Advanced Multivariable Fiber Orientation Control and Twist Optimization

Danlei Chu, Cristian Gheorghe, and Johan Backstrom

Honeywell Process Solutions, North Vancouver, BC, Canada V7J 3S4

ABSTRACT

Fiber orientation is an important sheet property that needs to be maintained within quality specifications. Failing to do so can result in twist, stress, and printability problems in paper and board manufacturing. Measuring and controlling fiber orientation online can provide the paper maker significant reductions in lost production. A CD controller needs modifications before it can be used to control fiber orientation since a different spatial process model is required. This paper covers modeling and control of fiber orientation with mill results from a multilayer board machine.

INTRODUCTION

Fiber orientation (FO) refers to dominant alignment direction of the fibers in a paper sheet. It can be expressed by the FO angle, the angle between the dominant fiber alignment direction and machine direction (MD). A camera based online FO angle sensor [1] makes it possible to continuously control FO angles. The FO angle profile is directly linked to the several paper quality properties, such as sheet strength and dimensional stability. A poor FO angle profile can cause many quality issues for the finished paper/board product. Examples are paper jams in sheet-fed devices, mis-registration in color printing, twist in multiply boards, weakening of corrugated containerboard, and poor runability of high speed newsprint.

Curl is defined as the inverse of the radius of curvature of a paper sheet. It has two representations: MD curl and CD curl. If the sheet is materially and structurally uniform, MD or CD curl can arise as a result of rapid drying which causes different shrinkage between the top and bottom sides of a paper sheet. When there is structural non-uniformity, i.e., the FO properties on the top and bottom sides are different, drying can cause twist in additional to curl [2]. Twist is the one of major paper deformation problems that paper mills want to reduce or eliminate, especially for multi-layer paper sheet products. In theory, twist can be formulated as a function of the thickness of the sheet, top and bottom FO angles, and CD and MD paper shrinkage. In practice, a twist proxy is expressed by the difference between the top and bottom FO angle profiles. A strong correlation between the FO angle difference profile and twist-curl is presented in [3] by comparing the offline measurement of the FO angle difference and the offline measurement of twist-curl.

The objective of this paper is to develop a multivariable model predictive CD controller to improve the FO angle and twist profiles.

PROCESS MODEL

A typical CD process, for example from the slice lip to dry weight or from water spray to moisture, can be modeled as a damped cosine function [4] that has low pass characteristics in the spatial frequency domain. This model is, however, not suitable for modeling a cross direction fiber orientation (CDFO) process. Numerous real mill tests have proven that the CDFO process has the band-pass characteristics in the spatial frequency domain [4, 7]. A two-component damped sine function was developed in [5] to model the CDFO processes. The model has five parameters: process gain, response width, attenuation, gain ratio, and width ratio. Both traditional single actuator bumps and the specific long wavelength bump tests were introduced for identifying these model parameters. This model has been implemented to a multi-layer board machine in Sweden, and mill trial results have shown that the model was able to accurately represent the spatial frequency characteristics of the CDFO process.

