Data Reconstruction Method for CD Basis Weight Analysis of Paper by using Compressed Sensing Technology

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Received July 9, 2021; Received in revised form October 15, 2021; Accepted October 16, 2021

ABSTRACT

The control of the cross-directional (CD) basis weight of paper is very challenging. The actuator of the system needs to control the properties of the entire sheet according to a set of restricted data measured by a scanning sensor. The scanning sensor measures the sheet in the cross direction of the paper. For the moving sheet, CD variations were those along an axis perpendicular to the motion of the sheet, while MD (machine direction) variations were those along the axis of motion. One of the problems that make the CD control difficult is data sampling, which is obtained by continuously measuring the CD basis weight of paper through multiple scanning sensors. As the paper moves vertically, the scanning sensor can only measure the “Z” shape area on the paper. When the scanning frequency was not at least twice the maximum frequency of the paper variation, it was difficult to estimate the sheet profile. According to the sparse characteristics of paper signal, a novel approach to accurately reconstruct the sheet properties by a random sampling protocol was proposed by using compressed sensing technology. Compared with the simple bandwidth based uniform sampling theory, it could accurately reconstruct the real process variations from less measurement data. Based on the reconstructed data and actual industrial process data, the CD response model was identified and the reconstruction effect was verified. The CD and MD basis weight data were separated by the predictive separation algorithm, which ensured the basis for CD control. The approach of the compressed sensing technology was found to be effective.

Keywords: Papermaking process, cross-directional control, compressed sensing, data sampling, signal recovering

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1. Introduction

Papermaking is by far the most complex and sophisticated of all the pulp and paper processes. An important quality characteristic in the production of paper sheets is the range of variation in basis weight, which should be as small as possible. During the papermaking process, the system actuators must control the properties of the entire sheet based on a limited set of data measured by a scanning sensor across the moving sheet. The quality of the produced paper is evaluated in two dimensions: one is the maintenance of the average sheet property profile along the paper sheet as it moves while it was being manufactured, which is called machine directional (MD) control, and the other is the maintenance of the sheet profile across the width of the paper machine, which is called cross-directional (CD) control. In papermaking with modern high-speed paper machines, the sheet properties must be continuously monitored and controlled to guarantee that the paper product quality specifications are satisfied along both the MD and CD. The CD basis weight profile is a very important quality index of paper in the papermaking process. Control of CD basis weight on paper machines has long been known as an especially difficult problem. This is due to several difficulties including the high dimensionality of the cross-directional system, the high cross-directional spatial interaction between actuators, the uncertainty in the model, and the limited control authority of the actuators.

The primary reason for the difficulty of CD control is the complexity of the profile response to a slice adjustment. The modern hydraulic headbox is equipped with dilution water supply equipment for basis weight profile control. The adjustment of the CD profile by dilution water is superior to the traditional slice adjustment. In pursuit of better paper quality, new demands have placed on CD control systems. Such as in CD profile control system, the number of sheet horizontal measuring points ranges from 200 to 2000, and the number of actuators is up to 300.

CD variations were those along an axis perpendicular to the motion of the sheet, while MD variations were those along the axis of motion. The scanning sensor measured the sheet in the cross direction of the paper. As the paper moves vertically, the scanning sensor could only measure the “Z” shape area on the paper web. The quantitative characteristics of paper could be described by a two-dimensional coordinate axis including MD direction and CD direction. In papermaking production, paper sheet with a length of 80 m was measured offline in a paper mill, and the basis weight scanning path was the zigzag path as shown in Fig. 1. The corresponding paper basis weight distribution was shown in Fig. 2 (These data are provided by the paper mill).

The measured data includes the CD fluctuation variation with relatively slow change and the MD variation with higher bandwidth. When the scanning frequency of QCS (quality control system) is no more than twice the maximum frequency, some process variations will be distorted or lost to aliasing in the filtered data. Due to the missing data, it is difficult to estimate the sheet profile. Current industrial practice is to separate the relatively slow variations of the CD profile from the higher bandwidth MD variations using low pass filters.

