MULTIVARIABLE CD CONTROL WITH ADAPTIVE ALIGNMENT FOR A HIGH-PRODUCTION LINERBOARD MACHINE

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ABSTRACT

Paper quality has greatly benefited from the application of multivariable cross-direction (CD) controls. There are, however, some challenging production processes that require an industrial adaptive alignment solution to prevent the degradation of optimal performance due to sheet wander and sheet shrinkage. A high-production linerboard machine, where it is typical to have multiple CD actuator beams with narrow zone spacing controlling critical parameters such as CD reel moisture and dry weight for a wide range of production grades, is a common example of a challenging control opportunity.

The multivariable controller presented in this paper has been configured to minimize CD reel moisture and dry-weight variability by coordinating three CD actuator beams: a dilution profiler, a steam shower, and an Aqualizer™ rewet system. The challenges have been handled by configuring the multivariable CD controller to operate both dilution profiler and rewet system CD actuator beams with adaptive alignment.

INTRODUCTION

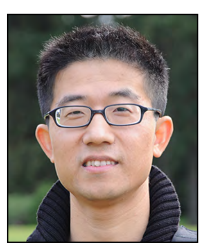
The application of cross-directional multivariable predictive control (CD-MPC) is becoming a trend in advanced control applications within the papermaking industry due to the excellent results achieved on all types of paper machines. The upgrade from traditional controls to CD-MPC on many paper machines has consistently shown improvements to the quality of the finished product. CD-MPC provides optimal coordination of the actuator beams controlling all sheet properties. The benefits of using CD-MPC in the paper industry are well documented in [2]–[11].

It is well known that a single actuator beam can affect multiple sheet properties and that multiple actuators can affect the same sheet property; for example, dilution profilers that are primarily designed to control dry weight have a strong impact on the moisture profile. A practical application to take advantage of this interaction is to coordinate the dilution profilers with steam showers and rewet systems to achieve optimal performance in reducing both dry weight and moisture profile variability.

CD-MPC uses multiple array-based models for all CD processes, which are identified using an industrial off-line identification tool [1]. The determination of tuning numbers to achieve optimal performance with CD-MPC within a reasonable time is also critical for its use in the papermaking industry. An industrial tool has been developed [2] that determines the tuning parameters using robust control tuning algorithms and takes physical constraints into account when predicting the steady-state and dynamic performance of the closed-loop system.

However, CD-MPC optimal performance achieved during commissioning can rapidly degrade due to varying sheet shrinkage and wander, which can lead to misalignment between the centres of individual CD actuators and the centres of the corresponding measurement responses. Misalignment may cause quality degradation in the finished product and unnecessary CD actuation at higher spatial frequencies, a phenomenon commonly referred to as “actuator picketing” by papermakers.

For the high-production linerboard machine described in this paper, in which 335 manipulated actuator zones are distributed over three actuator beams, the production challenges due to significant



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sheet shrinkage changes across a wide range of production grades have been addressed by implementing a centralized CD-MPC controller in which both dilution profiler and rewet system CD actuator beams operate with adaptive alignment [12]. The implementation of this strategy has significantly reduced the overall commissioning effort, has preserved the original CD-MPC optimal performance across all production grades, and has provided a financial benefit estimated at US$ 300,000 per year.

MULTIVARIABLE CONTROLLER

The underlying process model for CD-MPC with support for measurable disturbances is implemented using the augmented state-space representation described by Eq. (1):

$$X(k+1) = AX(k) + B\begin{bmatrix} \Delta U(k-T_d) \\ \Delta V(k-T_d) \end{bmatrix}, \qquad (1)$$
$$Y(k) = CX(k),$$

where $Y(k) \in \Re^{N_y m x 1}$, $U(k) \in \Re^{\sum_{j=1}^{N_u} n_j^u x 1}$ and $V(k) \in \Re^{\sum_{j=1}^{N_v} n_j^v x 1}$ are the measurement profiles, actuator profiles, and measurable disturbance profiles respectively. N_y, N_u, and N_v are the numbers of controlled sheet properties, actuator arrays, and measurable disturbance arrays respectively. m, n_j^u, and n_j^v are the common measurement resolution, the number of the j^{th} actuator array, and the number of the j^{th} measurable disturbance array respectively. T_d is the time delay, and k denotes the discrete time.

The optimization problem is formulated as a quadratic program (QP). The controller is implemented in velocity form, meaning that the controller outputs are changes to the actuator set-points rather than the absolute set-points. The optimization problem is reformulated at each control interval and solved using a specialized QP solver.

CD-MPC is different from a conventional MPC in two aspects, both resulting from the spatial component of the process. First, each CD actuator and CD measurement is an array rather than a single variable. This adds complexity to the implementation and results in very large system sizes. Second, the spatial aspects of the process come with specific control objectives that are not captured by a conventional MPC. Equation (2) shows the optimization formulation for CD-MPC. The optimization involves solving a quadratic objective function J subject to linear constraints.

