Advanced Multivariable Fiber Orientation Control and Twist Optimization

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RETHINK PAPER:
Lean and Green

Outline

- Introduction to Fiber Orientation (FO)
  - *FO angle, curl and twist*
- Process Model
  - *Band pass characteristics in the spatial frequency domain*
- Controller Design
  - *Actuator edge padding (AEP) and gain retune*
  - Mill trial results
  - Conclusions

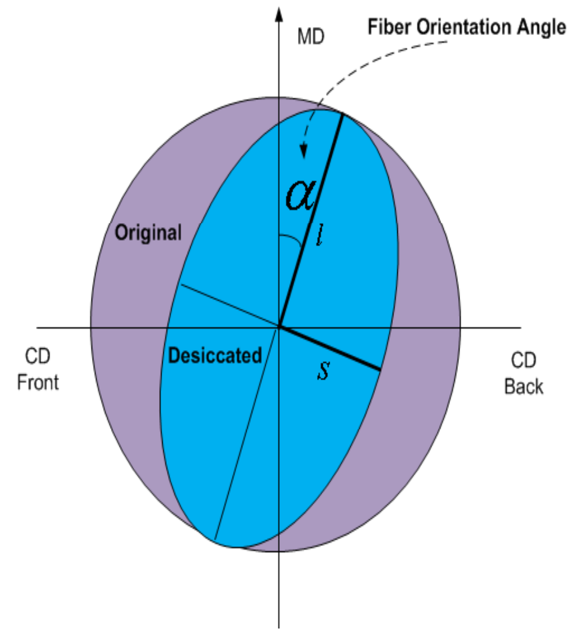
Introduction: Fiber Orientation

- Fiber orientation
  - Fiber orientation (FO) refers to the dominant alignment direction for fibers in a paper web. It can be expressed by a fiber orientation angle and a fiber ratio.

❖ α: Fiber Orientation Angle

❖ Fiber Ratio:

$$\frac{\text{Long Axis }(l)}{\text{Short Axis }(s)}$$



A cut and dry test

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Introduction: Practical Issues

- Several paper quality properties are highly related to fiber orientation, of which
  - The web strength, and
  - The dimensional stability are the most important
    (The ability of paper samples to retain their shape when subjected to varying degrees of temperature, moisture, stress, etc)
- Poor FO can cause multiple practical issues, including
  - Paper jam in sheet-fed device,
  - Mis-register in color printing,
  - Twist in multilayer board, and
  - Weakened corrugated containerboard.

Introduction: Curl & Twist

Rapid drying

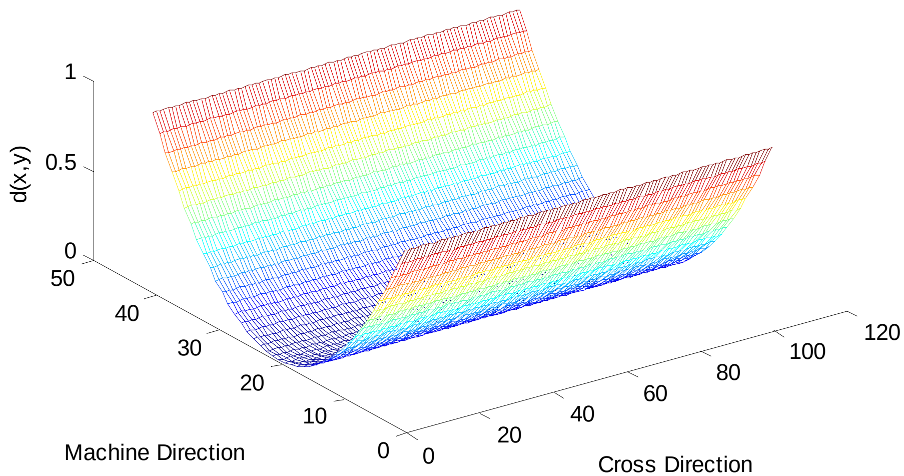
- Curl and twist are two measurements to indicate the deflection of a paper sheet

