Causality of manufacturing processes with significant time delays

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ABSTRACT: In this paper, the effects of flow rate, fiber consistency, and pressure fluctuation on basis weight variations were studied based on a set of paper mill operation data that include thick stock flow rate, consistency at eight different stock preparation stages, inlet and outlet pressure of the pressure pulsation attenuator, scanner position, β gauge, and scanner basis weight measurements. In order to focus on the important spectra and correlations within the low frequency range, a boxcar averaging procedure to eliminate high frequency extraneous information was employed. Moreover, two complete sets of data have been obtained for consistent and problematic operational conditions; namely, with and without a stuff box flow control system. The transfer function between the input and output spectra of certain components or processes within approach flow systems is also studied. Particular emphasis is placed on the synchronization procedure necessary for the study of low frequency range signals, as well as the correlation between two signals. All analysis results presented here are derived with an in-house developed program targeted for systems with significant time delays.

Application: This process control study has immediate application for streamlining and improving the operation of paper mills. The in-house developed software employed in this research can be used to monitor and study data and provide relevant recommendations with direct impact on mill operations.

Regardless of the damping features of individual headbox designs, it is important to minimize stock consistency variation and pressure fluctuation to achieve uniform and smooth stock delivery to the headbox. Various studies have been reported on the causes of basis weight variability, the most fundamental paper property. General methodology and analysis of basis weight variations have been documented [1-5]. Norman and Wahren discussed in detail the mass distribution and turbulence spectra based on micro- and macro-scale descriptions [6]. A focused investigation of wet-end vibration and its effects on basis weight was reported by Perrault [7]. In this paper, we employ a set of in-house developed programs to systematically study typical mill operation data, and provide an overview of various causes of basis weight variability. We employ the frequency analysis and correlation tools as stipulated by Carter and Epton [8]. To overcome the drawbacks of online signal processes discussed by Brendemuehl and Borchert [9], we recorded more than 2 h of multichannel mill operation data with a sampling period of 0.01 s. Moreover, two sets of mill data have been recorded. The first run with 2.817 h is recorded with the control valve on the stuff box turned off, whereas the second run with 0.8917 h is recorded with the same valve turned on. This enables us to focus more on the low frequency variation and perform multichannel cross correlations. Because a stable system may also have cyclic variations that can be reflected in the final product, such comprehensive signal analyses will help to discern the key influence factors from the culmination of a long series of stock preparation process steps and to weed out chronic system upsets.

Process variations, such as retention level and fines, could significantly affect the drainage and, consequently, the system stability [10]. In this paper, we will discuss the following issues: (1) consistency variations within different stages of stock preparation and their influence on the basis weight; (2) pressure pulsation effects on cross-machine direction (CD) and machine direction (MD) basis weight variations; (3) effectiveness of the current pressure pulsation attenuator; (4) effects of the stock flow rate on the basis weight; and (5) the correlations of stock flow rate, consistency, and pressure variations.

In the following section, we summarize the signal analysis techniques used in this work. In the data analysis section, we discuss the set of mill operation data and the analysis results, particularly focusing on the upstream impact on basis weight variations. In the concluding section, we reiterate the key findings from the analysis of this particular set of mill data and shed new light on the practical implications of such analyses.

RESEARCH APPROACHES

In this work, we use discrete signal analysis tools. If we have a discrete sampling $x[n]$ of a time varying signal with a sample period T for a time duration of interest Δt, the total number of sampling points is $N = \Delta t/T$. Moreover, we can only obtain a spectrum of frequencies up to the Nyquist critical frequency $f_c = 1/2T$, and the lowest sensible frequency is, of course, $1/\Delta t$.

Denoting the frequency domain signal as $X[n]$, we have the following discrete Fourier transform:

$$x[n] = \sum_{m=0}^{N-1} X[m]e^{j2\pi nm/N} \quad (1)$$

$$X[m] = \frac{1}{N}\sum_{n=0}^{N-1} x[n]e^{-j2\pi nm/N} \quad (2)$$

Notice that with N input data points, based on the periodicity in the frequency domain, we obtain the following frequency range:

$$f_n = \frac{n}{NT}, -\frac{N}{2} \le n \le \frac{N}{2} \quad (3)$$

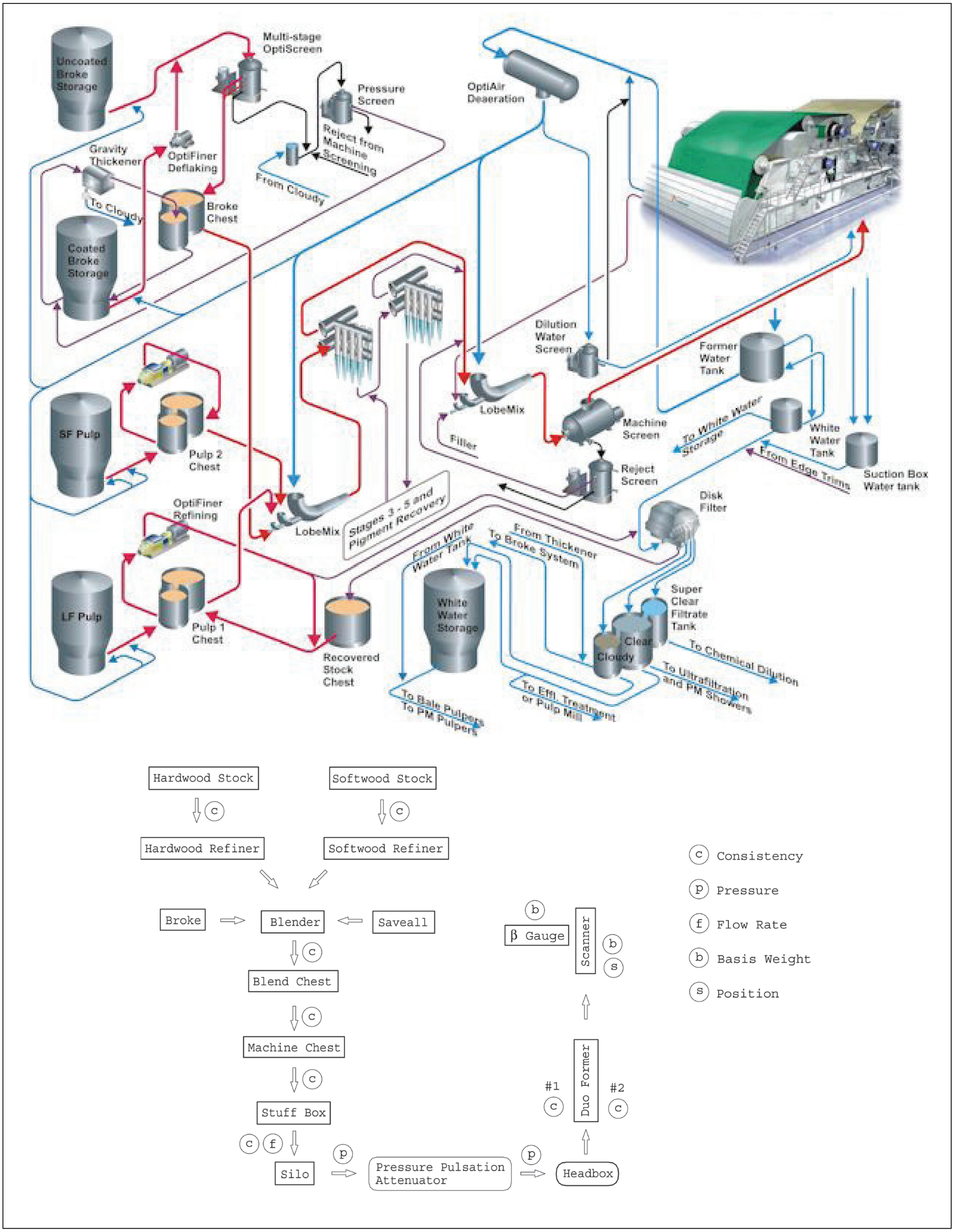
Since Eqs. (1) and (2) are implemented as the Fast Fourier Transform (FFT) in our in-house developed programs, the number of data points we select, out of more than one million data points gathered per channel, must be a power of two.

