SIMULATOR FOR TESTING MEASUREMENT, ESTIMATION AND CONTROL METHODS IN 2D PROCESSES

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Abstract. We present a simulator mimicking 2D quality variations and their measurement with scanning gauge in continuous web manufacturing. The simulator includes 2D web forming, measurement of quality variable, estimation of CD and MD variations and estimate based controls. In the simulator the movement of scanning sensors in the measurement frame can be chosen arbitrarily. Furthermore, it is possible to have several measurements. The simulator provides a tool to study how the measurement modes affect performance of estimation methods and control of quality variations.

1 Introduction

Industrial web processes, such as paper making and plastic film extrusion, use scanning gauges to measure properties of the web while it is produced. Measurements are made by sensors that are mounted in a frame, which allows the sensor to scan back and forth across the web. As the web is moving the sensor draws a zig-zag measurement path on the web (Fig 1). On the basis of such on-line measurements the entire 2-dimensional variation must be estimated. In these processes the material properties vary both spatially (referred as cross direction, CD) and temporally (referred as machine direction, MD). CD and MD variation have separate dedicated control systems: thus the measurement signal has to be separated into CD and MD variation estimates. Furthermore, there always exists 2-dimensional variation other than CD or MD, called the residual variation. Residual variation is hard to estimate from scanning measurements and there are no actuators to control it. However, excessive residual variation may severely deteriorate the estimation of CD and MD variation.

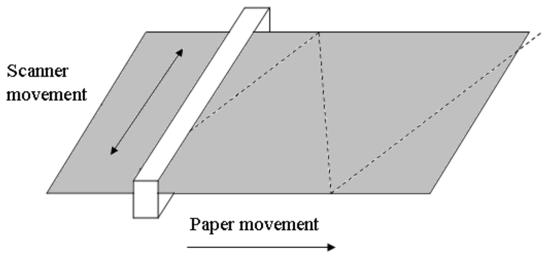

Figure 1 A zig-zag scanning path

Despite the development of new measuring systems [1], the single scanning sensor continues to be the predominant measurement system in the paper making and plastic films industry. It is obvious that the scanning sensor is not ideal, because the sensor sees only a tiny fraction of the web. For example, in the case with typical industrial scanning and web speed parameters, in which the width of the web is 10 m, the web is moving with speed 30 m/s and the sensor is moving at the speed of 0.5 m/s, during a single edge-to-edge scan, the web has moved 600 m. However, from the measurement signal it is necessary to estimate the variations that are not seen by the sensor to control variations over the whole web.

Estimation and separation of the CD and MD components have been intensively studied for some three decades. There have been many attempts to solve the estimation problems by using methods, such as wavelets [2], model-based [2, 3] and frequency domain approaches [4, 5]. There exist also new camera-based commercial measuring systems that measure 2D variation down to submillimeter spatial resolution [6]. The problem with such systems is that the cameras do not measure directly any of the relevant quality variables and therefore images from the system must be combined with scanning measurement.

CD control systems usually have an array of identical actuators located across the web. For example, on a paper machine where variations in basis weight, mass per unit area, are regulated by a dilution headbox, there can be up to 300 actuators. MD variation is usually controlled with the feeding pump.

We have developed a simulator that enables us to compare how various estimation methods interpret the measurement signals, and how various control algorithms manage the 2D variation. In particular, the general goal of our research is to analyze how much 2D variations can be reduced with estimation methods, new scanning modes [7] and with new camera based measurements.

2 Simulator

We present a Matlab-based simulator for 2D quality variations of the paper web such that the effects of incoming – user defined or based on process data – variations and actions of CD and MD controls are combined. Arbitrary scan paths, estimation methods of 2-D variation, methods of separation to CD and MD components, and CD and MD control methods can be studied. Furthermore, the inaccuracy of process models in the control can be analyzed. As results the simulator provides the simulated quality variation, estimated quality variation and their variances, the estimate separated into CD and MD variations, and the CD and MD control actions and the effect of the controls. Furthermore, the measurement and prediction error signals can be studied. Hence the overall control system performance and the robustness, of the estimation and control algorithms can be assessed.

The web is represented as a matrix whose rows stand for MD units and columns CD units. The size of the simulated web is user specified. In practice, the MD unit may be for example fractions of second and the CD unit one centimetre resulting typically in data matrices of 1000 (CD) x 10000 (MD). As the MD unit sets the time scale it determines also the dimensionless scanning speed, estimation interval and control interval in the simulator.

In the simulator the measurement mode can be the regular scanning where scanner moves at constant speed across the web or the scanner path can be irregular, where the speed and the scanning direction can be changed during normal operation. Irregular scanning path can be defined by the user, it can be heuristically determined with rules on the basis of the analysis of the measurement signal – say, the prediction error signal – or eventually it can be optimized with respect to expected control performance, for an example of a simplified case, see [7]. Furthermore, measurements can be made with several sensors, even with a simulated camera producing 2D measurements so that the 2D measurements and the interesting variable are correlated but not one-to-one.