$$d(x,y) = k_x x^2 + k_y y^2 + k_{xy} xy$$

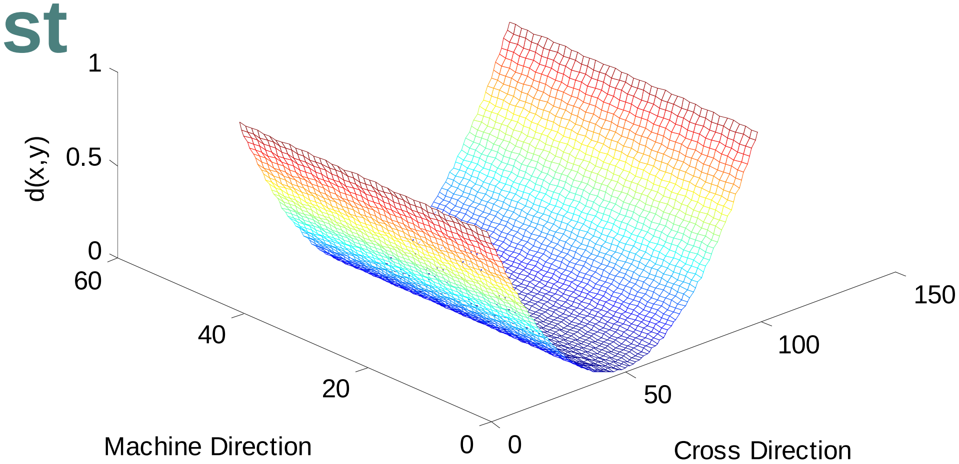
non-uniform FO properties

- x: CD coordinate
- y: MD coordinate
- k_x : CD curl coefficient
- k_y : MD curl coefficient
- k_{xy}: Twist coefficient (diagonal curl coefficient)
- d: deflection index

Introduction: Curl & Twist

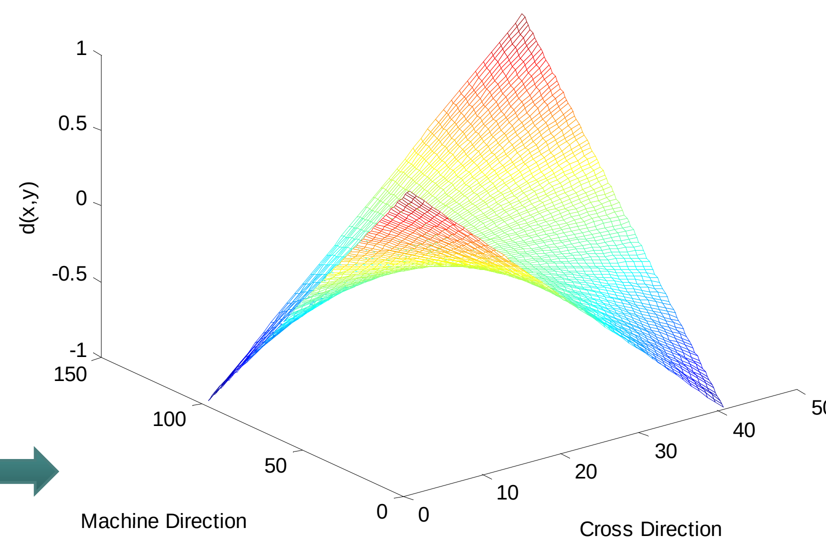


CD Curl



MD Curl

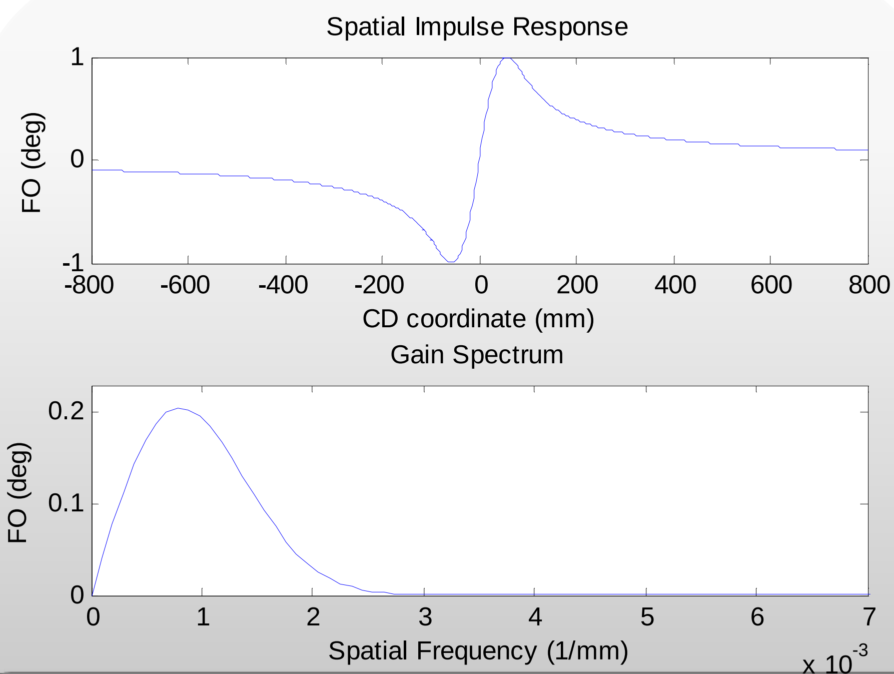
$$Twist = f(\theta_{top}, \theta_{btm}, \sigma_{CD}, \sigma_{MD}, \delta)$$
$$\approx \theta_{top} - \theta_{btm}$$