Assume that we have two functions $x(t)$ and $y(t)$, and their corresponding Fourier transforms $X(f)$ and $Y(f)$. The spectrum of their cross correlation $corr(x, y)$ can be denoted as XY^* [12], where * represents the complex conjugate. Therefore, we can easily obtain the cross correlation as well as the transfer function $H(f) = Y(f)/X(f)$ by using FFT.

The main feature of this work is to derive useful information within different frequency ranges based on signal-to-noise enhancement. The basic concept of this technique is to update a point with the average of a certain number of points around it. Of course, in this study, we assume that the signal of interest varies only slowly with time and the average of a small number of adjacent points is a better measure of the signal than any of the individual points. For example, to focus on the low frequency range up to 1/(2TNa) Hz, we select one

Deck # 1										
Channel #	Name	Unit	x_{min}	x_{max}	y_{min}	y_{max}	Attenuator	a	b	Delay, s
1	Pressure (attenuator inlet)	psi	0	10	0	80	10	8	0	3105
2	Pressure (attenuator outlet)	psi	0	10	0	32	5	3.2	0	3105
3	Flow Rate (thick stock)	gpm	1	5	0	4500	10	1125	-1125	3015
4	Consistency (stuff box)	%	1	5	2	4	5	0.5	1.5	3015
5	Consistency (duo #2 upper)	%	1	5	0	20	5	5	-5	3105
6	Consistency (duo #1 lower)	%	1	5	0	5	5	1.25	-1.25	3105
7	Ground (off)	V	0	1	0	1	5	1	0	0
8	Ground (on)	V	0	1	0	1	5	1	0	0
Deck # 2										
Channel #	Name	Unit	x_{min}	x_{max}	y_{min}	y_{max}	Attenuator	a	b	Delay, s
1	Position (scanner)	ft	1	5	0	30	10	7.5	-7.5	3115
2	Basis weight (scanner)	lb/3000 ft^2	1	5	0	80	10	20	-20	3115
3	Basis weight (β gauge)	lb/3000 ft^2	5	3.6	45	125	10	-57.14	330.71	3115
4	Consistency (machine chest)	%	1	5	2	4	5	0.5	1.5	2565
5	Consistency (softwood)	%	1	5	2	5	5	0.75	1.25	0
6	Consistency (hardwood)	%	1	5	2	5	5	0.75	1.25	0
7	Consistency (blend chest)	%	1	5	2	5	5	0.75	1.25	2115
8	Consistency (blender)	%	1	5	2	5	10	0.75	1.25	915

I. Data acquisition channel arrangements.



1. Measurement locations of various process variables and a typical approach flow system with both softwood and hardwood pulps [11].

data point out of every N_a data, and the boxcar average process is illustrated as follows:

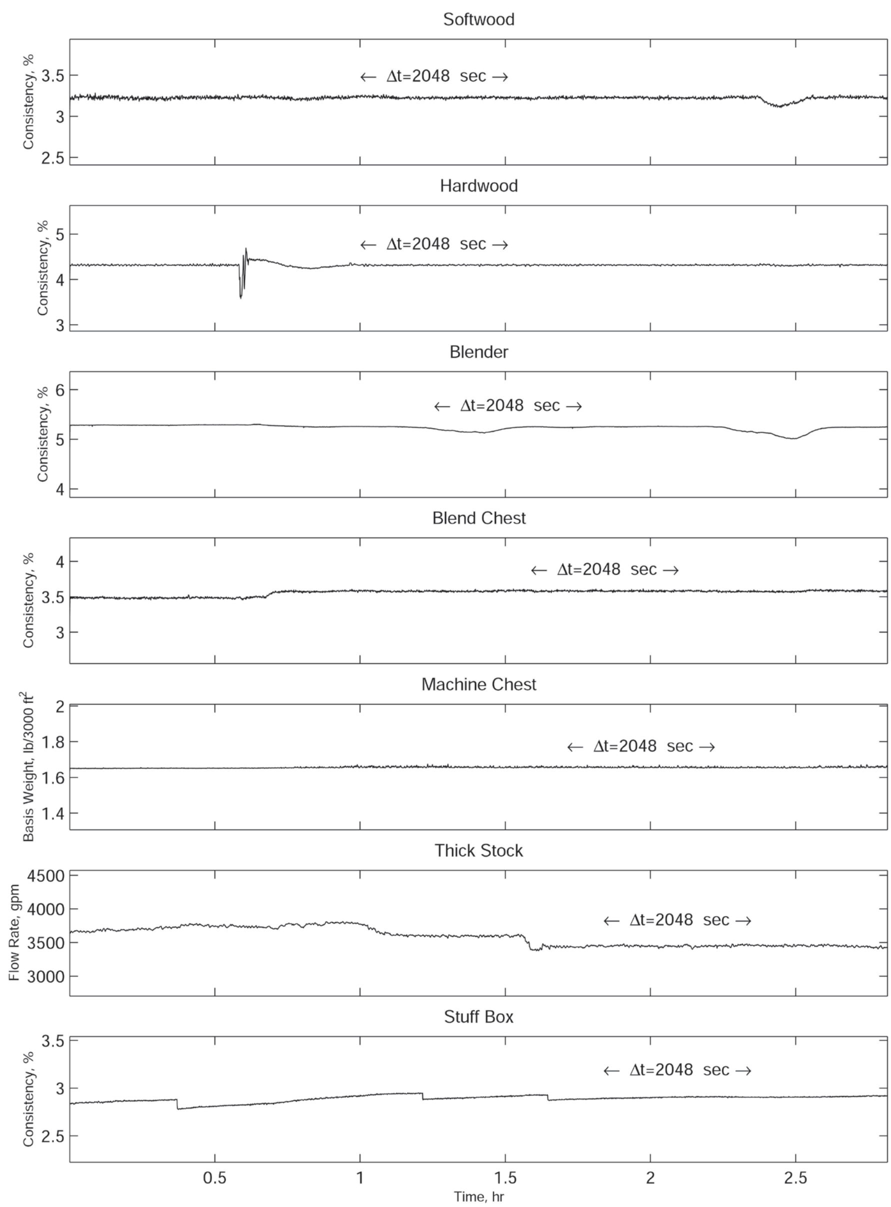
$$\hat{x}[n] = \sum_{i=(n-1)N_a+1}^{nN_a} x[i]/N_a, \ 1 \le n \le T/(\Delta t N_a) \qquad (4)$$