![Zigzag scanning path of basis weight scanner](image-url)
filtering, although the spacing and timing of the scanned data measurements made it inevitable that some process variations will be distorted or lost to aliasing in the filtered data. In order to overcome the limitations of insufficient sampling data, we propose a novel approach to accurately reconstruct the sheet properties by a random sampling protocol using a compressed sensing technology. It can accurately reconstruct the true process variations from far fewer measurements than those indicated by simple bandwidth-based uniform sampling theory. Based on the simulated and actual industrial process data, the CD response model is identified to verify the reconstruction effect. The approach of the compressed sensing technology is found to be effective.

2. Materials and Methods

2.1 Materials

The experimental process of data monitoring and calculation was carried out in a paper mill in Wugong city, Shaanxi Province of China. The CD basis weight on-line measurement was applied in the paper machine 12 (PM 12). The width of the PM 12 is 5400mm, and the design speed is 650 m/min. PM 12 produces corrugated paper.

The equipment used for CD basis weight on-line measurement, data monitoring, and calculations included an intelligent scanner equipped with an infrared quantitative sensor and microwave moisture sensor, PC workstation, and Siemens S7-300 PLC control cabinet. The detection experimental platform was shown in Fig. 3.

2.2 Measuring method of the process data

The process of CD control for a Fourdrinier machine equipped with a hydraulic headbox is shown in Fig. 4. Accompanying texts should be consulted for further details. [9] A scanning frame, located between the calender and the winder of the paper machine, supported the basis weight on-line detecting device that scans the paper sheet that moves through the opening of the frame. The system continuously obtained the instantaneous sample value of the basis weight along the machine direction and its CD profiles. These measurements could be taken only from the sufficiently dry paper at the end of the production line. This causes a long time delay between the actuators on the Hydraulic headbox and measurements from the scanner at the end of the paper machine.

![Fig. 2. Basis weight data distribution of the 80×2 m paper sheet.](image1)

![Fig. 3. On-line detection device for CD data.](image2)
The sheet typically moves at a velocity on the order of 10 m/sec, while the sensors travel back and forth across the paper web at a speed from 0 to 1 m/s. [10] Measurements of the variations are often made by mounting a gauge on a frame, which allowed the gauge to scan back and forth across the process. From this sparse data, the whole profile could be reconstructed.

2.3 Data reconstruction scheme based on compressed sensing

In the research of sampling and recovering of basis weight data by compressed sensing, the following methods could be considered. Firstly, the experiment project was designed, and the experiment equipment was established. The experimental device was used to obtain the full range basis weight data by the actual measurement method, and then the compressed sensing method was adopted to sample the paper and recover the full range basis weight data through the sampling data. Based on the comparative analysis, the compressed sensing method could be improved. Secondly, according to the characteristics of the full range of basis weight data, the full range data could be generated by simulation, and then the software simulation was adopted to verify the compression sensing and recovery method. Through these two methods, combined with the experimental and simulation results, the selection and application of observation matrix and optimal solution algorithm in compressed sensing sampling were verified, and the selection basis and solution method were provided, it could guide how to recover full-scale constant data based on compressed sensing method.

2.3.1 Methodology for compressed sensing

When the scanning frequency was not at least twice the maximum frequency of the paper variation, it becomes difficult to estimate the sheet profile. To overcome this limitation, compressed sensing was adopted. For the actual web, it could be assumed that there are several sampling points in the longitudinal and transverse directions, as shown in Fig. 5. The measured data at each sampling point corresponds to the quantitative data at the current position.

It could be used to represent the full width data of the paper by \( s \) (if the total number of data is \( i \), \( s \))

Fig. 5. Data points of paper basis weight.
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is \( i \times 1 \) order matrix). In the actual paper production process, due to the measurement limitation of scanning sensor, when sampling the paper basis weight data, only part of the basis weight data of sampling points (assuming the number of data is \( j, j<i \)) could be obtained, which was used to express by \( y \) (\( y \) is \( j \times 1 \) order matrix). Then the relationship between the full range of data and part of sampling basis weight data could be described as follow,

\[
y = \Phi s \tag{1}
\]

Where, \( \Phi \) is a observation matrix with the dimension of \( j \times i \).