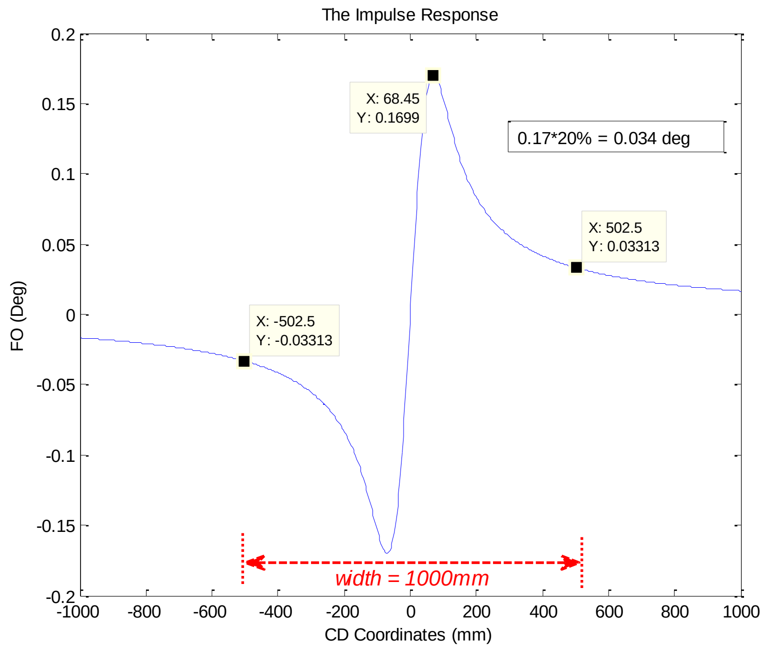

Figure 1: The spatial impulse response of CDFO processes

Based on the work of [5], this paper enhances the existing two component CDFO model. The number of model parameters is reduced from five to two. The two parameters of the new model are process gain and response width. Both parameters have the physical meanings: the process gain defines the peak value of the impulse response of a CDFO process, and the response width defines the location where the impulse response drops to 20% of the peak value. Fig. 1 illustrates the unit impulse response of the new CDFO spatial model. Here the process gain is set to 0.17 degree/mil and the response width is set to 1000 mm. Both parameters can be directly marked out from spatial impulse responses. This feature makes the new CDFO model more intuitive for engineers and easier to identify using automated identification approaches. Fig. 2 shows the gain spectrum of the simplified CDFO model in the spatial frequency domain. It can be seen that the new model still has the band pass characteristics in the spatial frequency domain.

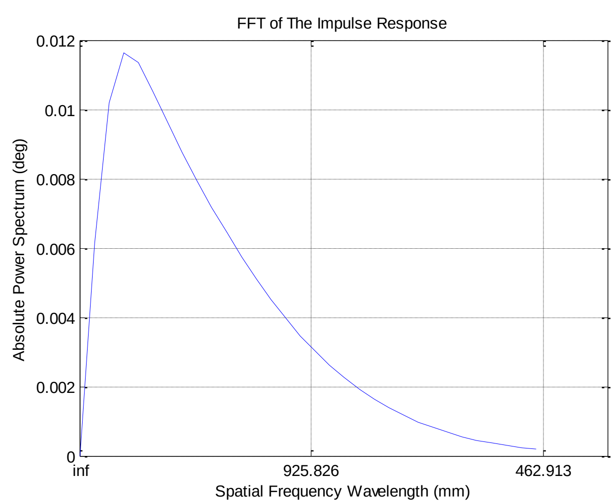

Figure 2: The gain spectrum of the impulse response of CDFO processes

Figure 3 shows the test results of the new CDFO model on a three-layer board machine in Finland. Six individual slice lip actuators formed into local sinusoidal waves are bumped on both the top and bottom headbox. The figure shows a high degree of fitness between the predicted FO angle profiles (dotted red line) and the FO angle measurements. The model parameters, process gain and response width are identified by using the two-stage model identification approach presented in [5].

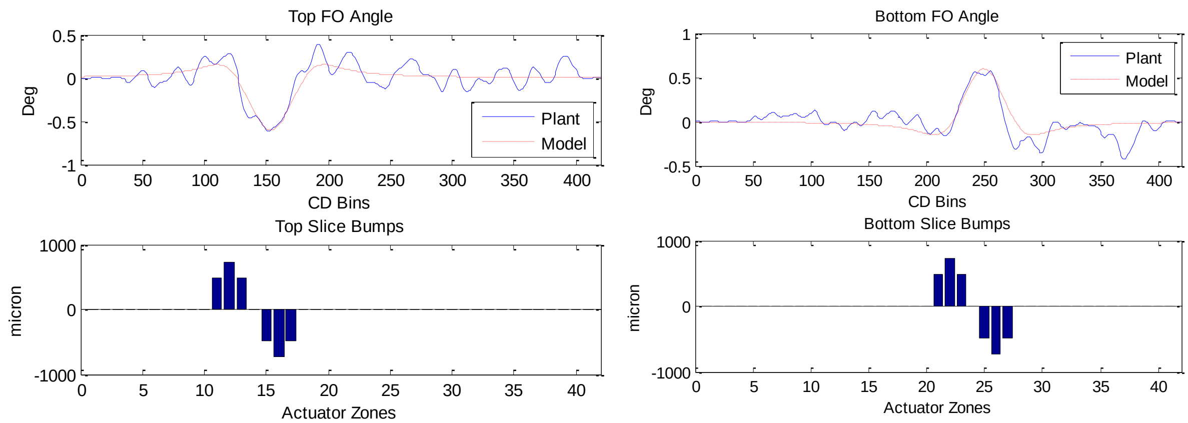

Figure 3: The Comparisons of model simulation and real mill data

CONTROLLER DESIGN

The fiber network of a paper sheet is established in the forming section of a paper machine. By regulating the opening of individual slice lip actuators, one can locally modify the stock flow propagation in cross direction and subsequently affect the local FO angle. Slice lip actuators are typically employed as the FO angle and twist control actuators. The change of slice lip actuator, however, has impact on the dry weight profiles in addition to FO angle profiles. Dilution headbox may be used as the dry weight actuator to attenuate the induced dry weight disturbances caused slice lip adjustments for FO angle profile correction. The design of CDFO controllers involves multiple actuator setpoint arrays and multiple measurement profile arrays; by nature it is a multiple-input-multiple-output (MIMO) feedback control problem.