where $\hat{x}$ represents the smoothed signal.

As illustrated in **Table I**, the recorded data from the sensors has been expressed in mV up to 6V. The accuracy of these sensors has been justified with the standard deviation of the calibrated signal at the level of a few percentage points.

DATA ANALYSIS

Two sets of measurements have been obtained for stock flow rate, consistency, and pressure at various stages to determine the effects on basis weight variations for consistent and problematic operations; namely, with and without stuff box flow control system, respectively. The measuring point locations are depicted in **Fig. 1**. We record all fourteen channels simultaneously for two separate runs; namely, consistent and problematic operations. One run has a duration of more than 2 h without stuff box flow rate control, and the other run includes a little less than 1 h of data with the flow rate control. In the ensuing signal analyses, we will synchronize the signal channels by taking into consideration the predetermined stock



2. Changes of process variables over time # 1 (first run of 2.817 h).

transit time between the measurement points, i.e., the time delays. To convert voltage measurements to physical quantities, we introduce the following calibration factors a and b:

$$y = ax + b \tag{5}$$

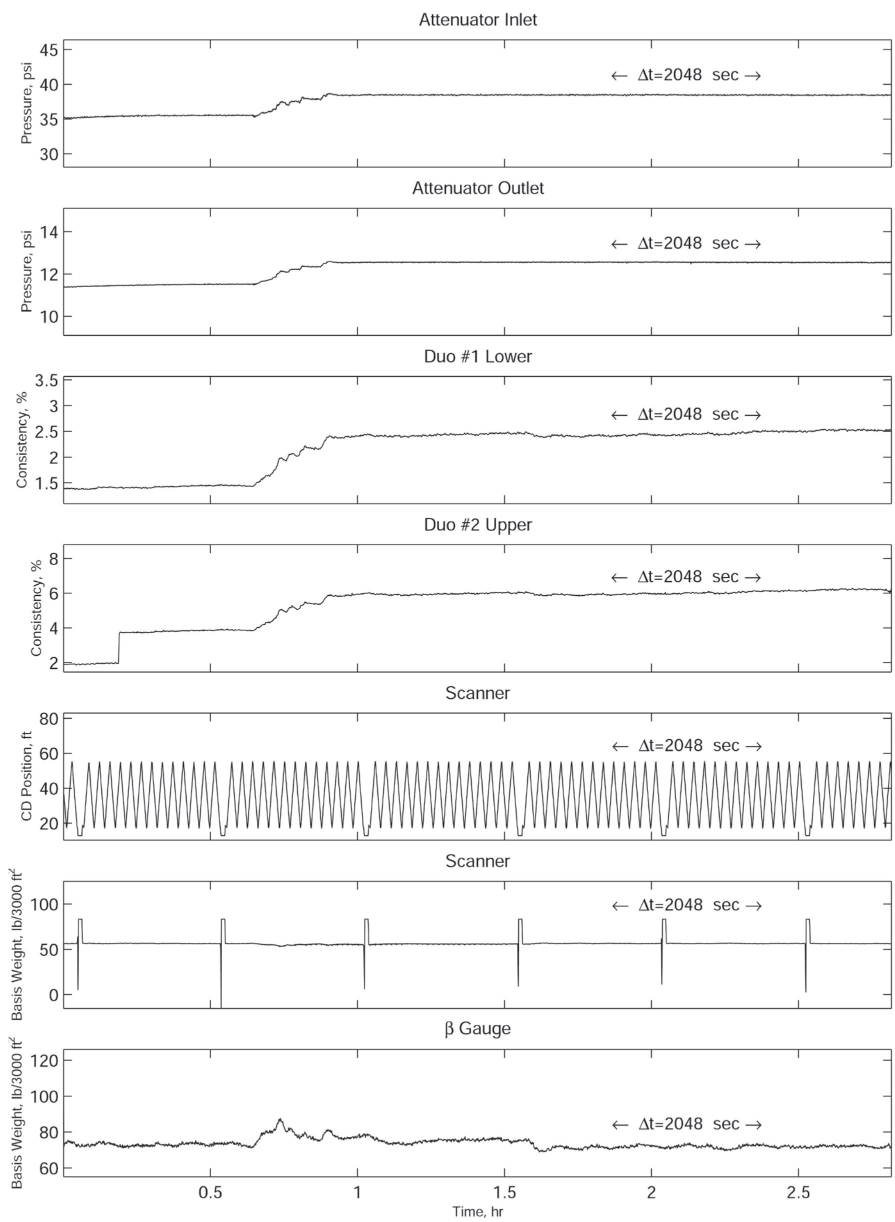
with $a = (y_{max} - y_{min}) / (x_{max} - x_{min})$

$b = (y_{min} x_{max} - y_{max} x_{min}) / (x_{max} - x_{min})$

where y and x stand for the physical quantity and the corresponding voltage measurement, while the subscripts max and min represent the upper and lower bounds.