Since \( y \) in the Eq. (1) is the measured data, on the premise of selecting the observation matrix, according to the theory of compressed perception, the problem of restoring the full range basis weight data is transformed into the known observation value of \( y \) and observation matrix of \( \Phi \), and the full range of data of \( s \) can be recovered by the solution of under determined equations \( y = \Phi s \).

As the sparse characteristics of the full range data, \( s \) can be detail represented as follows:

\[
s = \Psi x \tag{2}
\]

Where, \( \Psi \) is the base function, \( x \) is the coefficient.

According to Eq. (1) and Eq. (2), we can get:

\[
y = \Phi s = \Phi \Psi x = \Theta x \tag{3}
\]

In Eq. (3), \( \Theta \) it is recovery matrix. In this case, the optimization problem \( x = \text{argmin}_{\|x\|_0} \|x\|_0 \) needs to be solved. Since the minimum \( l_0 \) norm problem is a NP hard problem, it can be further converted into the minimum \( l_1 \) norm problem, detailed as \( x = \text{argmin}_{\|x\|_1} \|x\|_1 \). Then the full range data of \( s \) can be recovered from Eq. (3) only by solve of the \( x \).

The MD and CD positions of the sampled data are known and collected in the projection matrix. The problem of reconstructing paper attributes from a small set of samples can be expressed as \( l_1 \)-norm minimization of the sparse coefficient of \( x \), so that the regression matrix \( \Theta \) applied to can generate the measurement data vector of \( x \).

For sparse basis and observation matrix, the detailed selection of reconstruction algorithm was analyzed as follows,

(1) Selection of sparse basis

In a paper mill experiment, a fixed section of a roll of unbleached paper was tested. Two scenarios were tested. In one scenario a sheet of paper was generated based on available information regarding paper properties. [11] In another case, a brown sheet of paper was scanned at all data points and its basis weight and moisture were recorded. Through a specially programmed scanning sensor, the detailed measurement values of MD direction and CD direction were collected, the MD and CD location of the sampled data was known and collected in a projection matrix. The sheet of paper in both cases was represented in the form of a matrix. In the MD direction, each point had five measurements, and the average of the five measurements was used as the quantitative value of MD. In the MD direction, the sensor was used to measure the quantitative change of CD. Because the basis weight change of paper is smooth and sinusoidal, in order to test the compression sensing method, the two-dimensional paper characteristic signal was simulated. The analog signal was a combination of sine waves, which were in MD and CD respectively. A sheet of paper was the original signal in a spatial domain, as the original signal was CD quantitative data signal, its sparsity in frequency domain was better. We define the regression matrix to be the product of the measurement matrix in the spatial Dirac basis and another sparsifying basis such as Fourier or wavelet. [12] The
basis functions tested are Fourier, and three wavelet families: Daubcheies, Haar and Symlet. [13]

Considering the orthogonality of DFT, DFT, DCT and DWT, which were commonly used three kinds of sparsity bases, the relative structure was simple, the speed was fast, and it could better meet the real-time control of CD. Therefore, the sparse base selects the Fourier transform base. The basis functions were evaluated by random spatial sampling, and the Fourier basis was also tested by simulating the scanner along the Z shaped path.

(2) Selection of observation matrix
As the characteristics of independent distribution in the Gauss random matrix, and the correlation with most sparse basis was small, so Gauss random matrix was adopted as the observation matrix of CD basis weight data reconstruction in this paper.

(3) Choice of reconstruction algorithm
The CoSaMP algorithm adopted the least square method to reduce the error signal and realize the gradual approximation of the original signal, [14] so as to realize the reconstruction of the original signal and avoid the local optimization. Therefore, the CoSaMP algorithm was used to reconstruct CD basis weight data.