Model predictive control (MPC) was first used in industrial CD control in 2001 [6] and has since been widely applied in paper, board, and tissue manufacturing. It can explicitly incorporate the process physical constraints in the controller design and formulate the controller design problem into an optimization problem. By design, cross direction MPC (CD-MPC) is able to handle the strong off-diagonal coupling of multiple CD actuator arrays and multiple CD measurement arrays systems.

A CDFO process has two types of process coupling: one is the coupling between different actuator beams and different quality measurements; and the other is the coupling between the different zones of the same actuator beams. As an example of the first type of coupling, the change of slice lip actuators affects not only FO angle profiles, but also twist and dry weight profiles. The second type of coupling is very strong for the CDFO process from slice lip to FO angle. The response width may reach 10 to 20 times the individual actuator zone width. In order to systematically handle these two types of process couplings, a CD-MPC controller is developed to regulate the FO angle and twist profiles.

Fig. 4 illustrates the design of the CD-MPC control system used for fiber orientation control. The system has an offline and an online component. From bump test data, including the traditional single actuator bump tests data and the specific spatial long wavelength bump test data, the process model $\boldsymbol{G}$ is first identified. The actuator edge padding block is used to capture significant edge effects seen in CDFO processes. It derives the padded process model G' from the original process model G. By using actuator edge padding, one can achieve CDFO average control in additional to CDFO variation control by slice lip actuators alone. The CD-MPC tuning component automatically determines the values of the tuning parameters, including predictive horizon, control horizons, and the input/output weighting matrices of the objective function. Moreover, the tuning algorithm provides closed-loop performance prediction of the CDFO process [8]. A user can review the predicted final on-control FO angle and twist profiles before turning the controller on. The model identification, actuator edge padding, and CD-MPC tuning blocks are implemented offline and the tuning parameters are transferred to the CD-MPC controller over the process control network.

The FO sensors are mounted on one or multiple scanner beams and traverse back and forward across the paper sheet to provide the dynamic FO angle profiles. The profiles go through a measurement post-processing block to generate the FO angle control profiles and twist proxy for CD-MPC control.

The gain retune block is designed to handle the nonlinearity of CDFO processes. Numerous mill tests show that the process gain from slice lip to FO angle (and twist) are highly dependent on the jet/wire ratio and wire speed. The gain retune block provides the updated process gain for the CD-MPC controller once there is the change to jet/wire ratio or wire speed.

The process gain retune block automatically triggers the CD-MPC retuning algorithm. The measurement weighting matrices of the objective function are updated by the CD-MPC retuning algorithm. The algorithm makes the CD-MPC fiber orientation control adaptive to the variation of the CDFO processes.