Overview of signals

In Table I, we list fourteen channels of various process variables, their corresponding calibration factors, and time delays. More specifically, the consistency sensors 33KC053 and 33KC054 have been employed for lower (duo #1) and upper (duo #2) side measurements, respectively. Similar consistency sensors 32KC006, 32KC011, 32KC715, and 32KC141 have also been used for the measurement of consistency in Softwood Intake, Hardwood Intake, Blend Chest, and Blender, respectively. In addition, sensors 32KI144, 32KT304, and 33FC001 have been implemented for the measurement of consistency in machine chest, consistency in stuff box, and flow rate of thick stock, respectively.



3. Changes of process variables over time # 2 (first run of 2.817 h).

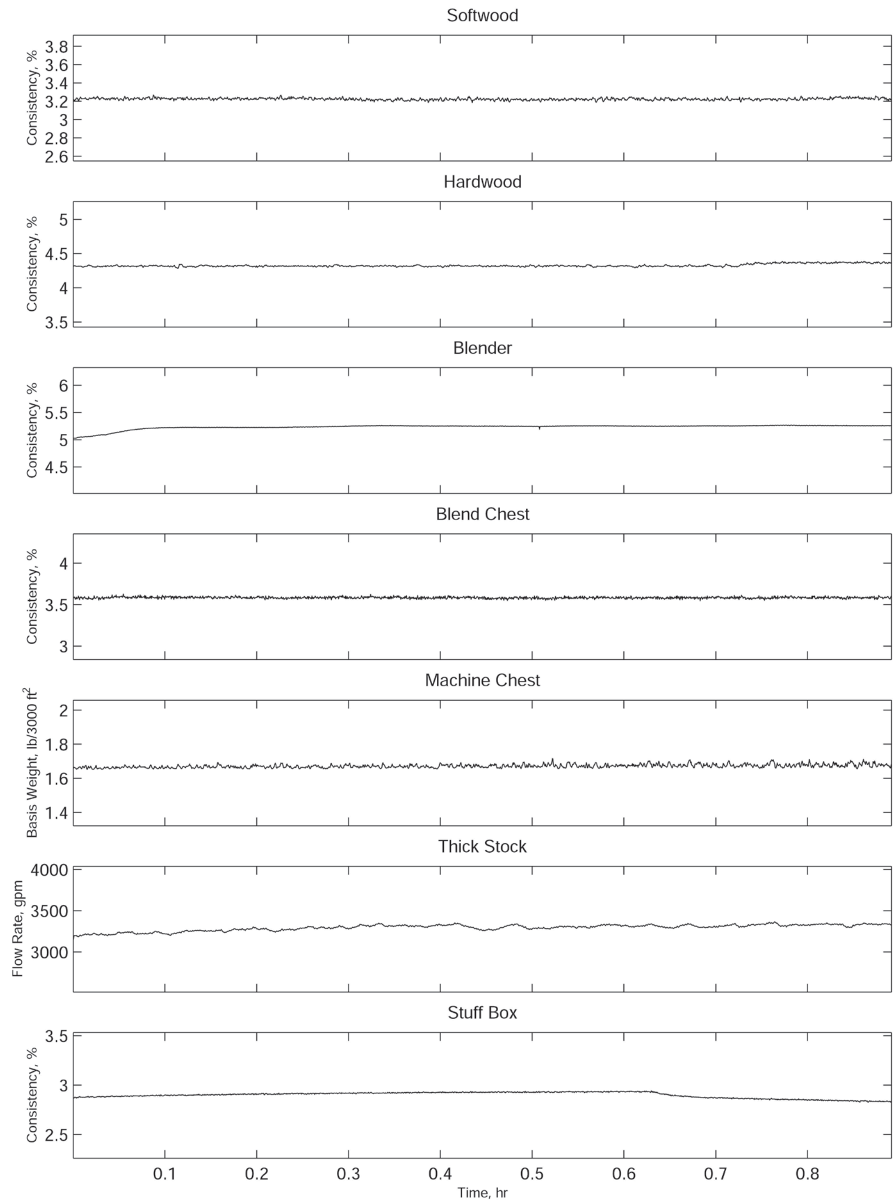
All fourteen channels of measured signals are presented in **Figs. 2**, **3**, **4**, and **5**, which show that most of the time delays happen within the stock preparation processes and that significant time lag (nearly 52 min) exists from various stock preparation stages to the measurement of basis weight downstream at the reel [13].

In general, there are only a few frequency ranges of interest to paper manufacturers, as shown in **Table II**.

In this work, for simplicity, we have evaluated all spectra using the percentage fluctuation of the signal around its average. The spectra of a few key measurements for three frequency ranges (~0.25 Hz, ~1 Hz, and ~50 Hz) have been documented in a comprehensive report [13]. In this paper, we focus on a few concrete findings.

	Period, s	Frequency, Hz	Paper Length, m
Long term	>200	<0.005	>40000
Medium term	1~200	0.005~1	20~40000
Short term	0.1~1	1~10	2~20
Formation	<0.1	>10	<2