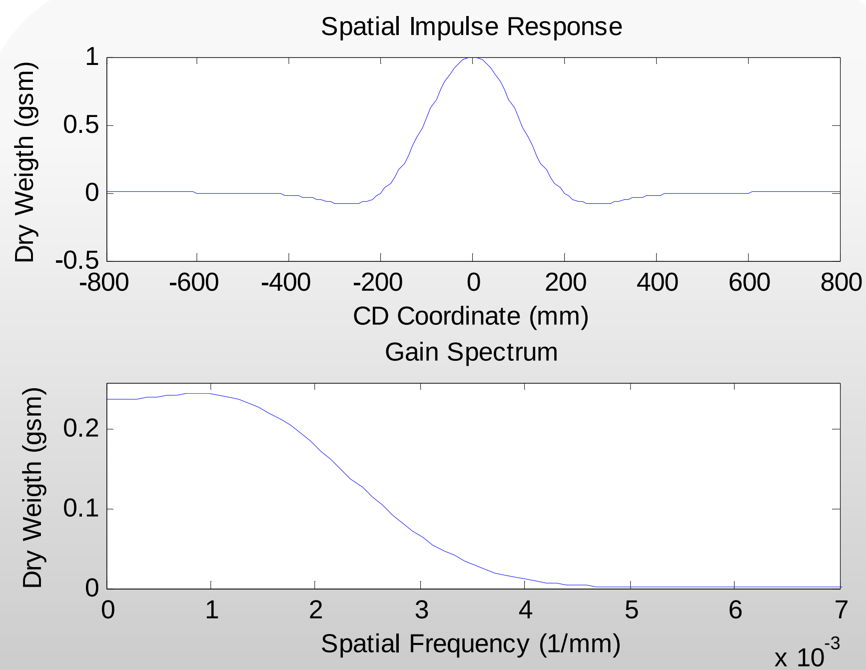
Twist

Process Model: Spatial Frequency Characteristics

- Compares CDFO Processes to Standard CD Processes



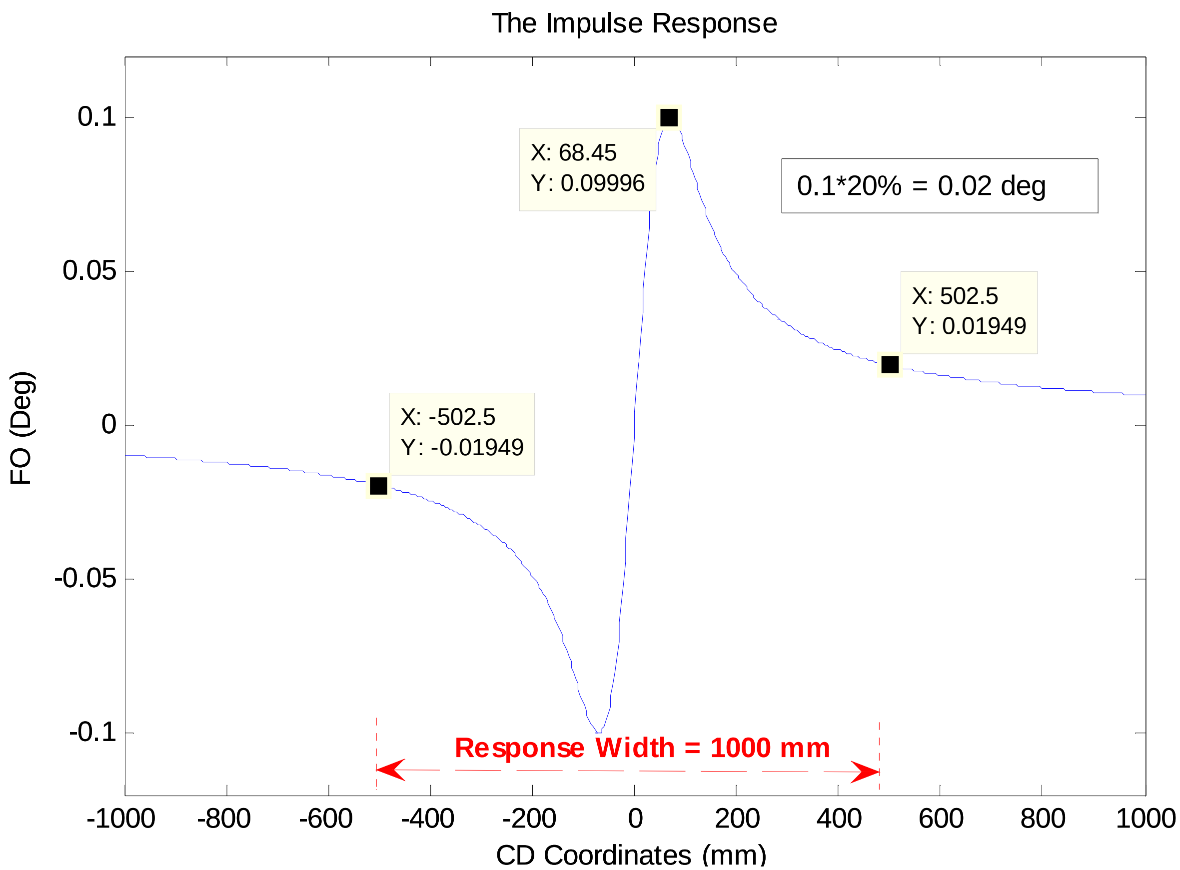
CD Fiber Orientation Processes
- Headbox Slice Lip → Fiber Orientation Angle
- band pass characteristics in spatial frequency