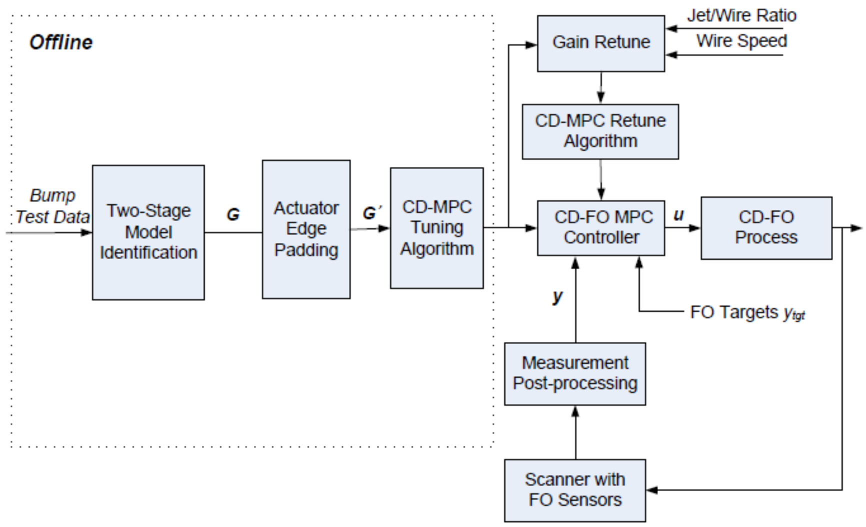

Figure 4: The CD fiber orientation MPC controller

ACTUATOR EDGE PADDING

Actuator edge padding is designed to capture the strong edge effects of the process, which result from the fact that the stock flow exiting the headbox is not allowed to propagate freely in the cross direction. These edge effects enable the slice lip actuators to control the average of fiber orientation angle profiles (for machine- directional control). The actuator edge padding algorithm pads a set of virtual zones at the beginning and the end of an actuator beam. The number of padded virtual zones is calculated from the response width and alignment of the spatial fiber orientation model. The setpoints of virtual zones are determined by the actuator edge padding mode. Three different actuator edge padding modes are supported: flat, linear, and reflection. Fig. 5 illustrates these three actuator edge padding modes. In the figure, the white bars represent the physical actuator zones, and the black bars represent the padded virtual zones. Refer to [5] for the details of the actuator edge padding algorithm.

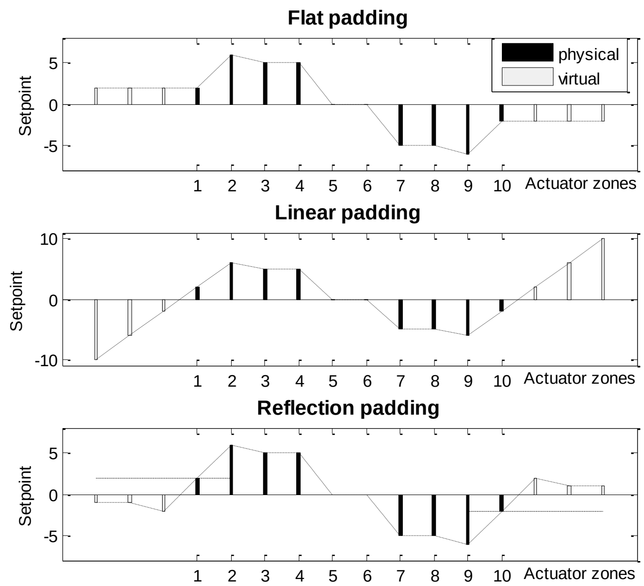

Figure 5: Actuator edge padding for CDFO control

GAIN RETUNE

The CD fiber orientation process is nonlinear with the process gain highly dependent on the difference between the jet speed and the wire speed (rushes or drag). Fig. 6 illustrates the gain retune function of the CDFO control solution. It includes three major components: a process gain table, a gain retune base function, and a process gain update function.

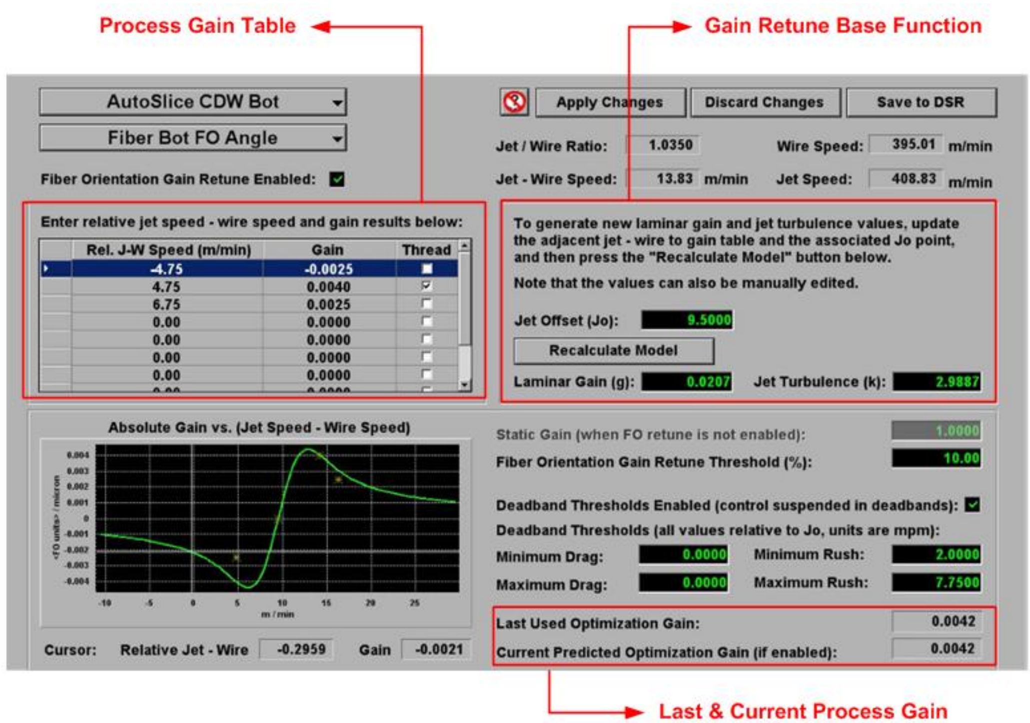

Figure 6: Gain Retune for CDFO control

The process gain table contains a set of (J-W speed, gain) pairs identified from a set of two-stage model identification bump tests.