The estimation of CD and MD variations in the simulator can be done by filtering the scans, for example averaging 4-8 last scans. However, irregular scanning requires different kinds of estimation methods so that the estimation can be done also ate any times rather than after completed scans only. Kalman filtering methods are the natural choices to estimate with irregular scanning, implemented in the current version of the simulator. However, depending on system model, measurement model and approximate state representations many alternative kalman filters can be set up.

Both CD and MD control takes actions at user specified intervals. The CD control simulates e.g. the paper machine slice screw response model and the number of actuators is determined by the user. Typical shape of such an actuator response is shown in Fig 2. The optimal unconstrained CD control action is determined in steady state as

$$\Delta u = \left(B^T B\right)^{-1} B \Delta y$$

where Δu is the change in control actions, Δy deviation from set CD profile and B is the actuator-to-CD response matrix. Only a part of the optimal actuator change is implemented in one control step (commonly 10 %) which is roughly describing the dynamics and also the conservative way to control applied in industrial systems.

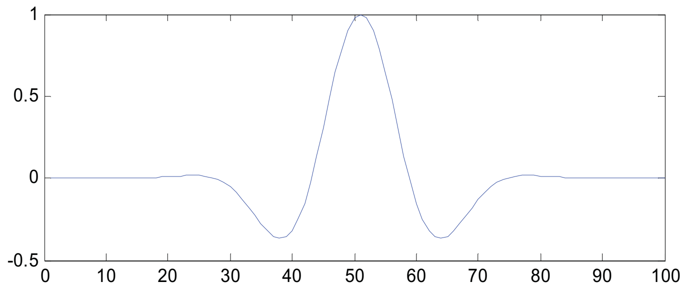

Figure 2 Actuator response

The MD component is controlled for example with PI-control but it can be replaced with some with other control methods, such model-predictive control.

At present the simulator is for a scalar quality variable only. In particular, we have considered paper basis weight or dry weight. Nonetheless, the model can readily be expanded to include other web process or quality variables. The simulator has been made modular to enable easy development and modifications of the functionality of the simulator in the future in particular for testing alternative estimation and control methods.

3 Simulation examples

Five simulation examples are shown. The first is a basic example in which the disturbance variations can be estimated and controlled. The others examples are problematic cases. The second example shows how incorrect CD control response model affects control performance. In the third case there are fast MD variations that can not be estimated because the period of the variation is shorter than the scanning crossing time. In the fourth case there are MD variations whose period is a multiple of scanning time. In the fifth case it is shown how structured residual variation affects to estimates.

In the simulations the web width is 500 units (a unit corresponding to a centimeter) the duration of the simulations vary but the MD unit corresponds to a second. The scanner is moved regularly with speed 50 cm/s, thus crossing the web is taking 10 seconds. The scanner is stopped for 5 seconds at the edges which simulates the acceleration and deceleration of the sensor system when turning. The scanner path is shown in Fig 3.

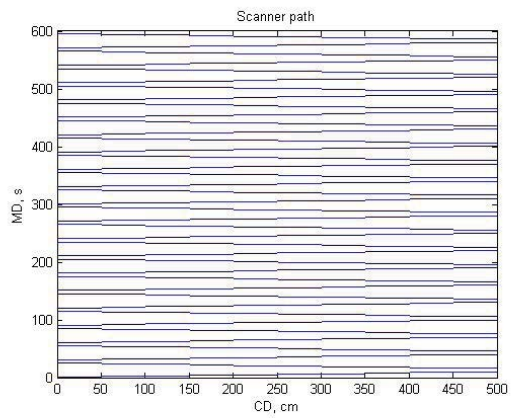

Figure 3 Scanner path

Estimation is done every second with a Kalman filter that has a model taking into account the control actions and a random walk noise model. CD variation is controlled with 50 slice screw actuators – response as shown in Fig. 2. MD variation is controlled with PI-control lambda-tuned with a model of a delay and second order dynamics. Both controls take action every 20 seconds.

3.1 Base case simulation

A bases case simulation for 600 seconds is presented. The control models are identical with simulated process response models. The incoming CD and MD variations are presented in Figure 4. The simulated variations in the web and the estimated variation are shown in Fig 5. In the beginning of the simulation incoming CD disturbance is clearly visible, but after 200 seconds the controls have reduced these variations. Due to the slow response of MD control its effects are not so visible.