$$\min_{\Delta U_{H_c}} \{J(\Delta U_{H_c}(t))\}$$

where

$$\begin{aligned} J(\Delta U_{H_c}(t)) = {} & E_{H_p}(t)^T Q_1 \hat{E}_{H_p}(t) + \Delta U_{H_c}(t)^T Q_2 \Delta U_{H_c}(t) + \\ & U_{H_c}(t)^T B^T Q_3 B_m U_{H_c}(t) + \\ & [U_{H_c}(t) - U_{H_c,\text{nominal}}(t)]^T Q_4 [U_{H_c}(t) - U_{H_c,\text{nominal}}(t)] + \end{aligned} \qquad (2)$$

subject to

$$AU_{H_c}(t) \le b(t)$$

where $E_{H_p}(t)$ contains the future predicted error profiles of the measurements over the prediction horizon H_p. The future predicted error profiles are a function of the current state, the process and measurable disturbance models, and the future actuator set-point profiles. $\Delta U_{H_c}(t)$ contains the future delta set-point profiles of the actuators, that are to be determined over the control horizon H_c. For prediction, it is assumed that the $\Delta U_{H_c}(t+k)$ are zero for time intervals beyond the control horizon. B_m is the bending moment matrix, and $U_{H_c}(t)$ contains the future absolute actuator set-point profiles. Each $U_{H_c}(t)$ term can be expressed in terms of $\Delta U_{H_c}(t)$ as:

$$U_{H_c}(t) = U_{H_c}(t-1) + \Delta U_{H_c}(t) \qquad (3)$$

The Q_i matrices are diagonal and contain the tuning parameters. The Q_i parameters all represent closed-loop quality aspects that are easy to explain.

Q_1 enables the user to specify the relative importance of the controlled sheet properties. For example, the moisture profile could be given more importance than the weight profile in a linerboard application.

Q_2 is used to specify the dynamic aggressiveness of the controller. The controller can be dynamically detuned by increasing Q_2.

Q_3 enables the user to specify the spatial aggressiveness of the controller. The controller can be spatially detuned by increasing Q_3. By selecting Q_3 appropriately, actuator picketing can be guaranteed not to build up over time.

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

For each tuning parameter, the user can apply different weightings to different measurement zones or different actuators across the sheet width.

The hard constraints are implemented in the form of matrices A and b in $AU_{H_c}(t) \le b(t)$, where A is a constant block matrix and b is a time-varying block matrix that is updated with each control execution. The hard constraints taken into account for CD control are:

- Maximum actuator set-points.
- Minimum actuator set-points.
- Maximum actuator set-point changes between consecutive scans.
- Maximum first-order bending limit.
- Maximum second-order bending limit.
- Maintaining CD actuator set-point averages within specified ranges.

Q_3 and the three last hard constraints are unique to the CD process and are not found in the standard MPC formulation. Please refer to [13] for a comprehensive description of CD-MPC.

MISALIGNMENT DETECTION

Misalignment detection has attracted considerable attention in both academia and industry. One on-line alignment diagnostic technique uses a vector auto regression (VAR) representation of the closed-loop CD responses [14]. This approach has been successfully implemented on a plastic film extrusion process over five years. However, the technique has the limitation that it applies only to traditional CD control systems with an explicit closed-loop representation. Another scheme monitors the CD alignment in closed-loop mode by calculating the fitness (cross-correlation) between predicted and measured CD profiles [15]. An advantage of this approach is that using the cross-correlation between prediction and measurement decreases the sensitivity of the detection algorithm. The drawback is that the algorithm cannot distinguish a cross-correlation change caused by a process model change from one caused by an alignment change or a CD disturbance change. A third method uses the concept of a local variability index (LVI) for on-line misalignment detection [16]. An LVI provides a more efficient index of CD misalignment than a global CD variance. However, like the previous method, it would have trouble distinguishing a CD disturbance change from a CD alignment change.

ADAPTIVE ALIGNMENT

Adaptive alignment works in coordination with CD-MPC to maintain the correct alignment between the zones of an actuator beam and the measurement locations at a downstream scanner. Adaptive alignment maintains the correct alignment by monitoring CD-MPC performance, identifying the alignment in closed-loop mode, and automatically deploying the alignment parameters with or without user intervention. The adaptive alignment technique has been presented in [12].

The overall adaptive alignment logic is illustrated in Fig. 1.