The gain retune base function is a function of the jet speed minus the wire speed [5]. It includes three model parameters: jet offset (J_0), laminar gain (g) and jet turbulence (k). The jet offset defines the square point (neither rush nor drag) of the machine; the laminar gain defines the gain from slice lip to FO angle with pure laminar jet inside of the headbox; and the jet turbulence defines the degree of turbulence inside of the headbox. These three parameters are identified by the gain retune algorithm.

The current and last process gains from the slice lip to the FO angle are displayed at the bottom of Fig. 6. These gains are calculated by using the current jet/wire ratio and wire speed, which are displayed at the upper right corner of Fig. 6. The CDFO controller automatically adapts to changes in J-W speed through the CD-MPC controller retune function, which is automatically triggered when the process gain changes.

MILL TRIAL RESULTS

The CDFO solution presented here has been implemented on a multi-layer linear board machine in Finland. This section will use the mill trial results to illustrate the effectiveness of this solution.

The discussed machine produces one and two sided coated board for graphics and packaging, and has a capacity of 210,000 t/a, speed range from 200 – 550 m/min, wire width of 5.98 m, maximum trim width of 5.60 m, and base weight ranging from 170 to 500 g/m^2. Both the top and bottom headbox slice lip actuators are motorized and used to control top FO angle, bottom FO angle, and twist proxy (the top FO angle profile minus the bottom FO angle profile). The middle ply headbox dilution actuators are used for CD dry weight control. Two online FO angle sensors are installed on this machine and synchronized to measure the top and bottom FO angle profiles. Fig. 7 illustrates the multiple actuator arrays and multiple measurement arrays model used by the resulting CDFO process. The process gain and response width of each loop can be read out the spatial impulse responses in Fig. 7.

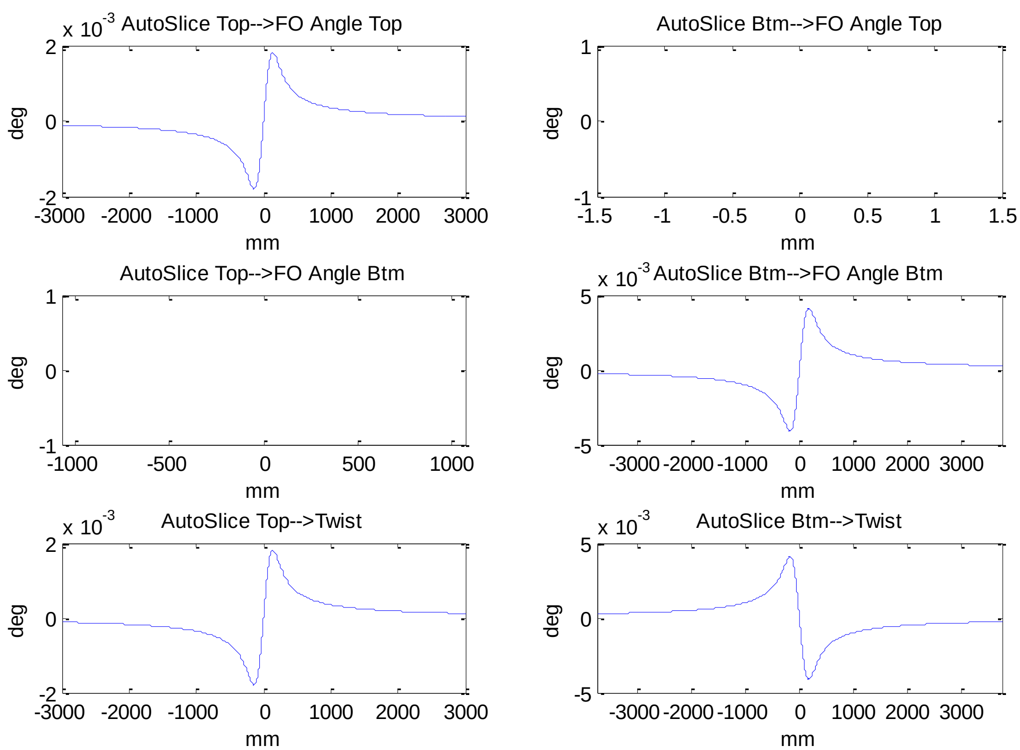

Figure 7: The Process Model of the CDFO Controller

Fig. 8 shows the steady state profiles before and after implementing the CD-MPC controller. From the figure, it can be seen that both the 2-sigma spreads (two times of the standard derivation) and the averages of FO angle profiles and twist profiles are improved significantly.