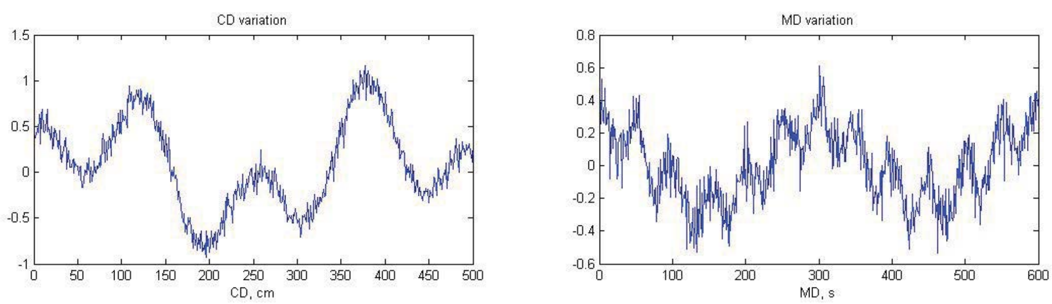

Figure 4 Incoming CD and MD variations

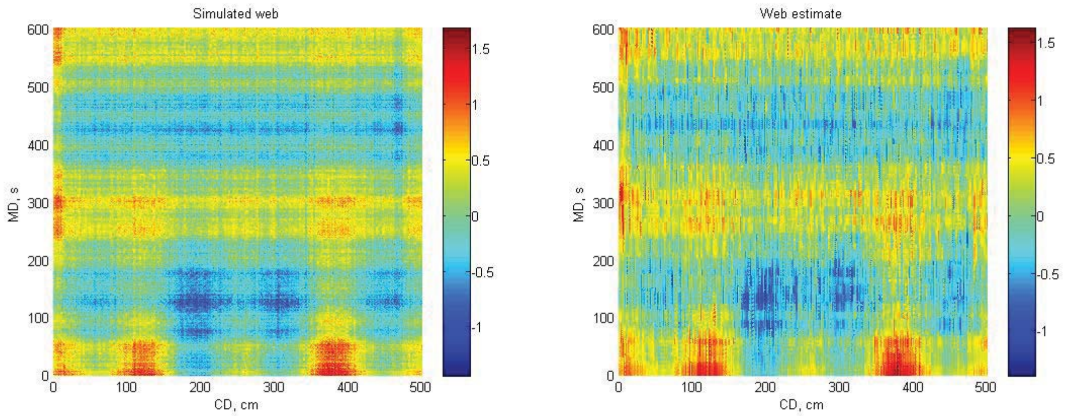

Figure 5 Simulated web and estimated web

Figure 6 shows the estimated quality variations separated in to CD and MD components, so that the MD estimate is the mean of the web estimate at each time instant and the CD estimate is the web estimate without the mean. In MD estimate graph the estimate is drawn with blue and the true MD variation with red. Because of the estimation and separation methods, the MD estimate lags slightly the true variation.

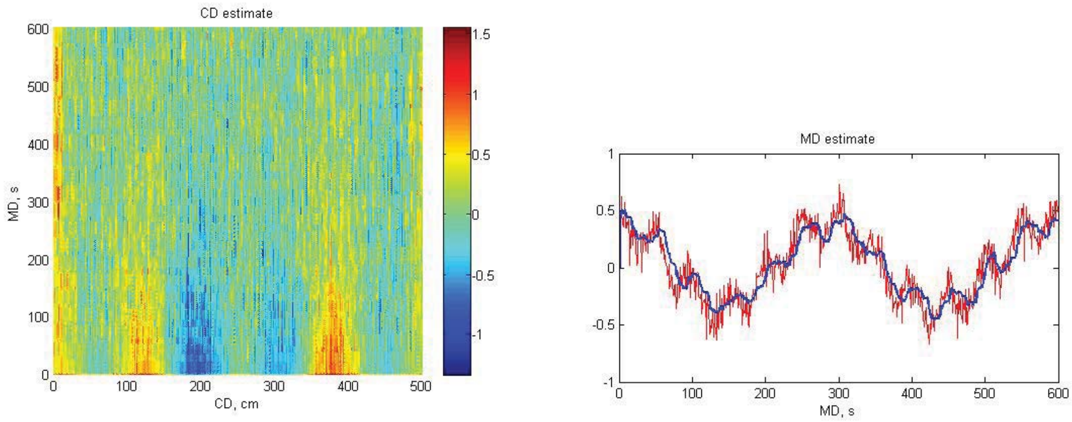

Figure 6 CD and MD estimates (estimate with blue and true variation with red)

Figure 7 presents the CD controls and the effects of the controls and the MD controls and the effect of the controls are shown in Fig 8. The slowness of the MD control is due the second order dynamics.