2.3.2 Compressed sensing process for basis weight data

Based on the experimental QCS data online detection device, the scheme of basis weight data acquisition and processing was formulated as follows.

Step 1, QCS(Quality Control System) on-line detection device experiment,
① Make the paper on the detection device stop running.
② The scanning sensor was used to detect the quantitative data along the transverse direction. After detecting a frame (i.e. the scanning sensor runs from one side of the transverse direction to the other), [15] the scanning sensor stops moving.
③ Control the paper to step in the longitudinal direction, and stop the paper after stepping.
④ Repeat step ②—③ to obtain basis weight data, take the obtained data as the actual approximate full range basis weight data.
⑤ Using the compression sensing method, the scanning frame and the paper operation were controlled, and the basis weight data of the paper web measured in the above steps were detected again.
⑥ For the data acquired in step ⑤, the compressed sensing method was adopted for reconstruction.
⑦ Compare and analyze the data in step ④ and step ⑥, evaluate the performance of compression sensing method, make a further correction and adjustment.

Step 2, Software simulation
① According to the characteristic curve of basis weight data, the full range basis weight data was generated by MATLAB software.
② The compressed sensing method was used to sample and reconstruct the data generated in step ①.
③ Compare and analyze the data in step ④ and step ⑥, evaluate the performance of compression sensing method, and make further correction and adjustment.

Step 3, Field experiment
① In the actual scene, the compressed sensing method was used to control the operation of the scanning frame.
② By using the method of manual basis weight measurement, the paper width measured in
step ① was measured quantitatively, [16]
③ According to the data in step ①, data reconstruction is carried out by using compressed sensing method,
④ Compare and analyze the data in step ② and step ③, evaluate the performance of compressed sensing method, and make further correction and adjustment.

3. Results and Discussion

3.1 Results
Through the experimental process of compressed sensing technology, basis weight data reconstruction effect could be on-line detectioned and the identification of CD model was obtained.

3.1.1 Reconstruction effect of on-line detection
In the data simulation, 155 signals were selected from the measured data of the paper mill as the experimental data, 255 groups of data are reconstructed by compression sensing technology. The data reconstruction effect of CoSaMP algorithm is shown in Fig. 6.

Meanwhile, the scanning sensor was used to detect the basis weight data along the horizontal direction, and the same amount of basis weight data was obtained through repeated measurement by the QCS online detection device. Take the obtained data as the actual value, the full range quantitative data could be approximated. The reconstructed 255 sets of data were compared with the experimental measured 255 sets of data, the effect is shown in Fig. 7.

3.1.2 The identification result of CD profile model
The reconstruction data and experimental data were used to identify the model of CD profile, as shown in Fig. 8, the red line was the peak curve,

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![Fig. 6. Normalized reconstruction effect by CoSaMP compression sensing.](image)

![Fig. 7. Comparison of measurement data and reconstructed data.](image)

![Fig. 8. The result of CD profile identification.](image)
the blue line was the measured curve and the green line was the simulated curve, which was basically consistent with the CD profile fluctuation model. It shows that this method has a certain accuracy in the simulation of industrial data.

3.2 Discussion
3.2.1 Factors for reconstruction effect
In the actual production process, limited by the objective detection conditions, scanning sensors can only obtain part of the basis weight data. The compressed sensing method is adopted to reconstruct the full range of basis weight data. In the part of data reconstruction, usually, the general Fourier transform basis is selected for sparse basis. For sparse basis, signal sparsity is simply understood as that most of the coefficients in the signal are zero. In this paper, Fast Fourier transform was adopted as sparse basis, the Gaussian random matrix was selected as observation matrix.

In order to test the compression sensing method, the two-dimensional characteristic signal of paper was simulated. Analog signal was a combined signal based on a sine wave, in MD direction, a sine wave simulation was used, and in CD direction, a sine wave simulation was adopted. Two-dimensional signal was integrated as a row vector, and randomly collected samples are put into a column vector. The paper signal simulation is shown in Fig. 9.