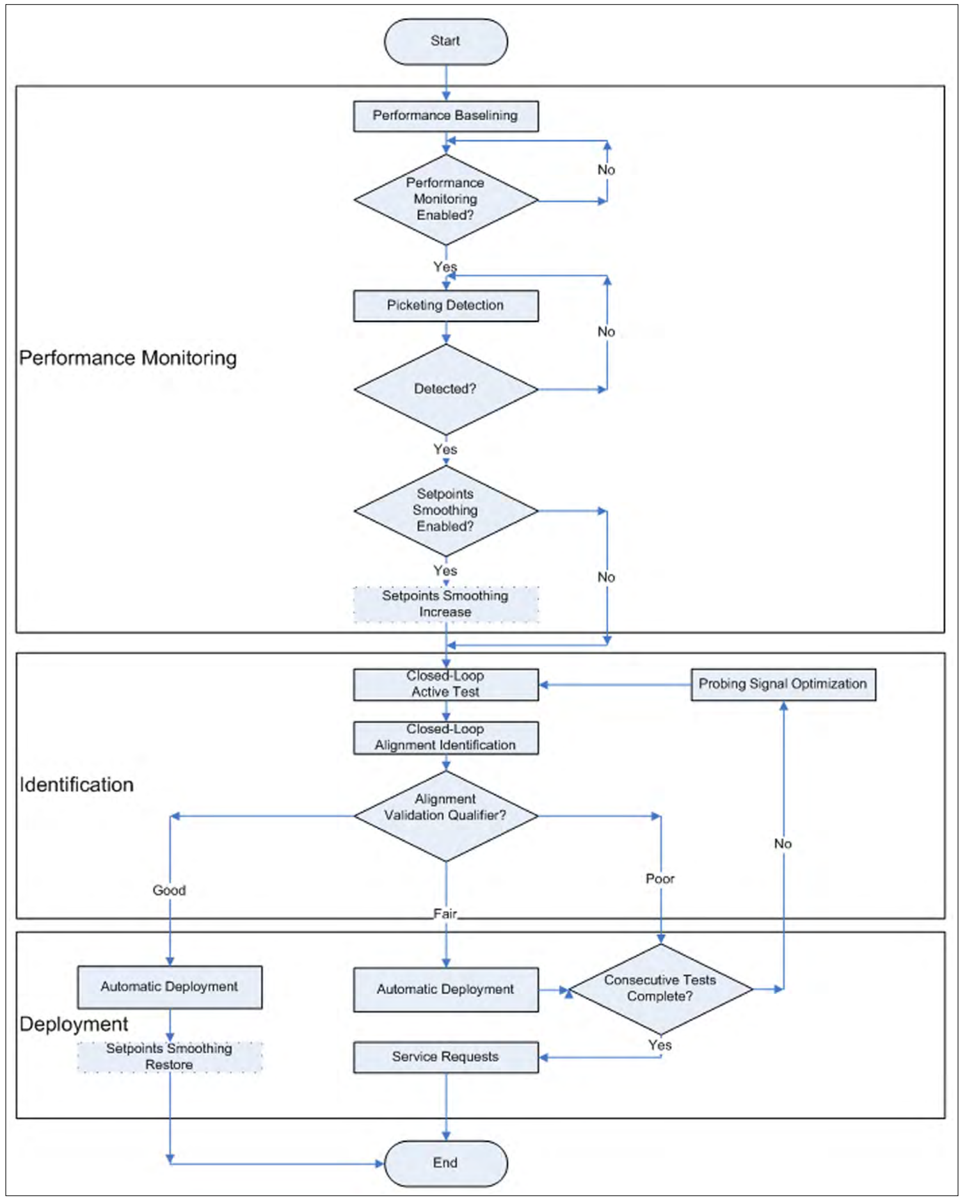

Fig. 1 - Adaptive alignment logic.

The performance monitoring function provides baselining of controller performance and monitoring of CD-MPC performance in real time. The objective of performance monitoring is to evaluate the current CD-MPC performance continuously against a recorded performance baseline to detect rapidly the onset of "actuator picketing". Actuator picketing refers to a specific actuator set-point profile pattern that is dominated by high-spatial frequency components and resembles a picket fence. This phenomenon is well-known symptom typically associated with CD alignment problems and occasionally related to very aggressive CD tuning.

Performance monitoring will automatically trigger a closed-loop identification test whenever the typical misalignment symptom of "actuator picketing" is detected. Optionally, after misalignment detection, performance monitoring can automatically smooth actuator set-points to mitigate the effects of misalignment by reducing the undesired high spatial frequencies in both actuator set-points and measurement profiles before calling the identification function.

The identification function performs the active closed-loop identification test required to calculate the alignment parameters using an intelligent closed-loop PRBS (pseudo-random binary sequence) "probing test" which is optimized for process conditions. A matrix inversion algorithm is used to extract the alignment parameters from the closed-loop data collected during the "probing test".

Compared to a traditional persistent open-loop "bump test", an adaptive PRBS

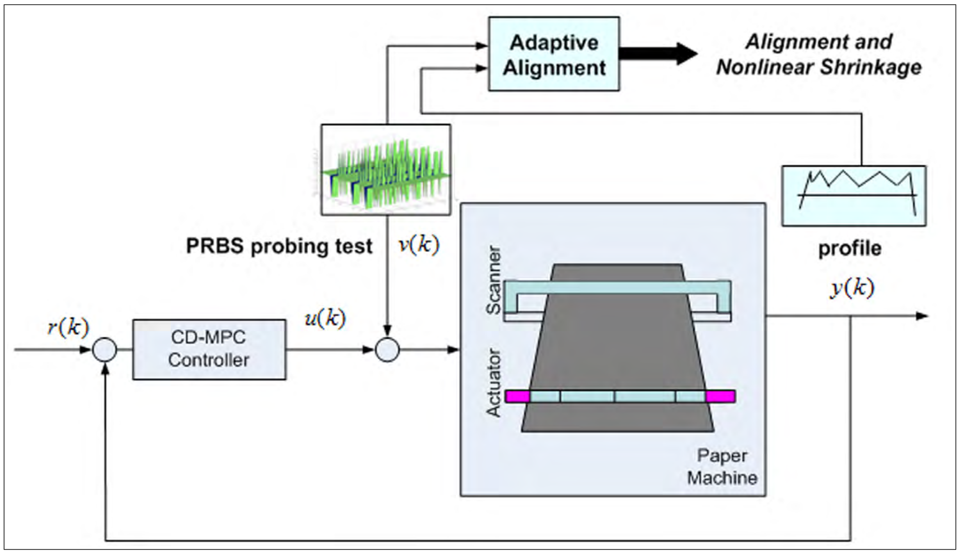

Fig. 2 - Schematic of closed-loop identification using PRBS “probing test”.

probing test reduces the CD variation that is induced in the sheet during the experiment. Another significant benefit of closed-loop identification is that normal process operation is not interrupted and process disturbances can be rejected by feedback control during the “probing test”.

The schematic of closed-loop identification using a PRBS “probing test” is shown in Fig. 2.

The objective of the deployment function is to ensure that the alignment parameters calculated and validated by the Identification function are correctly deployed to prevent any performance degradation that may occur in the presence of misalignment. If the value of a model validation qualifier is not sufficiently high, the identification test will be re-designed and then repeated for a user-defined number of consecutive trials. The deployment function can also generate service requests (alarms) when the adaptive alignment solution is operated in a user-assisted mode.

COMMISSIONING

The commissioning of a CD-MPC consists of plant process model identification, multivariable controller tuning, and adaptive alignment setup. Identification and tuning are performed using the industrial tools presented in [1] and [2].