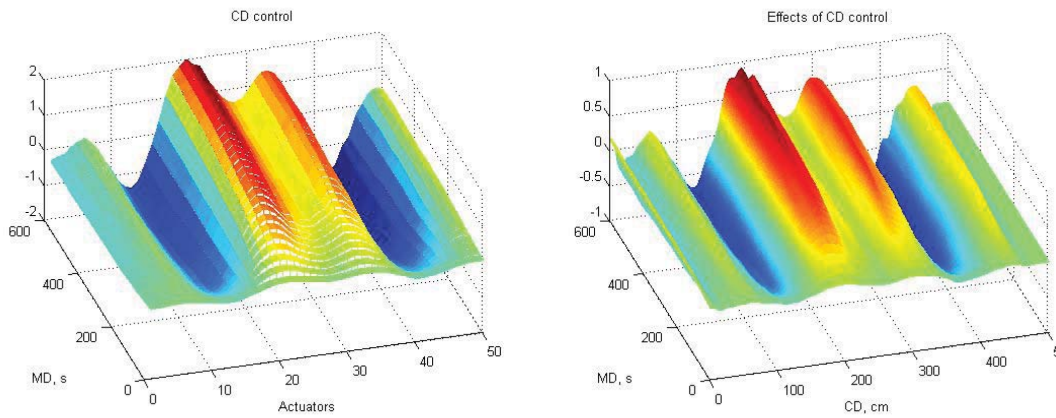

Figure 7 CD controls and effects of the controls

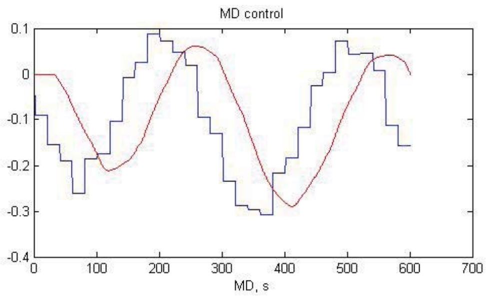

Figure 8 MD controls (blue) and effects of the controls (red)

3.2 Shrinkage

In the previous example the control models were identical with simulation response models, which give the best achievable performance. In reality there are always some modelling errors in the shapes of the actuator responses or in mappings of the actuator response to CD locations.

Paper web shrinkage is one common cause for CD response model errors. Shrinkage is large-scale nonuniform in CD so that the web is shrinking more near the edges than in the middle. This causes that both the locations and the shapes of the actuator response are distorted if incorrect web shrinkage model is applied in response modelling.

Three examples of shrunken response models are shown. In the first the shrinkage is the slightest and in the last largest. The incoming CD disturbance is the same as in the base case but now there are no other MD variations but white noise so that the affects of the shrinkages are easier to notice.

Figure 9 shows the shrinkage profile and in Fig 10 there are the simulated web on the left and the last simulated CD estimate on the right.

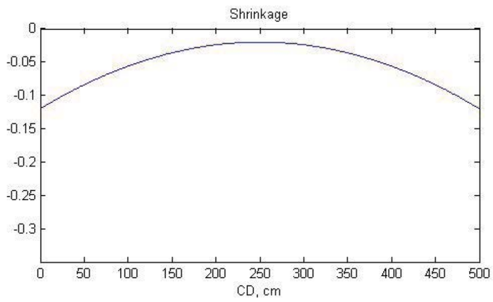

Figure 9 The first shrinkage profile

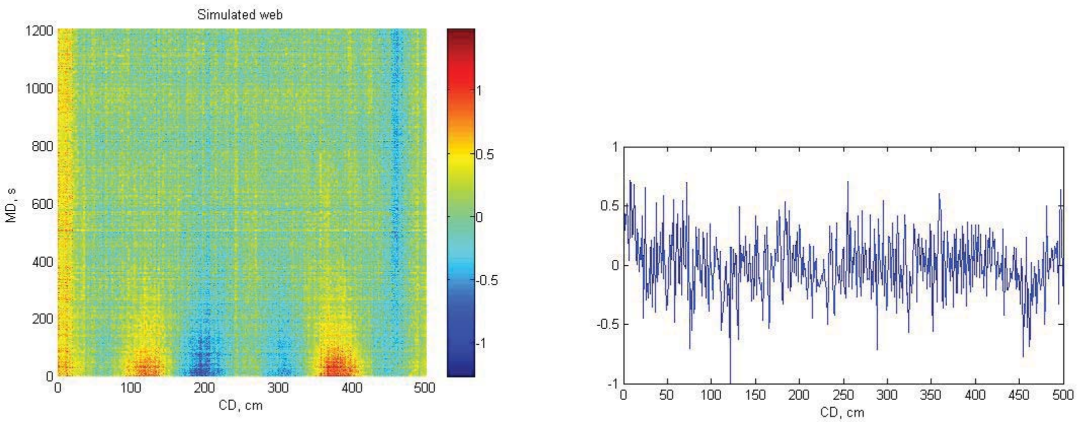

Figure 10 Simulated web and the last CD estimate with the first shrinkage profile

It can be seen that the estimation and control are almost not at all disturbed. Only position where the effect of the shrinkage response model can be seen is the low spot between 400 and 500 in CD.