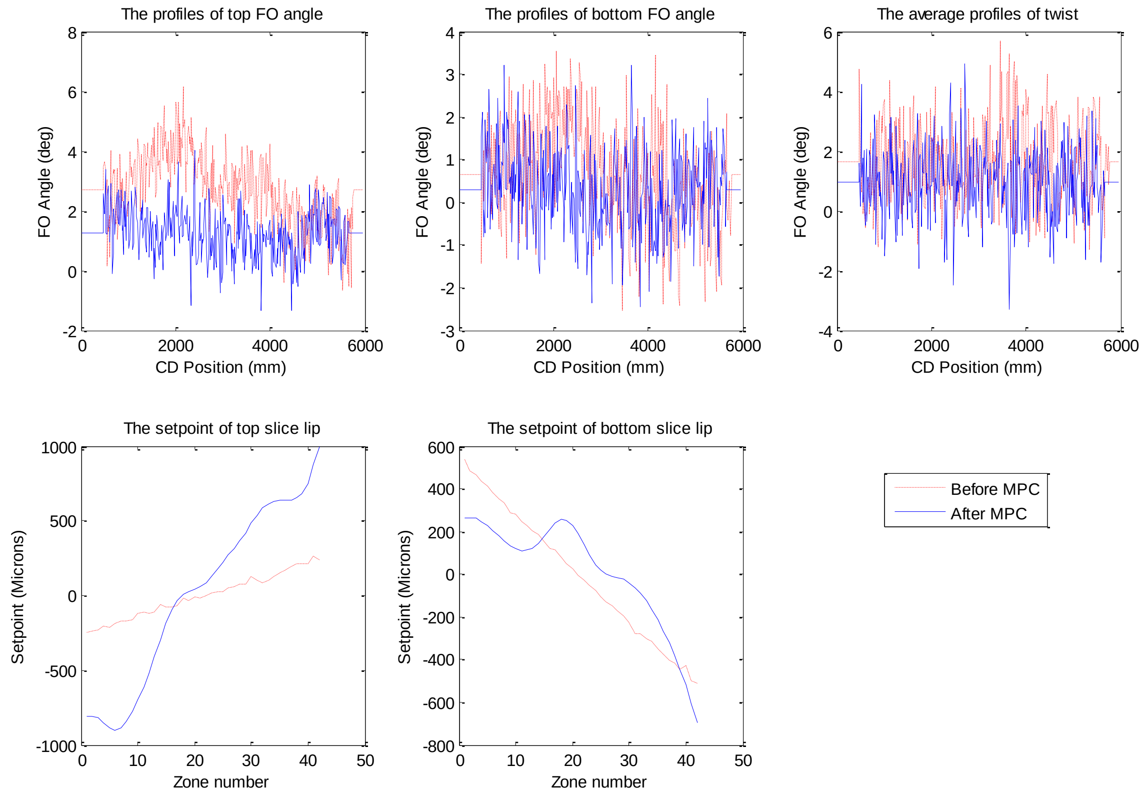

Figure 8: The steady state profiles before and after CD-MPC control

Fig. 9 shows the power spectrums of the steady state profiles before and after implementing the CD-MPC controller for the CDFO process. One can see that the long wavelength disturbances of FO angle profiles and the twist profile are attenuated effectively by the CD-MPC controller.