Standard CD Processes:
- Headbox Slice Lip → Dry Weight
- Low pass characteristics in spatial frequency

Process Model: Spatial Model

- Slice Lip → FO Angle Model



- *Process Gain*

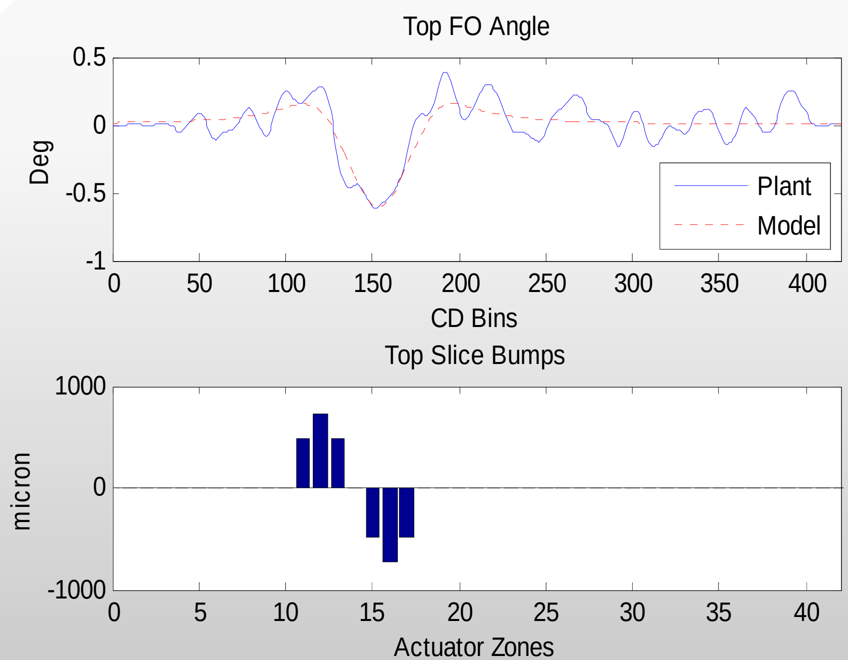
  Defines the peak value of the spatial impulse responses of a CDFO process
  (*gain = 0.1 deg/mil*)

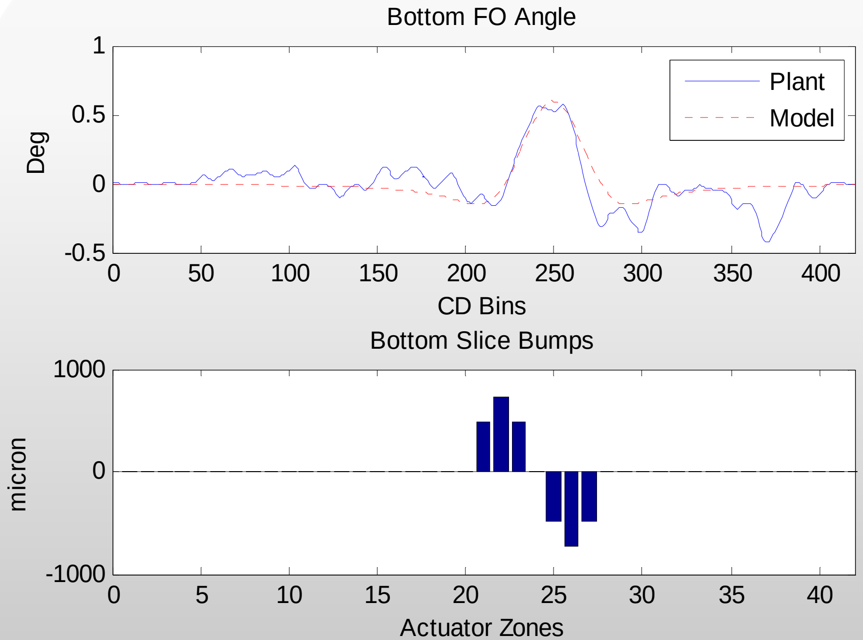
- *Response Width*

  Defines the location where the impulse response drops to 20% of its peak value
  (*width = 1000 mm*)