Simplify the set sampling signal, the sampling signal can be described as

$$x = \sin \left( \frac{2\pi}{256} t \right) + \sin \left( \frac{2\pi}{128} t \right)$$

Fig. 9. Two-dimensional signal simulation of paper.

Fig. 10. Time-Frequency distribution of sampled signal.
transform was used as a sparse basis. Then the best approximation was obtained. In addition, the error decreases with the increase of sample size.

When the paper passes through the paper machine, the compression sensing needs to estimate the paper characteristics. Scanning takes at least 15–60 seconds. The calculation time can be adjusted by selecting the frequency of running the solver and the size of the paper characteristic signal to be estimated. By scanning the noiseless signal and reconstructing it with compression sensor, the minimum error was obtained.

The reconstructed signal time domain local map is shown in red in Fig. 7, it can be seen that the reconstructed data could represent the actual measurement data, which shows that the data reconstruction method based on compression perception was effective.

The calculated reconstruction error is $e=5.9617 \times 10^{-14}$. It can be seen that the reconstruction effect is good and the reconstruction accuracy is high. If conditions permit, there should be more selectivity for factors to improve the reconstruction effect. For the observation matrix, the Gauss random matrix was selected in this paper, besides the Gauss random matrix, the signal observation matrix could also consider using the binary sparse matrix as the observation matrix. [17] As the sparse representation of signal and the selection of sparse basis have some influence on data reconstruction, there should be more selectivity when conditions permit.

3.2.2 Evaluation of MD and CD identification profiles

In our target paper board machine used a scanner with 450 data boxes and travel time of 45s with a sampling period of 5s meaning that 50 samples were collected in the data group. According to the data separation algorithm, the separated MD data could be obtained as shown in Fig. 11, the CD fluctuation data as shown in Fig. 12.

The total variance is the variance of all measured data points compared to the mean value. The MD/CD variance corresponds to the actual stable MD and CD profiles. The sum of variance components MD, CD gives the total variance.

The Fig. 11 demonstrated that the estimated MD profile (solid) follows the actual profile (dotted) of a sheet with two MD steps, despite being fed a measurement corrupted with noise of standard deviation 1 g/m².

The Fig. 12 showed that the estimated CD profile eventually converges to the true CD profile, CD profile and the estimated CD profile was shown at each sampling instance. But please note that this was not the case, the disturbance of the estimated CD profile caused only minor corresponding disturbances of the MD profile estimate.

In practical application, the result is often a com-
4. Conclusions

Since the paper was moving forward while the sensor traversing the width of the sheet, measurements were gathered along a zig-zag path over the sheet. In current industrial practice, the relatively slow variations of the CD profile was separated from the higher bandwidth MD variations based on low pass filtering, although the spacing and timing of the scanned data measurements made it inevitable, that some process variations would be distorted or lost to aliasing in the filtered data. Aiming at the problem of insufficient sampling data caused by scanning frequency, the experimental method and software simulation were combined to obtain the full range basis weight data. According to the sparse characteristics of CD basis weight data, a new algorithm based on compressed sensing was used in this paper to reconstruct the properties of the entire paper. The compressed sensing algorithm was used to sample the paper range basis weight data, and the full range data was recovered by using the sampling data. By changing the working mode of the scanning sensor, the full range basis weight data could be obtained by the actual measurement method. By the reconstructed data and the actual measured data, the basis weight fluctuation model of CD had been identified respectively. Comparing the consistency of the simulated data obtained by the different methods, the validity of the reconstruction method based on the compressed sensing technology was verified. It can be a fundamental work to develop the control system for MD and CD control of a paper machine.

Due to the nature of the inverse problem, some signal interpolation and averaging may be required in some cases. Work is continuing on the implementation of compressed sensing on paper machine data in real time. In a word, by mathematical modelling and data reconstruction method, a theoretical reference for CD profile control strategy was provide.

Acknowledgment

This work was partially supported by Natural Science Foundation of China (NSFC) under grant No. (62073206). We sincerely thank for the funding of the project.

Literature Cited