PLANT PROCESS MODEL IDENTIFICATION

The high-production (up to 50 T/hour) linerboard machine produces liner with a basis weight range of 115–275 gsm. The CD control system consists of three actuator beams controlling dry weight and moisture. The headbox is equipped with dilution profiler actuators, steam shower actuators are installed in the press section, and an Aqualizer™ rewet system is installed in the third dryer section.

The CD-MPC takes into account the interaction of each actuator beam with sheet properties. An industrial identification tool [1] is used to identify the plant CD spatial and dynamic models. The spatial and dynamic impact of the dilution profiler actuators on basis weight, dry weight, and moisture is shown in Fig. 3.

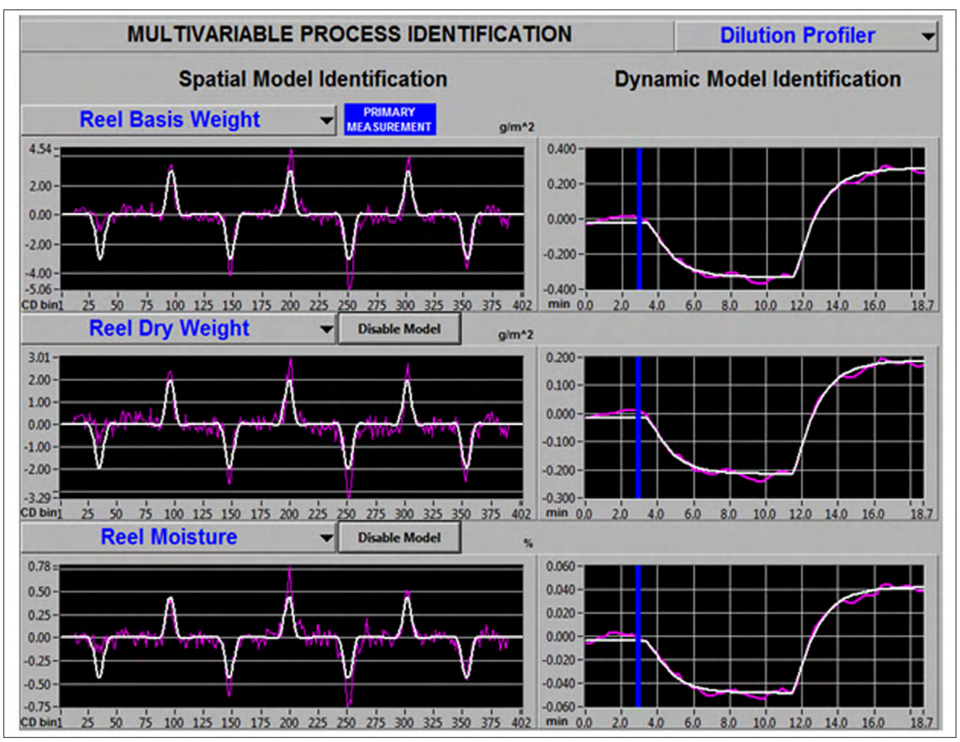

Fig. 3 - Multivariable process identification results.

CONTROLLER TUNING

Once the plant process model has been identified, an industrial multivariable automated tuner [2] is used to determine the multivariable controller tuning parameters. Figure 4 shows the spatial tuning of the CD-MPC, which is tuned to achieve optimal performance with respect to reduction of moisture profile variability. The user can access fine-tuning knobs for setting the controller’s spatial robustness and adjusting the relative energy savings and relative picketing-prevention aggressiveness for each actuator beam before running the closed-loop simulation

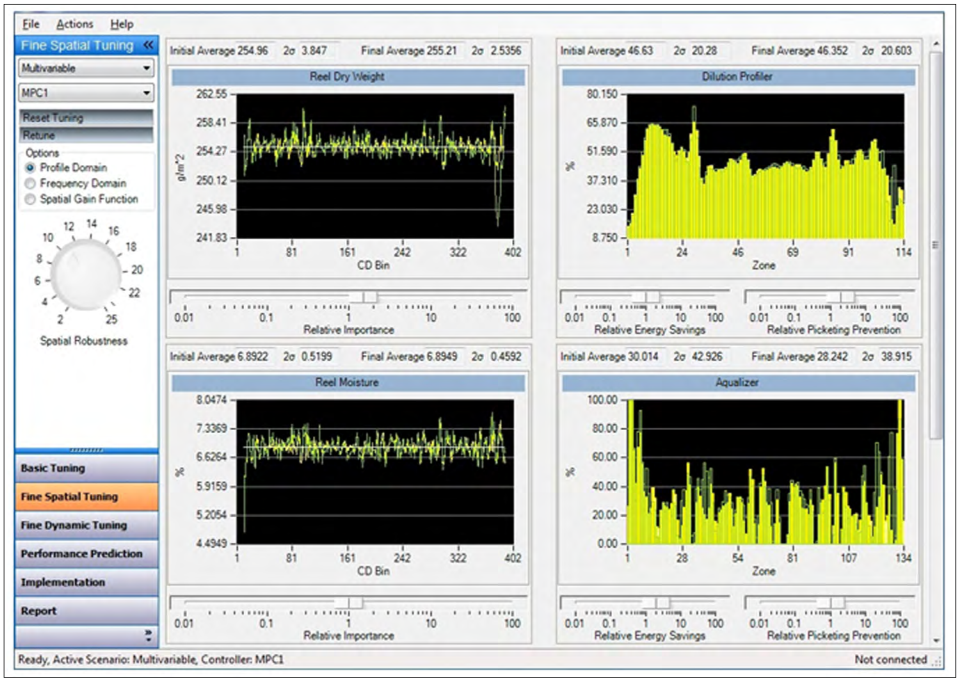

Fig. 4 - Multivariable CD-MPC tuning and steady-state performance predictions.

that automatically generates the spatial performance predictions. The spatial performance predictions are provided in terms of average and two-sigma values of the initial (in green) and steady-state (in yellow) measured sheet properties and actuator set-point profiles.