Process Model: Identification

- Model Test Results on a Three-layer Board Machine





Model identification results on the top headbox

- *Process Gain = -0.0025 deg/micron*
- *Response Width = 2000 mm*

Model identification results on the bottom headbox

- *Process Gain = 0.002 deg/micron*
- *Response Width = 2000 mm*

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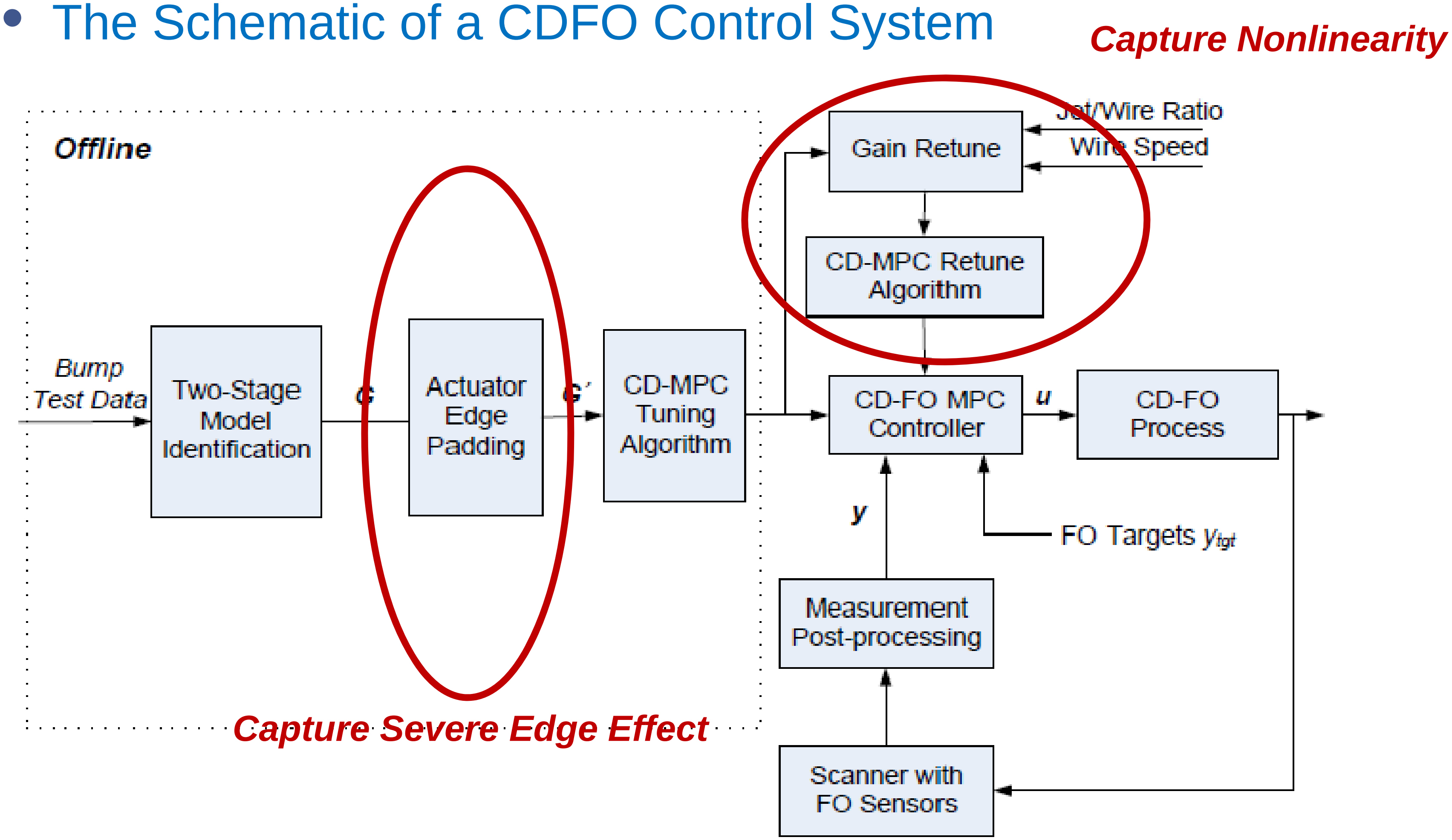
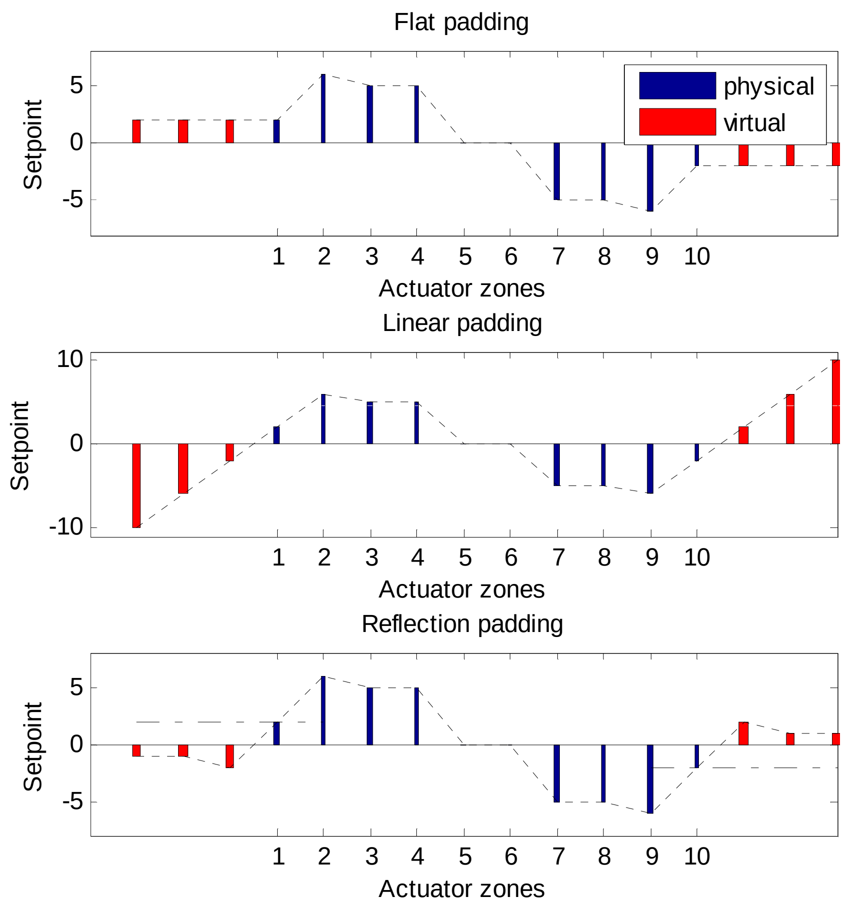
Controller Design