The second shrinkage profile is shown in Fig 11. It is more significant than the first profile. The effects of it can be seen in Fig 12. There is a clear control mis-mapping near the edges that causes the control to increase the variations in locations where actuators are mis-mapped.

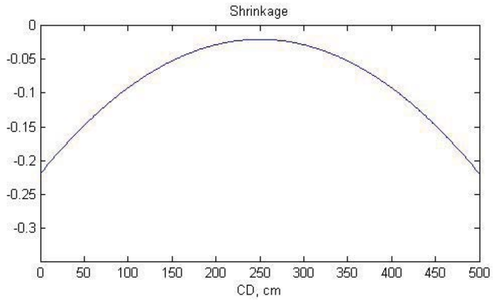

Figure 11 The second shrinkage profile

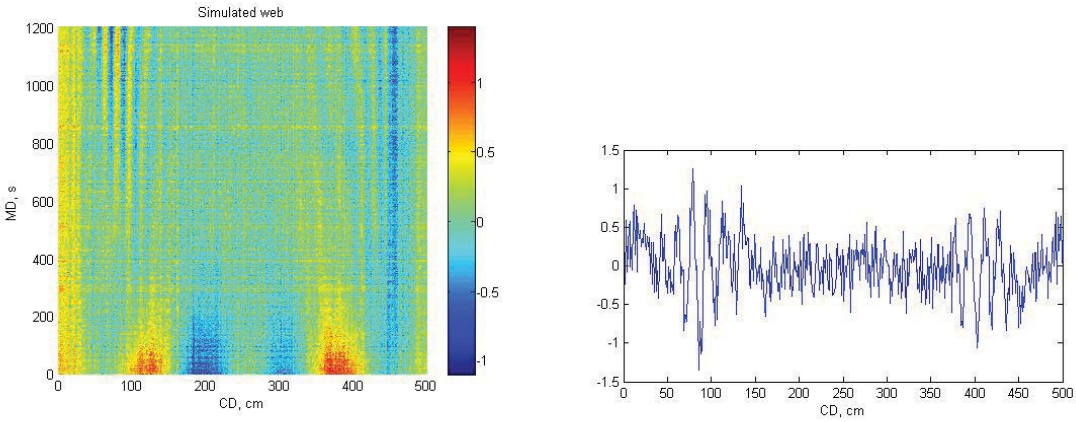

Figure 12 Simulated web and the last CD estimate with the second shrinkage profile

In the third case, the shrinkage profile is even more pronounced (Fig 13). Thus, the disturbances the control affects are more significant. The simulated web and its last CD estimate are shown in Fig 14.

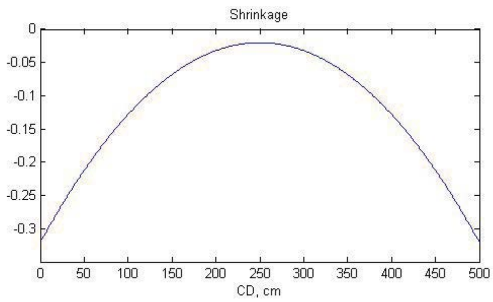

Figure 13 The third shrinkage profile

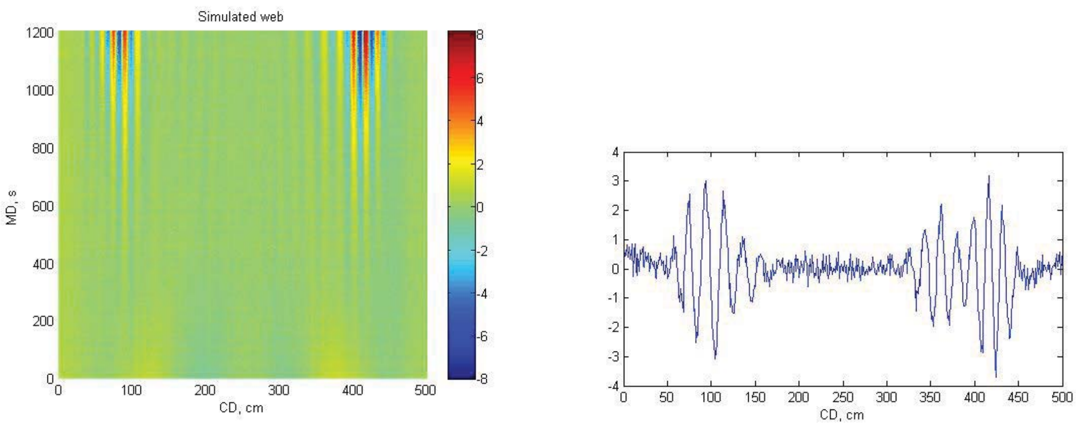

Figure 14 Simulated web and the last CD estimate with the third shrinkage profile

In all the three simulation cases shown above the simulated time was 1200 second. If the duration is longer, the variations caused by control would be higher in the two latter cases. Indeed, as the CD controller actions are not constrained in the simulation, the system may become unstable as a result of actuator model mis-mapping.

