References