The CD-MPC closed-loop final (in yellow) predicted performance in terms of final two-sigma spreads depends on accurate alignment specifications for all the dilution profiler's 114 dilution valves with narrow (60-mm) zone spacing and all the Aqualizer™ rewet system's 134 vortex air atomizing nozzles with very narrow (50-mm) zone spacing.

The dynamic tuning for the CD-MPC is shown in Fig. 5. The user can access the fine-tuning knobs to adjust the desired controller recovery speed and the dynamic robustness for each actuator beam before running the closed-loop simulation that automatically generates the predictions associated with dynamic performance. The dynamic performance predictions are provided in terms of recovery time, which is defined as the predicted length of time, in minutes, for the controller to remove 90% of a process upset.

When the user is satisfied with the closed-loop performance in terms of steady-state and transient behaviour, the calculated tuning parameters can be easily activated for on-line use in the CD-MPC by pressing a tuning transfer button.

PERFORMANCE MONITORING

Once the CD-MPC has been tuned, the controller performance is baselined to determine the baseline spread values for both actuator set-points and measurement profiles. Current spread values are calculated every end-of-scan and compared against quality limits using a modified cumulative sum (CUSUM) detection algorithm. Performance baselining can be initiated by pressing the Start Baselining button. Closed-loop identification is automatically initiated whenever the cumulative thresholds for actuator set-point picketing and measurement-error controllable short wavelengths are exceeded.

Figure 6 shows the Performance Monitoring page for the dilution profiler actuators, which has performance monitoring enabled and active. The baseline and current-spread values for actuator set-point picketing and measurement profiles are shown in the upper left-hand portion of the page. The lower portion of the page shows the current (in green) and baseline (in yellow) power spectra for dilution profiler set-points and dry-weight measurement profiles.

Current and baseline spread values are calculated relative to the controllable range of the dilution profiler actuators as defined by the X3dB (461 mm) and the critical cut-off wavelength Xc (247 mm), as shown on the right-hand side of the

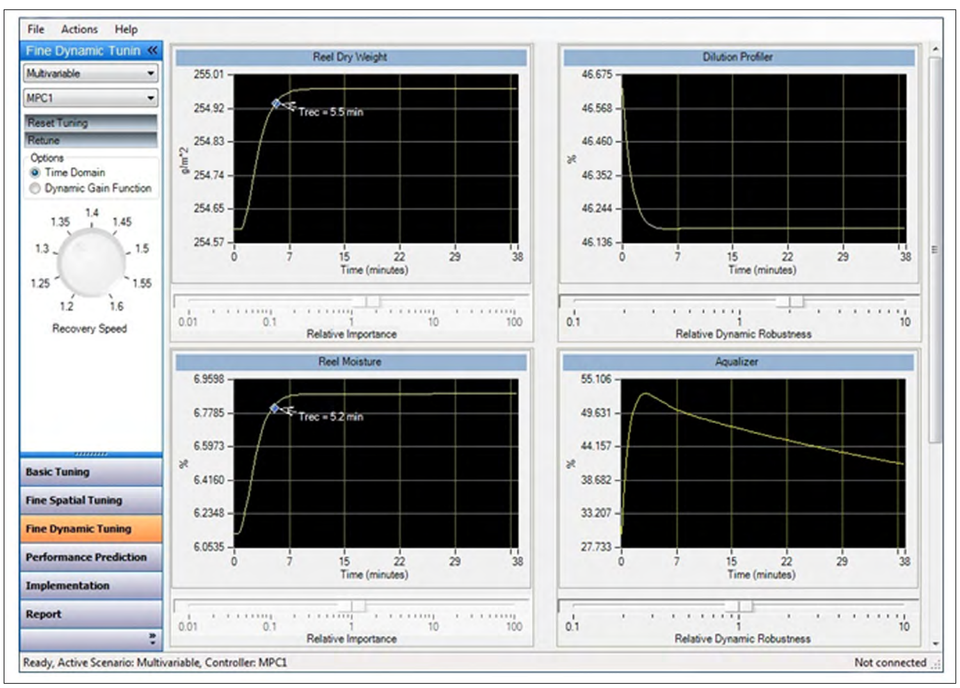

Fig. 5 - Multivariable CD-MPC tuning and dynamic performance predictions.