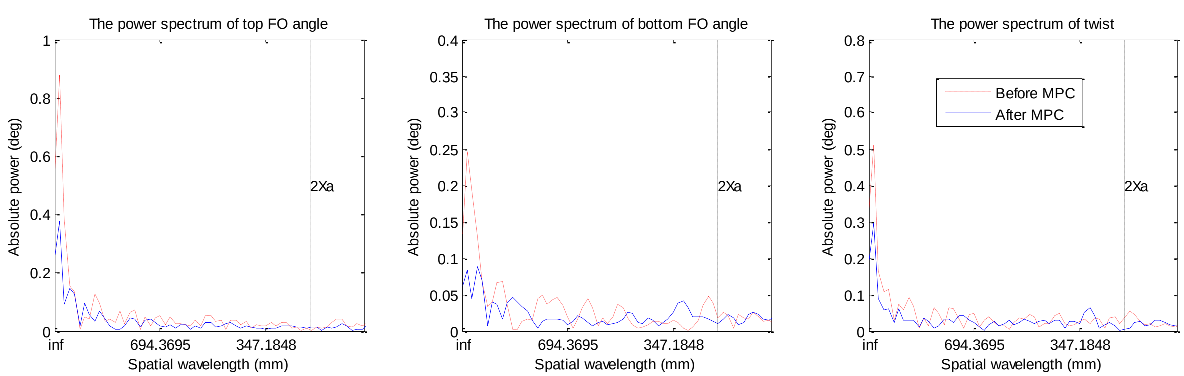

Figure 9: The power spectrum analysis of the steady measurement profiles

Table 1 summarizes the improvements in the average and two-sigma of the steady state profiles.

Table 1: Comparison before and after implementing the CD-MPC controller

Statistics / Meas.	Average			Two-sigma		
	Before	After	Improvement	Before	After	Improvement
FO Top	2.72	1.26	54%	2.26	1.54	32%
FO Btm	0.66	0.30	54%	2.33	1.85	20%
Twist	1.65	0.96	42%	2.50	2.20	12%

The twist is the most important quality measurement for this mill, specially the twist average value of the some production grades. The resulting CD-MPC controller may put more control emphasis on the twist profiles in order to improve the twist profiles further. Fig. 10 shows the testing results on a production grade of this mill after re-tuning the CD-MPC controller with higher emphasis on the twist profiles. Comparing with the initial profiles (dotted red lines, the profile before MPC), the final twist profiles (blue solid line, the profile after MPC) has a smaller two-sigma spread (two time of the standard derivation) and a much smaller average values. The average was reduced from -0.63 degree to -0.006 degree (99% improvement), and the two-sigma was reduced from 0.92 degree to 0.84 degree (8.7% improvement). The significant improvement on the average value of twist profiles can be explained by doing the spatial power spectrum analysis on both the profiles before MPC and after MPC. The lower subplot of Fig. 10 shows that the absolute power spectrum of the twist profiles. The long wavelength disturbances of the initial twist profile (the profile before MPC) are effective attenuated by the CD-MPC controller.