- The Schematic of a CDFO Control System



Control: Actuator Edge Padding

- Actuator Edge Padding Captures Severe Edge Effects



- $y = h(z) G_{aug} u_{aug}$
- $u_{aug} = \begin{bmatrix} u^{l}_{pad} \\ u \\ u^{h}_{pad} \end{bmatrix} = \Gamma_{\mathrm{mod}} u$
- $y = h(z) G_{aug} \Gamma_{\mathrm{mod}} u$

G'

MPC: Gain Retune

- Gain Retune Captures the nonlinearity of Fiber Orientation Process

$$g = \frac{g_{lam}}{q - q_0}\left(1 - e^{-\frac{(q-q_o)^2}{k}}\right)$$

- ***q*: the difference between the Jet Speed and the Wire Speed;**
- ***q_0*: The crossover point where the paper machine is operated in neither "rush" nor "drag"**
- ***g_{lam}*: Laminar Gain (Model Parameter)**
- ***k*: Jet Turbulence (Model Parameter)**

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Control: MPC

- The Fiber Orientation CD-MPC Controller

$$\min_{\Delta U(k)} \sum_{i=1}^{H_p} (\| Y(k+i) - Y_{sp} \|_{Q_1}^2 + \| \Delta U(k) \|_{Q_2}^2$$

$$+ \| U(k) - U_{tgt} \|_{Q_3}^2 + U(k)^T Q_4 U(k)$$

Subject to,

$$A \Delta U(k) \leq b - CU(k-1)$$ ⇐ ***Actuator Physical Limits***

$$Y(k) = \underline{G}\underline{h}(z) U(k)$$ ⇐ ***Fiber Orientation Process Model***