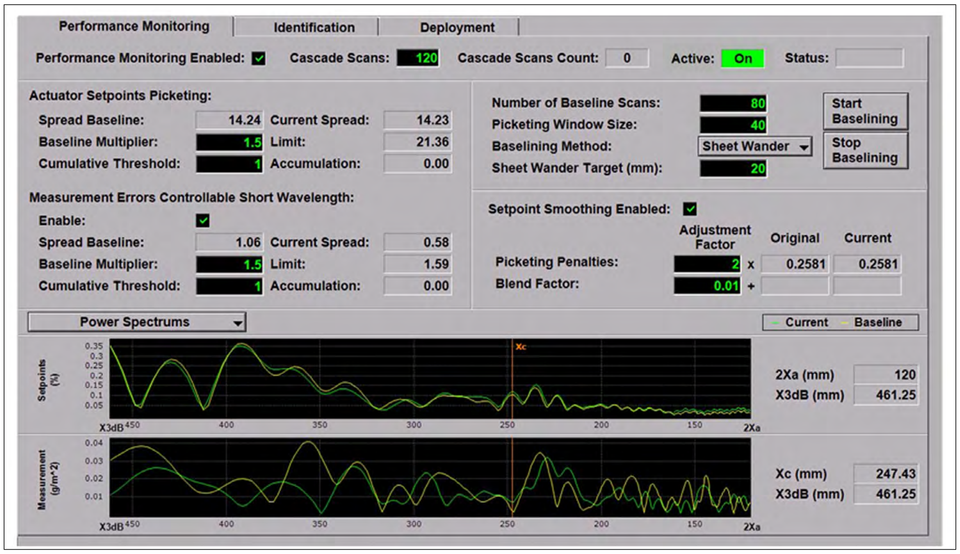

Fig. 6 - **Performance Monitoring page with active detection for the dilution profiler actuator.**

power-spectrum plots. X3dB (mm) is defined as the wavelength where the CD actuator gain is reduced to 70% of the maximum CD actuator gain. The critical cut-off wavelength Xc (mm) is defined as the wavelength where the CD actuator gain is reduced to 20% of the maximum CD actuator gain. 2Xa (mm) represents the two-times-actuator-spacing wavelength, which for the dilution profilers is equal to 120 mm.

Performance is considered to be degraded and misalignment to be detected whenever the accumulated differences between the current spreads and their limits exceed the specified cumulative thresholds.

IDENTIFICATION

Once performance monitoring has detected that CD-MPC performance has degraded with respect to the accumulated excess between the current and baseline spread values, the closed-loop identification test is automatically initiated without user intervention.

Figure 7 illustrates a color map of dilution profiler relative set-points during a closed-loop identification test. Here the *relative* set-points represent the difference between the absolute actuator set-points during the closed-loop test and the actuator set-points before the test was initiated (at scan #300). A set of seven individual actuators distributed across the sheet are probed using a PRBS with a duration of 80 scans (from scan #310 through #390). Note that unlike a conventional open-loop bump test, the closed-loop PRBS does not suspend the feedback control required for normal production operation.

Figures 8 and 9 show the dry-weight and moisture measurement profile color maps and illustrate the small variances introduced by the PRBS during the identification test.

Figure 10 shows the test results for the dilution profiler actuators displayed on the Identification page at the completion of the identification test. Identification has calculated new alignment parameters using an alignment model based on non-linear shrinkage. Note the large difference between the newly calculated overall shrinkage values and those currently used by the CD-MPC, which indicates a 1% net increase in the shrinkage. Such a significant shrinkage increase in a typical production sheet with a width of 6400 mm represents a 64-mm reduction of the sheet width due to changes in drying conditions. This amount of sheet reduction is wider than the actuator spacing for this type of dilution profiler (60 mm) and can lead to rapid degradation of CD-MPC optimal performance. The calculated model fit of 82.09% between the process data graph (in green) and the alignment model graph (in yellow) indicates that the newly calculated alignment parameters are GOOD and safe for use by the CD-MPC.

DEPLOYMENT

Once the identification routine has calculated a valid set of alignment parameters, the deployment function can automatically update these parameters with or without user intervention.

Figure 11 shows the Deployment page for the dilution profiler actuators configured to operate in a user-assisted mode with the automatic-deployment-enabled option turned off. In the user-assisted mode, the user has the option to

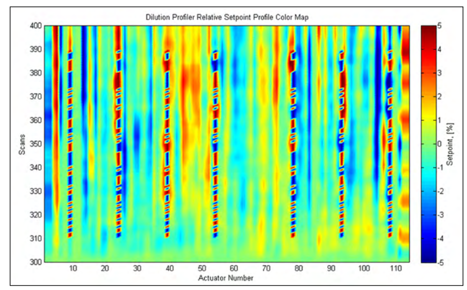

Fig. 7 - **Color map of dilution profiler *relative* set-points during the closed-loop identification test.**

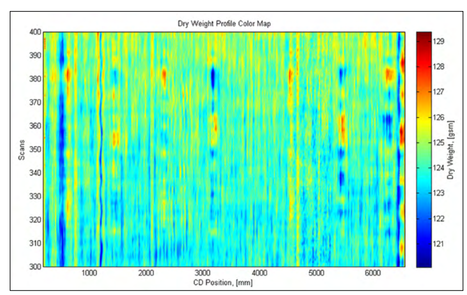

Fig. 8 - **Color map of dry-weight profile during the closed-loop identification test.**

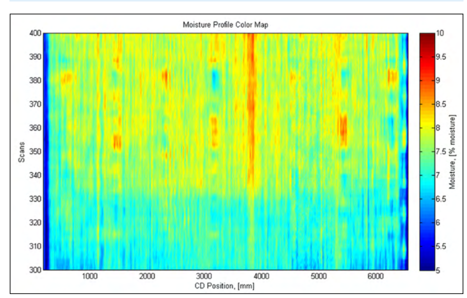

Fig. 9 - **Color map of moisture profile during the closed-loop identification test.**