II. Frequency ranges of interest to paper manufacturers. (Machine speed [reel speed] V is assumed to be 3600 ft/min.)



4. Changes of process variables over time # 1 (second run of 0.8917 h).

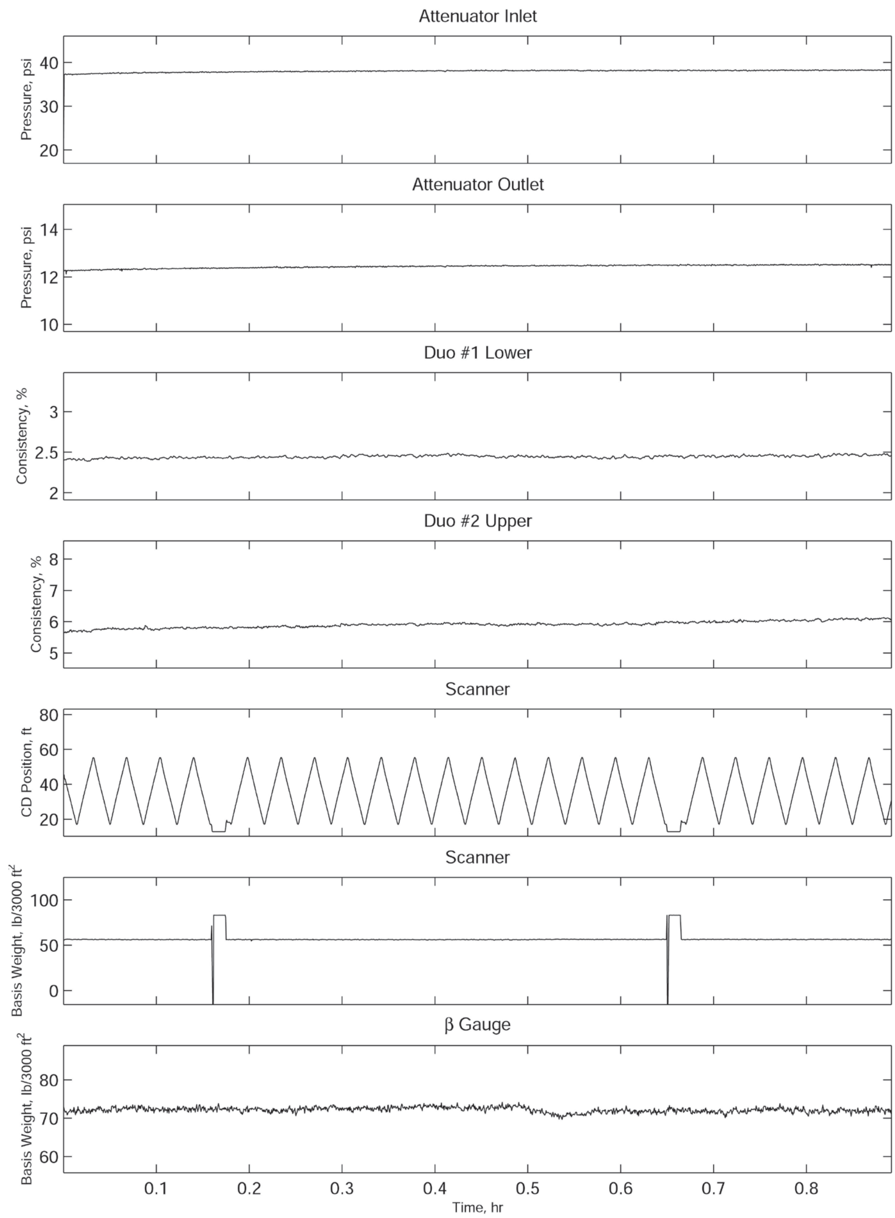
As pointed out in [13], the frequencies of 0.1 and 0.75 Hz show up in the thick stock flow rate variation as well as the pressure fluctuation. This can be explained by the relation $\rho \frac{\partial \upsilon}{\partial t} : \frac{\partial p}{\partial z}$, derived from the Navier-Stokes equation by neglecting the viscous and convection effects, where υ, ϱ, z, and p stand for the axial velocity component, fluid density, axial coordinate, and pressure, respectively. Surprisingly, the same frequency component shows up in the stuff box consistency measurement as well, which indicates that the consistency sensor was picking up flow variations in the axial direction. Moreover, the frequency 0.75 Hz strongly affects the β gauge basis weight variation.

Pressure pulsation

As shown in **Fig. 6**, the effectiveness of the pressure pulsation attenuator is quite different in three frequency ranges (~ 0.25 Hz, ~ 1 Hz, and ~ 50 Hz). We define the transfer function $H(f)$ as,

$$H(f) = 20\log_{10} \left| P_{out} / P_{in} \right| \qquad dB \tag{6}$$

and to better illustrate the pressure pulsation attenuator performance, we also use the boxcar average. As shown in **Fig. 7**, the overall attenuation for the frequency significantly higher or lower than 1 Hz is very strong. However, the pressure attenuator does not seem to perform well for oscillations around 0.8 Hz, which could be introduced within the head-



5. Changes of process variables over time # 2 (second run of 0.8917 h).

box manifold and the recirculation line. Detailed discussions and a preliminary study on the current pressure pulsation attenuation device are reported Wang and Feng [14].

Basis weight

Basis weight (or grammage) is the commercial term used to represent the paper mass per unit area, and a common unit is lb/3000 ft^2. In general, we represent the paper basis weight variability by the sum of three components, i.e., CD variation (σ_c), MD variation (σ_m), and residual variation (σ_r) [15,16], where the scanner basis weight variation (σ_s) satisfies:

$$\sigma_s^2 = \sigma_c^2 + \sigma_m^2 + \sigma_r^2 \tag{7}$$

In addition to the online scanner basis weight measurement, we also use in this work a fix point β gauge measurement. For the scanning period T_o, we have N_o sampling points per scanning period with $N_o = T_o/T$. If we select N_c CD points in the cross-machine direction ($N_c < N_o/2$), we can construct the following N_c series of MD variations:

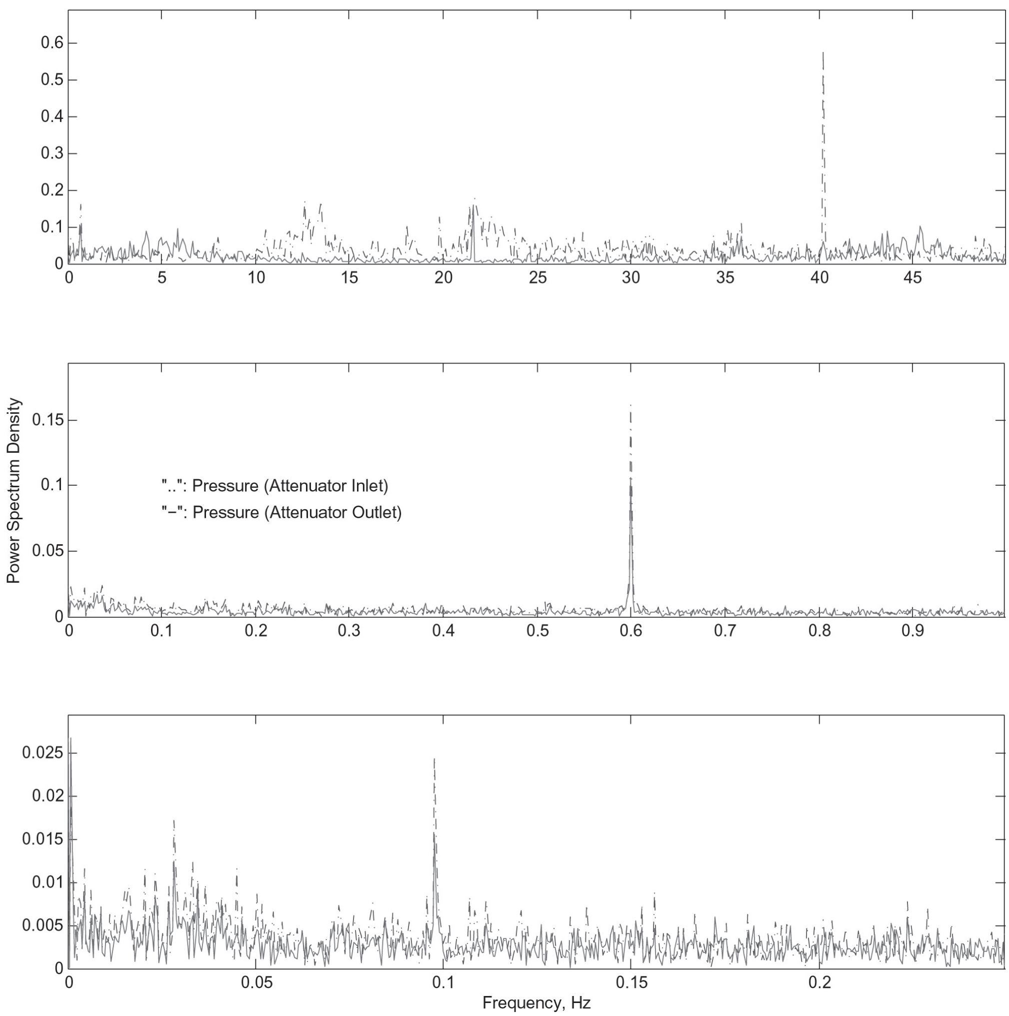
$$x_i[n] = x_i[(n-1)N_o + i], \quad 1 \le i \le N_c \tag{8}$$

where $\tilde{x}_i$ stands for the i^{th} fix point basis weight measurement with the sampling period T_o. Furthermore, we derived the following CD profile by averaging each MD variation series $\tilde{x}_i$:

$$x_c[i] = \sum_{n=1}^{N_s} x_i[n] / N_s \tag{9}$$

where N_s stands for the total points within each MD basis weight measurement series $\tilde{x}_i$.

Paper basis weight is influenced by every stage of the stock preparation and papermaking processes. In general, there are two types of consistency effects on basis weight variations. The temporal variation of consistency can be viewed as the variation of the total fiber mass passing through a fixed pipe cross-sectional area, and it affects

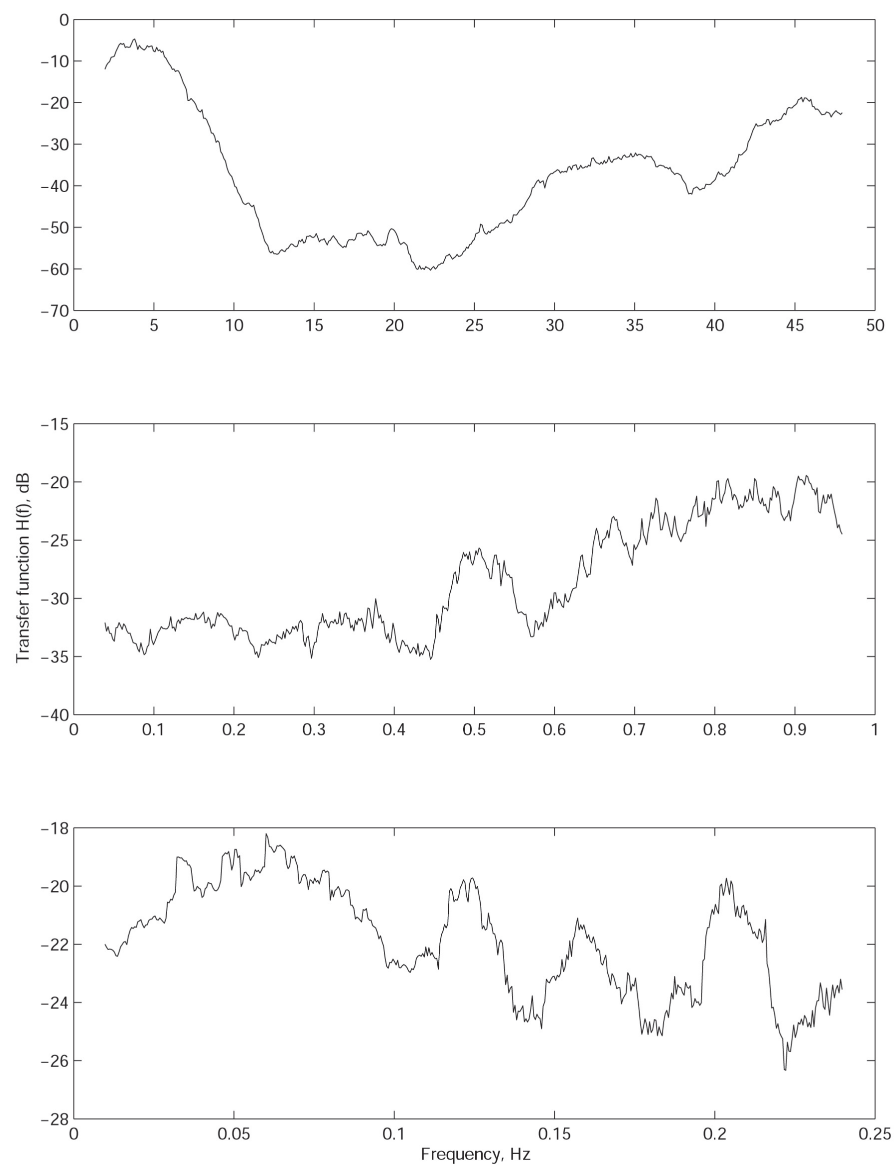


6. Effects of the pressure pulsation attenuator within three frequency ranges (first run of 2.817 h).

mainly the MD and residual basis weight variability. The spatial variation of consistency corresponds to the fiber distribution at the pipe cross section, which is often called fiber stratification. If such fiber stratifications exist before the stock enters the headbox manifold, it exerts strong effects on the CD and residual basis weight variation. A detailed study of the use of perforated plates or the reservation of enough pipe length between the last elbow turn and the headbox manifold requires the solution of a three-dimensional turbulent pipe flow field, as well as the associated mass transfer equations [17]. **Figure 8** shows the spectra of CD, stock flow rate, pressure, and consistency of the first run measurements. We find the following in the CD basis weight spectrum:

- The frequency spikes at 1.6 Hz, 4.3 Hz, and 4.45 Hz correspond directly to the same spikes in the pressure pulsation spectrum.
- The frequency spike at 1.8 Hz corresponds directly to the same spike in both the pressure pulsation and thick stock flow rate spectra, and furthermore, with the control valve turned on, the perturbation with this frequency is significantly reduced.
- The frequency spike at 3.3 Hz corresponds directly to the same spike in the stuff box consistency variation spectrum.
- The frequency spike at 3 Hz existing in both the pressure pulsation and thick stock flow rate spectra disappeared with the control valve turned on.

As also shown in **Fig. 9**, during the second run, the stock



7. Transfer functions of the pressure pulsation attenuator (first run of 2.817 h).

flow control did smooth out some thick stock flow rate variation, such as the frequency spikes at 3 Hz and 3.3 Hz. However, the main features of the stuff box consistency and pressure pulsation remain the same. It is interesting to note that with the stock flow control loop, the CD profile is improved significantly.

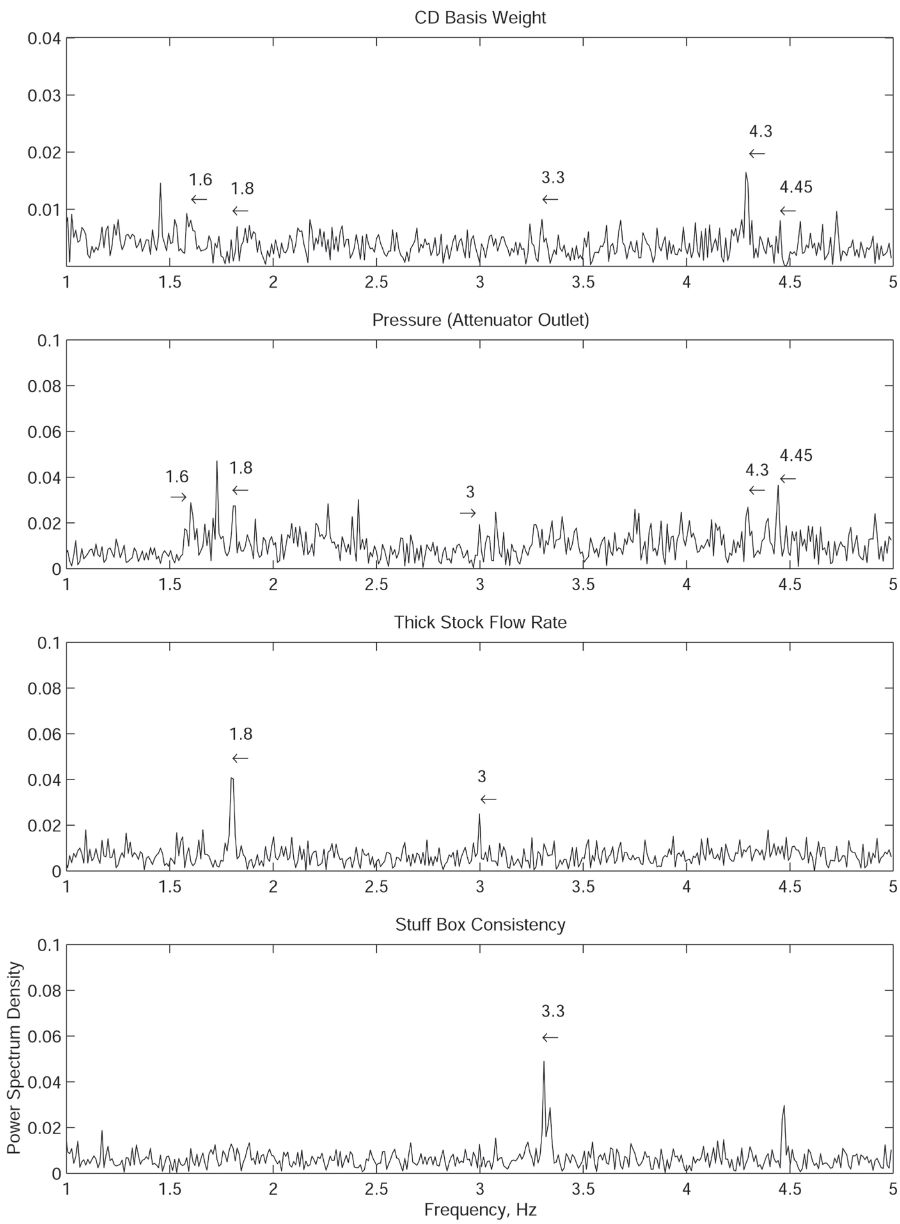
Correlation

As reported by Wang et al. [13], low frequency variability, which is different from the relative high frequency "barring" discussed by Cuffey and Ingram, Crouse, and Schöning and Jörgensen [1,18,19], can be traced all the way back to the machine chest and high density tanks. In this paper, the correlation analysis is also employed to reveal that the causality of the basis weight variation within various stages of the approach flow system.

Consider a random discrete signal $\mathbf{X} = [x_1, x_2, \ldots, x_N]$ with N samples or observations. The variance V can be calculated with Bessel correction factor as below:

$$V = \sum_{i=1}^{N} (x_i - \bar{x})^2 / (N-1) \quad (10)$$

where $\bar{x}$ is the average value defined as $\bar{x} = \sum_{i=1}^{N} x_i / N$.