3.3 Fast MD

The MD estimate is often calculated as the mean of the CD estimate. This makes the MD estimation rather slow in reacting the true MD variation. This causes problems especially when the MD variations are fast.

This third case shows how fast MD variations affect estimation. In this example the frequency of the variation is 0.19 Hz. This means that the period of the variation is smaller than the scanner crossing time. There are no CD input disturbances. The simulated web and the scanning path is shown in Fig 15 on the left and the estimated web quality variation is on the right. Figure 16 shows MD estimate with blue and the true variation with red. As expected, the MD variation can not be estimated. In fact, MD variations are shown as CD variations at some positions thus making the CD estimates rather unstable.

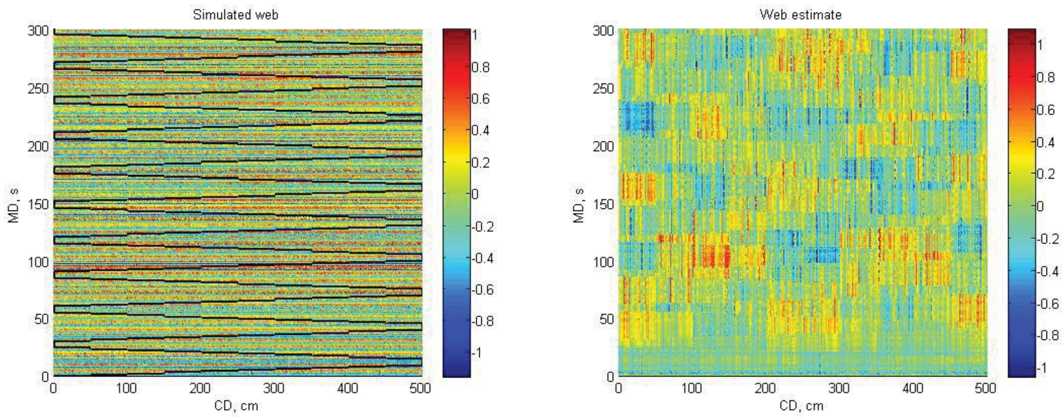

Figure 15 Simulated web and estimated web

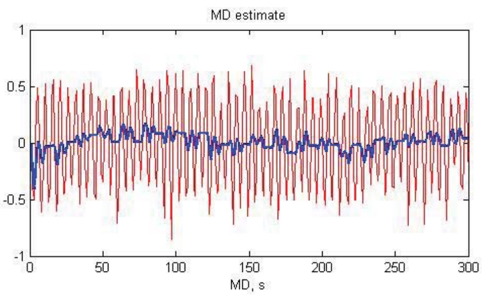

Figure 16 MD estimate (blue) and true variation (red)

3.4 Period of MD variation a multiple of scan time

In the previous case, the fast MD was mixed to the CD variations. That effect increases, if the MD period is a multiple of the scanning time. Then the scanner always sees the same phase of the variation in the same CD position. Here are three examples where the periodic time of MD variation is same, half and one fourth of the scanning periodic time. In each of the examples the CD input disturbance is flat.

In the first example the period of the MD variation is 30 seconds as the time that the scanner takes to move across the web and back. The simulated web and the scanner path are shown in Fig 17 on the left and the estimated web on the right. When the scanner is on the right edge of the web, it measures the top of the MD variation and on the left edge bottom. That causes that the form of the estimate quality. Figure 18 shows the MD estimates (blue) and true MD variation (red). Because of the slowness of the MD estimation the estimate is almost completely opposite phase to the real variation.