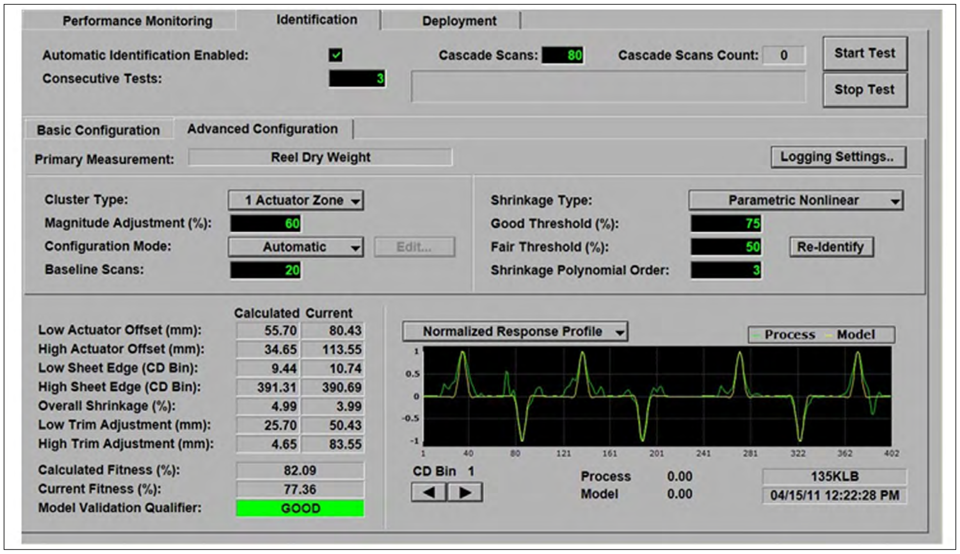

Fig. 10 - **Identification page with a GOOD set of calculated alignment parameters.**

inspect the test results before updating the CD-MPC with the newly calculated alignment parameters and shrinkage profile (in yellow) shown on the graph depicted in the lower part of the page. Note the larger amount of sheet shrinkage that has occurred towards the sheet edges (8% and 14% for the front and back sheet edge respectively) relative to the shrinkage in the middle of the sheet (3%). The newly calculated alignment parameters and shrinkage profile that are rated by the Model Validation Qualifier to be GOOD can be safely deployed by pressing the Update Alignment button beside the shrinkage profile graph.

RESULTS

Multivariable CD control with adaptive alignment results has been evaluated across all production grades using 200 scans of high-resolution profile data (402 data boxes at 16.8 mm) logged at a scanning rate of 16 seconds. Figure 12 shows typical results for the heaviest and most challenging production grade, which has an average dry weight of 255 gsm. The two-sigma of the high resolution dry-weight profile, 1.04 gsm (representing 0.41% of the dry-weight profile average value of 254.9 gsm), is outstanding for this type of process.

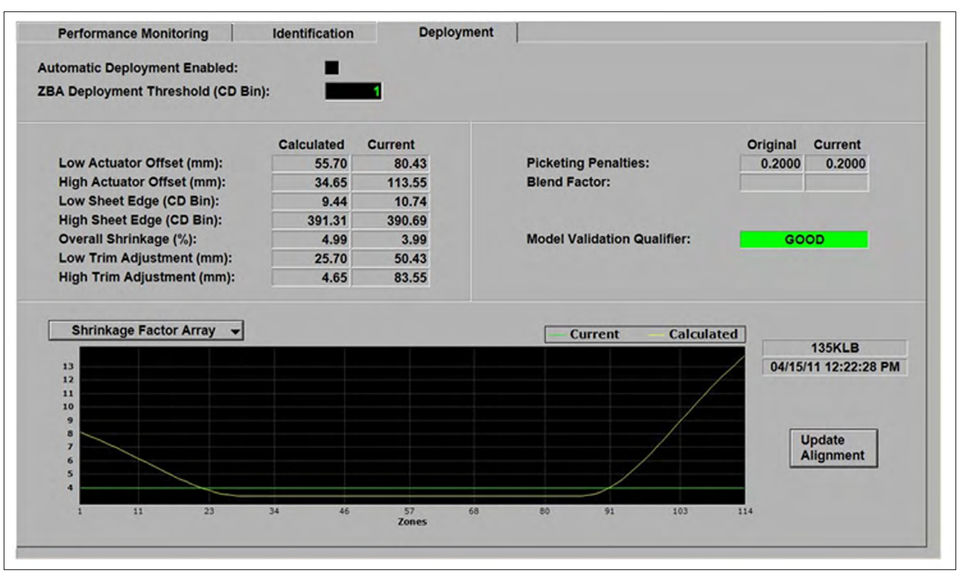

Fig. 11 - **Deployment page showing the calculated non-linear shrinkage profile.**

Figure 13 shows a typical average dry-weight profile power spectrum and its cumulative power spectrum. The top graph shows that all wavelengths within the controllable range of the dilution profiler actuators have been effectively removed from the dry-weight profile. The controllable range of the dilution profiler actuators is defined as the set of wavelengths longer than its critical cut-off wavelength (Xc cut-off) of 247 mm. Therefore, the dominant short wavelength of 193 mm in the dry-weight profile is outside the controllable range of the dilution profiler actuators.

Figure 14 shows the average high-resolution moisture profile and its stability. The two-sigma of the high resolution moisture profile, 0.25% (representing 3.14% of the moisture profile average of 7.97%), is outstanding for this type of process.

Figure 15 shows the typical average moisture profile power spectrum and its cumulative power spectrum. The top plot shows that all wavelengths within the controllable range of the rewet system actuators have been effectively removed from the moisture profile. The controllable range of the rewet system is defined as the set of wavelengths longer than its critical cut-off wavelength (Xc cut-off) of 137 mm. Therefore, the dominant short wavelength of 127 mm in the moisture profile is outside the controllable range of the rewet system actuators.