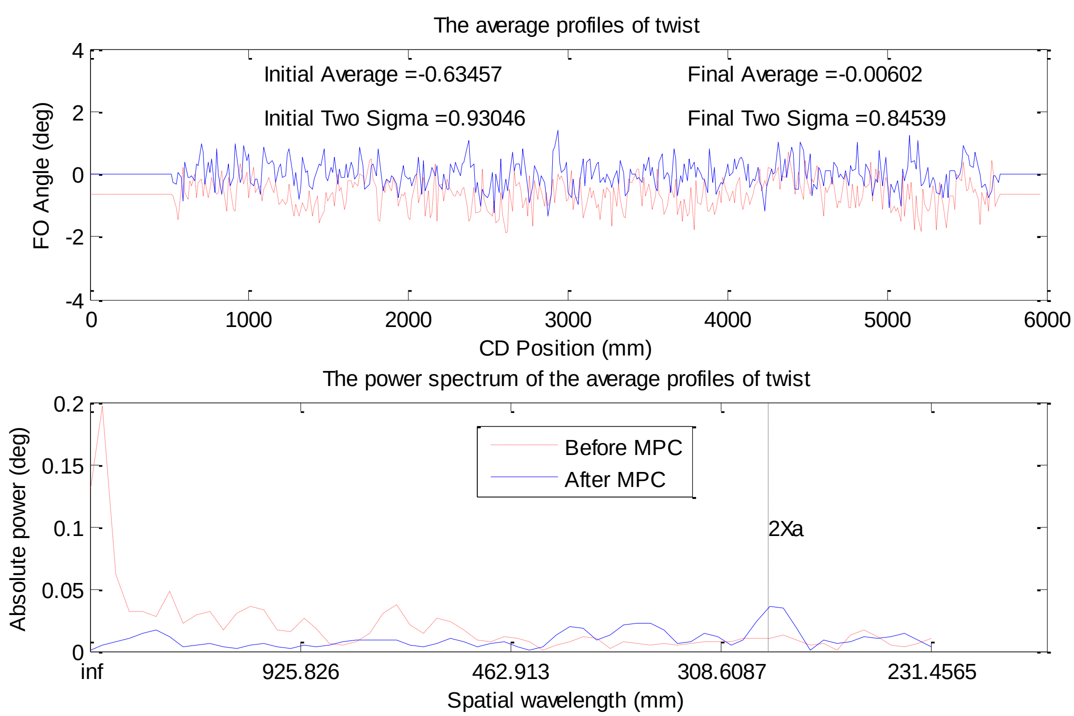

Figure 10: Twist Profiles before and after CD-MPC

Fig. 11 is the histogram of the twist average values of multiple reels. The green bar (light grey bar) shows the statistics of the reels with CD-MPC and the orange bar (dark grey bar) shows the statistics of the reels without CD-MPC. Here the twist average values are measured in the lab. Lab measurements prevent the influences of the calibration and measurement noises of the online FO sensors on the twist average values. The histogram in Fig. 11 clearly shows that the average twist values of all 6 production reels with CD-MPC have been in the range of $\pm$ 0.1 degree, while in the absence of CD-MPC some reels have twist higher than 0.2 degree.

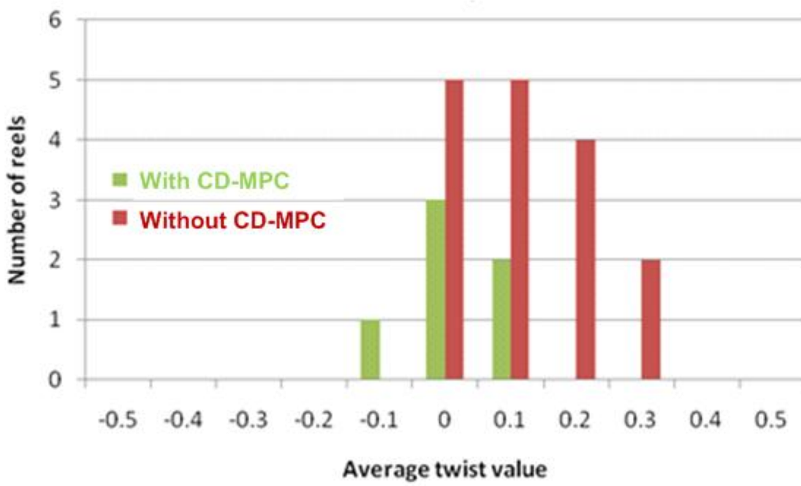

Figure 11: The histogram of the twist average values of multiple reels

CONCLUSIONS

Fiber orientation is an important sheet property for many paper and board products. Multiple paper qualities are highly dependent on fiber orientation, of which web strength and dimensional stability are the most important. In order to accurately model a CD fiber orientation process, a new spatial model structure is proposed and a two-step system identification approach is introduced. The resulting spatial model for CD fiber orientation successfully captures the process characteristics over all spatial wavelengths. The new process model, actuator edge padding, and gain retune functions are systematically integrated into a CD-MPC controller. The CD-MPC fiber orientation controller has been implemented at multiple mills and trials have shown that significant quality improvements in fiber orientation and twist profiles can be attained.

REFERENCE

[1]. J. Shakespeare and A. Paavola, "Online measurement of surface fiber orientation," in *Papermaking Research Symposium 2009*, Kuopio, Finland, 2009

[2]. J. Shakespeare, "Tutorial: Fiber orientation angle profiles – Process principles and cross-machine control", in *TAPPI Proceedings of PCEIC*, pp. 593 – 636, Vancouver, BC, Canada, 1998.

[3]. T. Sasaki, H. Sano, J. Yamamoto, K. Ono, and T. Ochi, "On-line fiber orientation measurement and control", in *Pulp & Paper Canada*, March/April 2010, p.p. T32 – T36.

[4]. D. Gorinevsky and C. Gheorghe , "Identification tool for cross-directional processes", in *IEEE Trans on Control Systems Technology*, Vol. 11, pp. 629-640, 2003.

[5]. D. Chu, C. Gheorghe, J. Backstrom, H. Naslund, and J. Shakespeare, "Fiber orientation modeling and control", in *Proc. Control Systems 2010*, pp. 202-207, 2010.

[6]. J. Backstrom, C. Gheorghe, G. Stewart, and R. Vyse, "Constrained model predictive control for cross directional multi-array processes", in *Pulp & Paper Canada*, May 2001, pp. T128– T102, 2001.

[7]. S. Chen, J. Berggren, and A. Zehnpfund, "Closed-loop control of fiber orientation on sheet-making processes", in *Proceedings of TAPPI/PIMA PaperCon '08 Conference*, Dallas, TX, U.S., 2008.

[8]. J. Fan, G. Stewart, G. Dumont, J. Backstrom, and P. He, “Approximate steady-state performance prediction of large-scale constrained model predictive control systems”, in *IEEE Trans on Control System Technology*, 13(6), pp.884 – pp. 895, 2005.