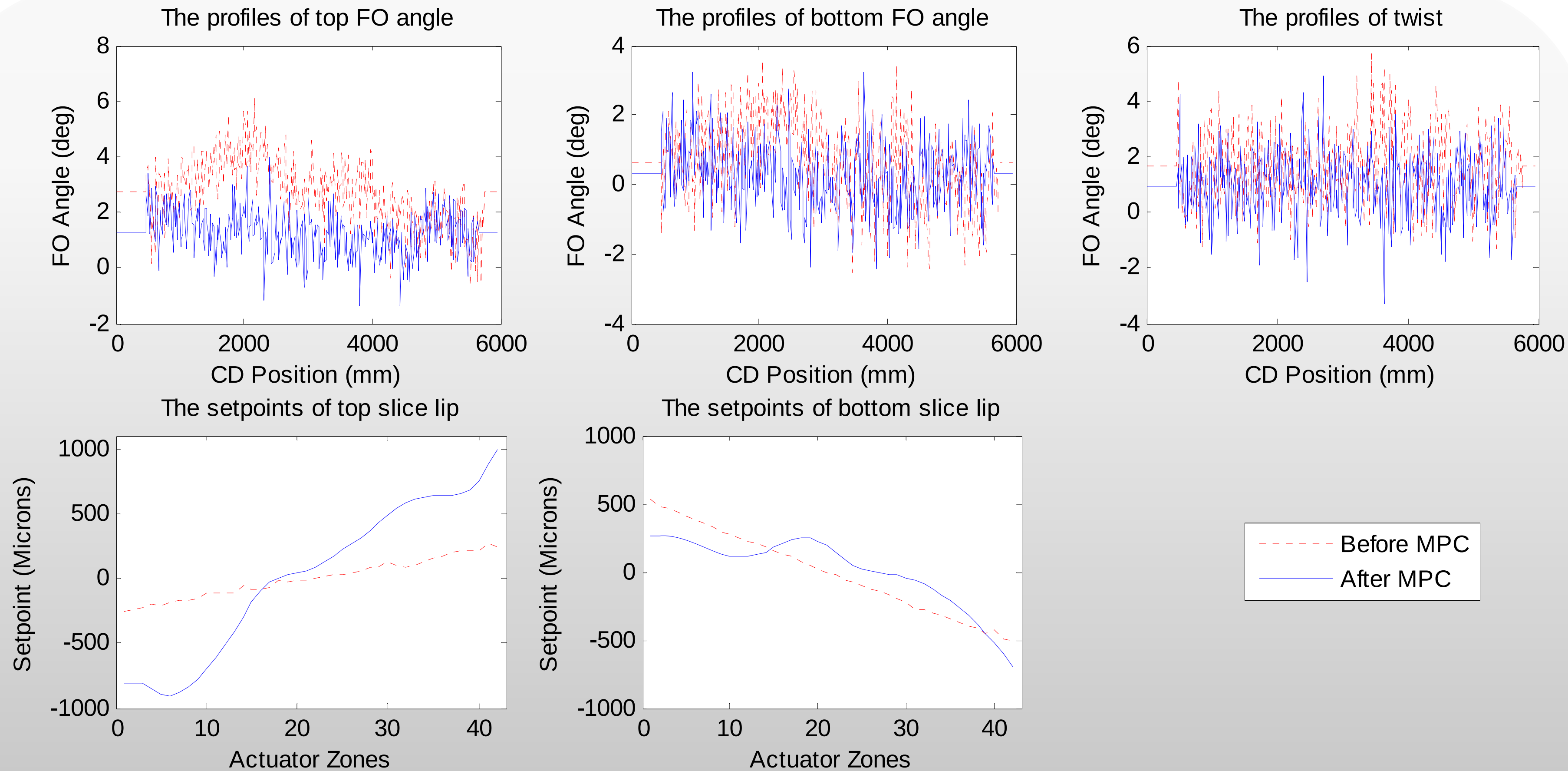
Besides FO angles and twist profiles, other CD measurement, (dry weight, moisture, caliper) can be optionally added to the above MPC controller.

Mill Test Results

- Mill Configuration
  - A multi-ply carton board machine in Finland.
  - Control Scenario

Controller Type	Actuators	Measurements (420 CD Bins)
MPC	Top Headbox Slice Lip (42 zones)	Top Fiber Orientation Angle
		Bottom Fiber Orientation Angle
	Bottom Headbox Slice Lip (42 zones)	Twist Proxy (Top – Bottom Angle)

Mill Trial Results - Profiles



Fiber Orientation Angles and Twist Proxy Profiles

- All controllable disturbances are effectively removed by the MPC controller.

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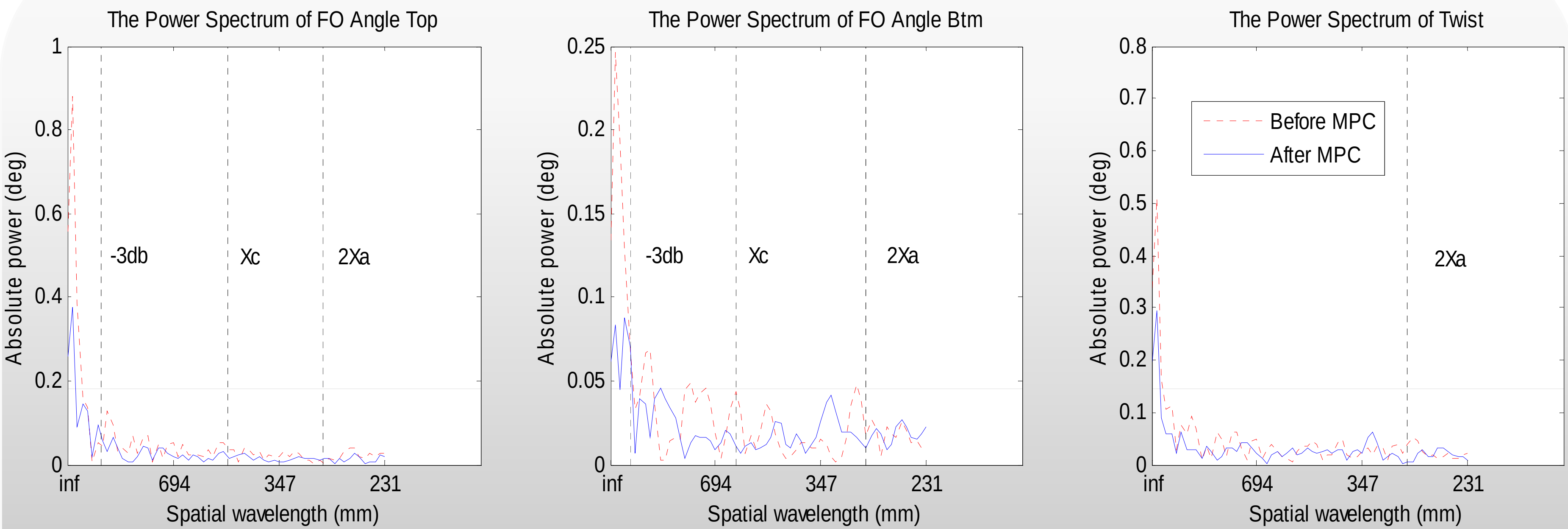
Mill Trial Results – Power Spectrum