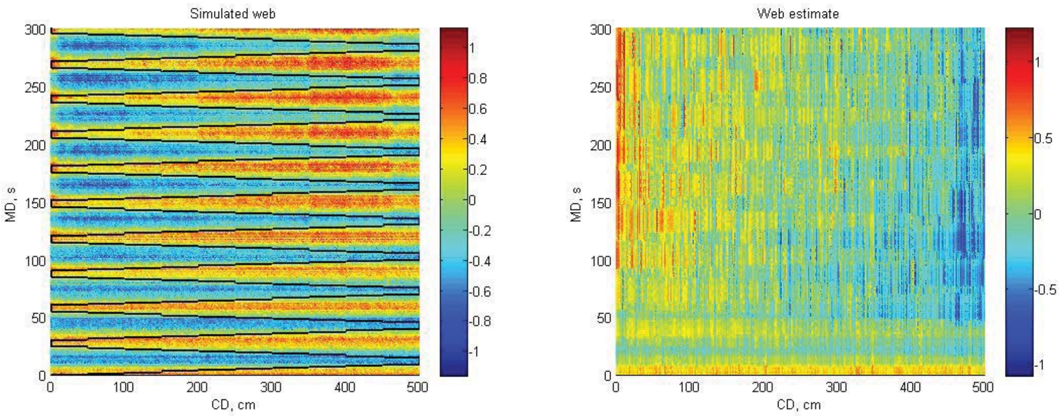

Figure 17 Simulated web and scanning path and estimated web

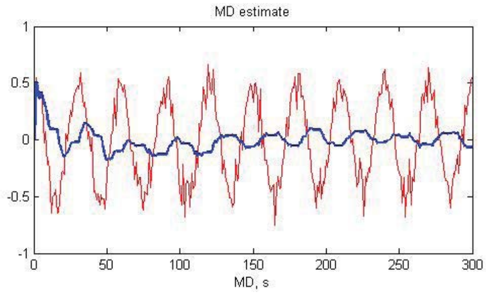

Figure 18 MD estimate (blue) and true MD variation (red)

Figure 19 shows the simulated web and the scanning path when the period of the MD variation is half of the scanning time. On the right is the estimated quality variation. Now the MD variations are interpreted as CD variations to both edges of the estimated web. The MD estimate is shown in Fig 20. As expected, the estimation can not handle such fast variations.

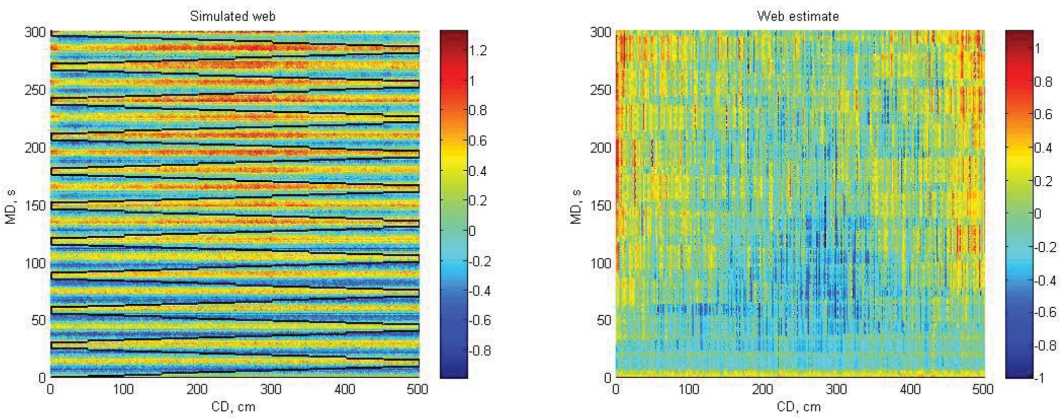

Figure 19 Simulated web and scanning path and estimated web

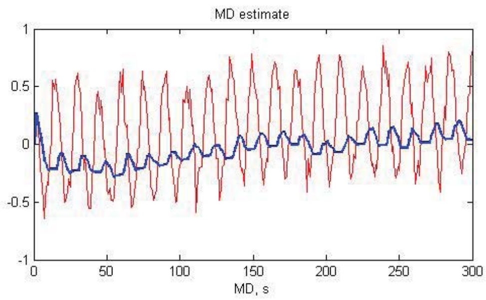

Figure 20 MD estimate (blue) and true MD variation (red)

The simulated web and estimate quality variation when the periodic time of the MD variations is one fourth is shown in Fig 20. The MD variations are shown as CD variations with different kind of pattern. Figure 22 shows the MD variation.