CONCLUSIONS

The adaptive alignment solution for multivariable CD control has three major components:

- Performance monitoring based on algorithms designed for early detection of actuator picketing
- An active closed-loop identification algorithm that is capable of accurately extracting alignment parameters from production processes operating under feedback control
- A reliable model validation approach which enables safe deployment of alignment parameters without user intervention

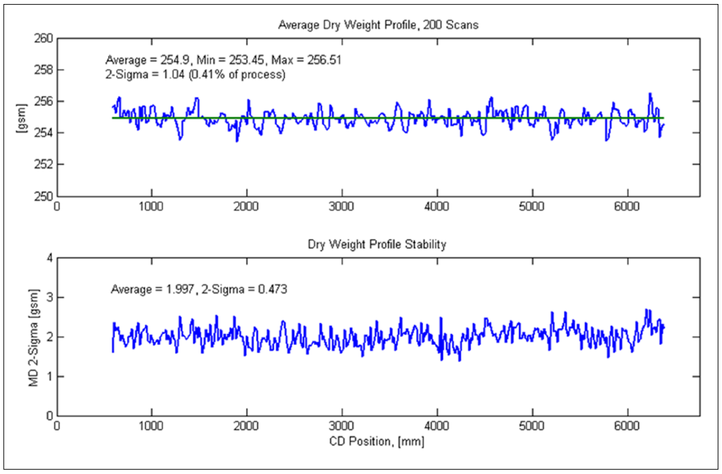

Fig. 12 - Average dry-weight and profile stability.

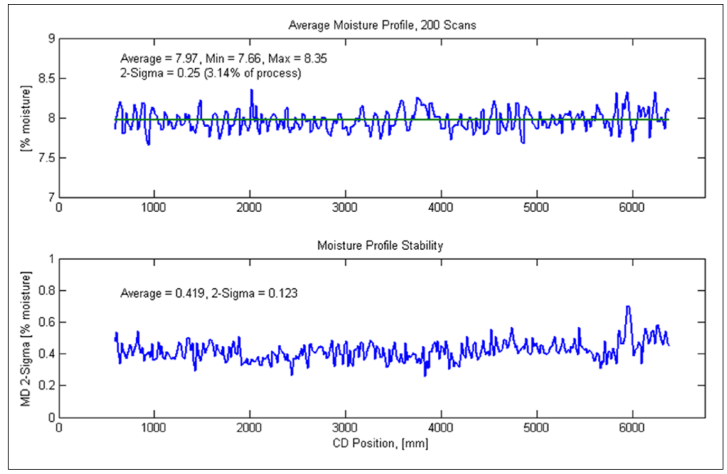

Fig. 14 - Average moisture and profile stability.

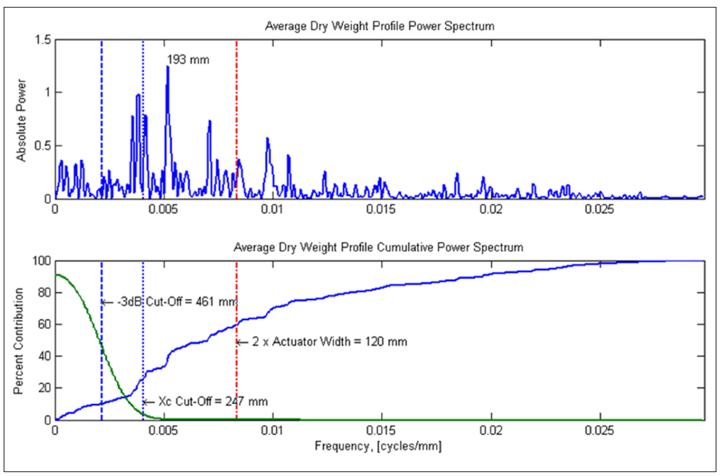

Fig. 13 - Average dry-weight power spectrum and cumulative power spectrum.

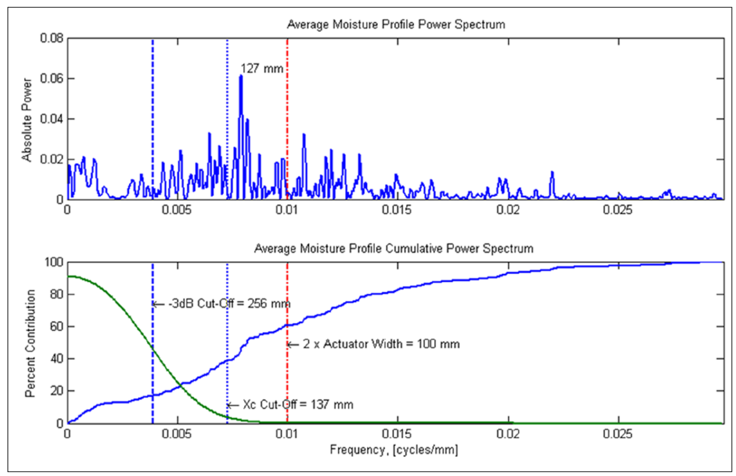

Fig. 15 - Average moisture power spectrum and cumulative power spectrum.

The results presented in this paper are based on a successful implementation of a multivariable CD controller configured with an adaptive alignment solution for two actuator beams (a dilution profiler and a rewet system), which is of critical importance in achieving robust CD moisture control in a high-production linerboard machine. Since commissioning, the adaptive alignment system has continuously monitored production performance with respect to both CD dry-weight and moisture profiles and has proactively updated the multivariable CD controls with accurate alignment parameters and shrinkage profiles across all production grades and operating conditions. No production losses due to controller performance have been reported since the adaptive alignment system was turned on more than a year ago.

The whole process is fully adaptive and does not require any intervention. Optionally, it can be configured to allow a user to evaluate the test results and make the ultimate decision with respect to updating the newly calculated alignment parameters and shrinkage profiles.

Multivariable CD control with adaptive alignment has been applied on many paper machines since 2010 and has consistently demonstrated its ability to achieve and maintain optimal performance across all production grades and under various operating conditions.

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