Fiber Orientation Angles and Twist Proxy Profiles

- All controllable disturbances are effectively removed by the MPC controller.

Mill Test Results – Average & 2-Sigma

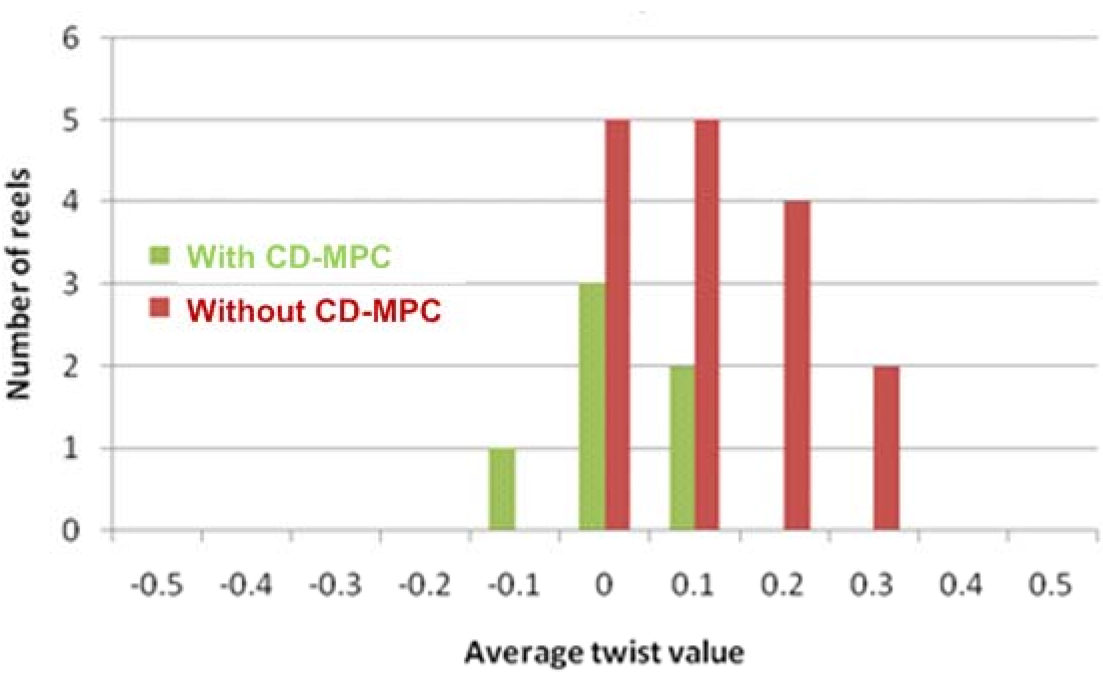
- Comparisons Before and After the Fiber Orientation Control

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%

***Both the averages and the 2-sigma spreads (two times of the standard derivation) of FO angle profiles and twist profiles are improved significantly*.**

Mill Test Results – Lab Measurements

- Comparisons Before and After the Fiber Orientation Control



Here, the twist average values are measured in the lab.

Conclusions

- The CDFO spatial model has only two parameters. The model is very intuitive and easy to identify.
- Actuator edge padding algorithm captures the severe edge effects of the fiber orientation process.
- Gain retune algorithm captures the nonlinearity of the fiber orientation process with respect to Jet/Wire ratio and wire speed.
- Automatic controller retune algorithms make the CDFO controller adaptive to the processes variation
- The resulting MPC controller is able to significantly reduce the variance of twist and CD fiber orientation angle profiles.