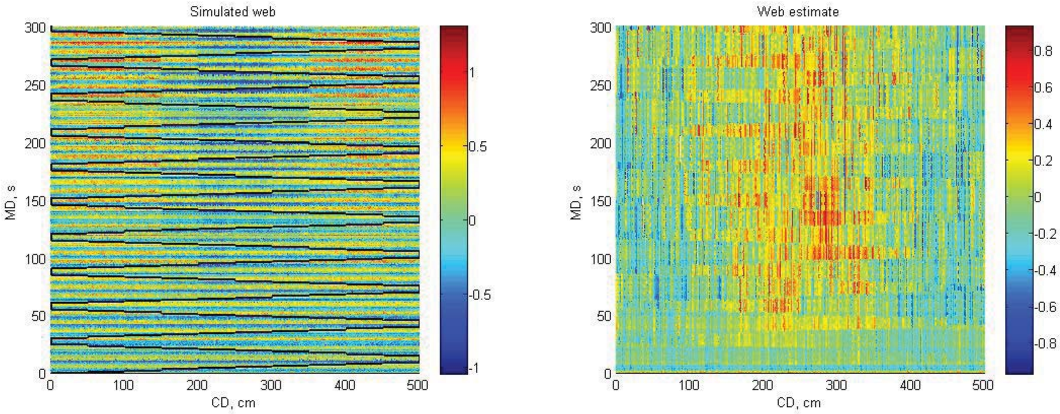

Figure 21 Simulated web and scanning path and estimated web

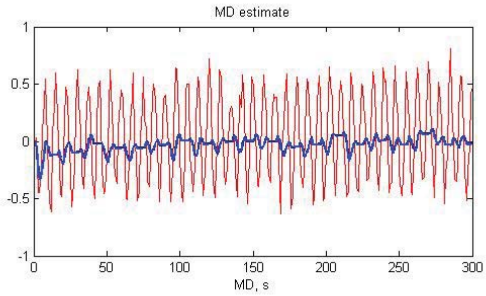

Figure 22 MD estimate (blue) and true MD variation (red)

3.5 Diagonal waves

Diagonal waves are not purely CD or MD variations but they are one kind of structural residual variation that is occasionally known to exist in a paper web. Residual variations can not normally be estimated and controlled. Thus structural residual variations are extremely harmful for estimation and control.

In this case the frequency of MD component is 0.07 Hz and the wavelength of the CD component is 0.01 1/cm. The simulated web with diagonal waves and the scanner path is shown on the left in Fig 23. On the right in Fig 23 is the estimated web where the diagonal waves are folded as CD variations. The CD and MD estimates are presented in Figure 24. As predicted there is no evidence of presence of diagonal waves in neither estimate.

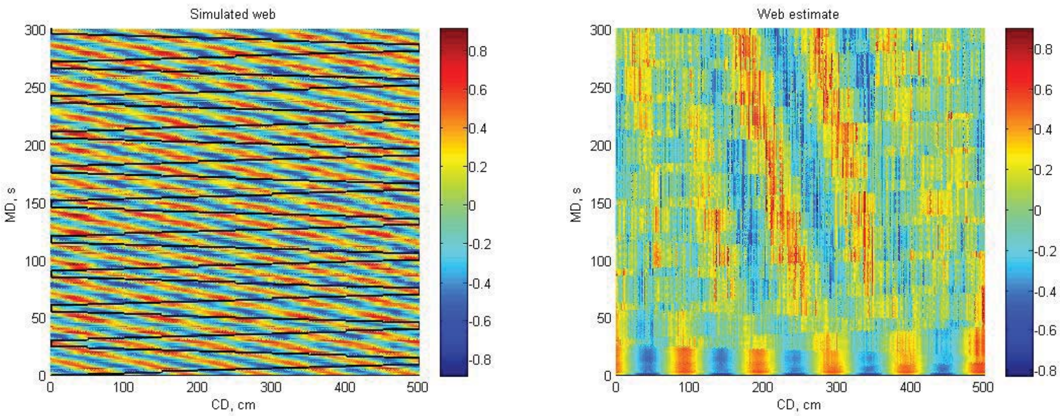

Figure 23 Simulated web and scanning path and estimated web

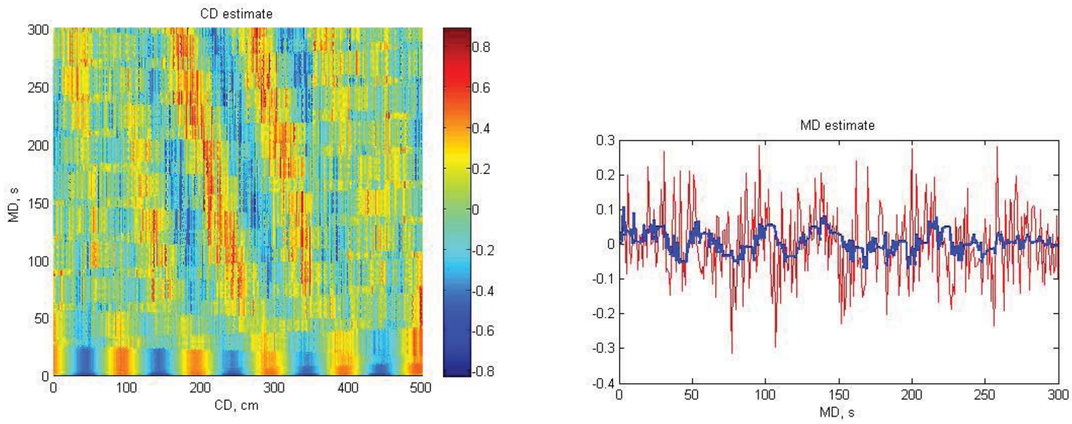

Figure 24 CD and MD estimates (estimate with blue and true variation with red)

4 Conclusions

The presented simulator provides a tool for studying the web forming processes. It is possible to change measurement modes and estimation and control methods. The simulator also produces possibility to study and analyze measurement signals that can be used for example to change measurement routine [7]. Due the modularity of the simulator, modifications are easy to implement.

5 References

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