8. Typical spectra associated with basis weight variations (first run of 2.817 h).

Consider two random discrete signals $\mathbf{X} = [x_1, x_2, \ldots, x_N]$ and $\mathbf{Y} = [y_1, y_2, \ldots, y_N]$, both with N samples or observations. The covariance C_{xy} of signal **X** and **Y** can be determined with Bessel correction factor as follows:

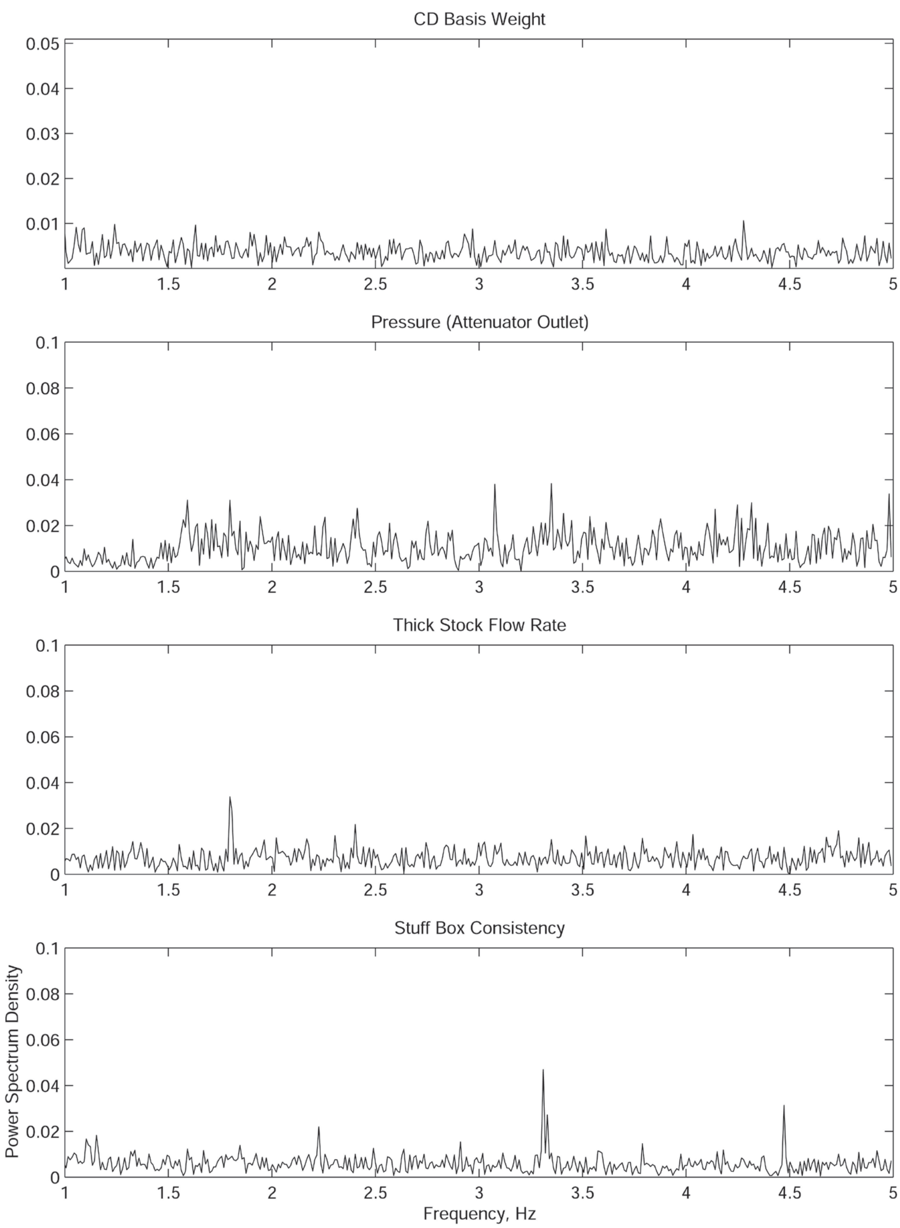
$$C_{xy} = \frac{\sum_{i=1}^{N}(x_i - \bar{x})(y_i - \bar{y})}{N-1}, \quad (11)$$

where $\bar{x}$ and $\bar{y}$ are the average of signal **X** and **Y**, respectively.

The correlation coefficients R_{xy} between the random discrete signals **X** and **Y** can then be evaluated as given below:

$$R_{xy} = \frac{C_{xy}}{\sqrt{V_x V_y}} \quad (12)$$

where V_x and V_y are the variance with Bessel correction factor for signals **X** and **Y**, respectively. If the correlation coefficient is close to 1, the random signals **X** and **Y** are positively linearly related; if the correlation coefficient is close to −1, the random signals **X** and **Y** are negatively linearly related; if the correlation coefficient is close to 0, there is a weak linear re-



9. Typical spectra associated with basis weight variations (second run of 0.8917 h).

lationship between the random signals **X** and **Y**.

Using the previously mentioned methodology, the correlation coefficients are calculated for data of problematic formation (first run of 2.817 h). In **Table III**, the correlation coefficients of basis weight (β gauge) signal to other signals are summarized. As can be seen in Table III, the match score of basis weight to inlet and outlet pressure are 0.0451 and 0.051, respectively. This means the basis weight is not directly affected by the pressure in the system. The match score of the basis weight to the flow rate is given as −0.5218, which means there is a negative linear relationship between the two. With a higher flow rate, the basis weight consistency will not be as good compared to a lower flow rate. Similarly, there is a weak linear relationship between the basis weight and stuff box; the consistencies at the Duo formers, machine chest, and softwood refiner do not directly affect the basis weight too much; and the consistency of the hardwood refiner is weakly related to the basis weight. Finally, there is a relatively strong linear relationship between the consistency of the blender and the basis weight. In addition, the correlations are investigated for the consistency of blender, blender chest, and stuff box as shown in **Table IV**. The match score between the consistency of the blender and blender chest is −0.2959, which indicates a relatively strong negative linear relationship, and the match score between the consistency of the blender chest and the stuff box is 0.603, which indicates a strong linear relationship. In summary, for bad formation, the flow rate and consistency of blender directly affect the basis weight, and the consistency of the blender also affects the consistency of the stuff box.

In a similar pattern, the correlation coefficients of basis weight (β gauge) signal to other signals are summarized in **Table V** for data of consistent formation (second run of 0.8917 h). And the correlations are investigated for the consistency of blender, blender chest,

	Channel Name	
Correlated Signals	CH11-β Gauge	CH01-P Inlet
Match Score	0.0451	
Correlated Signals	CH11-β Gauge	CH02-P Outlet
Match Score	0.051	
Correlated Signals	CH11-β Gauge	CH03-Flow
Match Score	-0.5218	
Correlated Signals	CH11-β Gauge	CH04-Stuff Box
Match Score	0.1175	
Correlated Signals	CH11-β Gauge	CH05-Duo#2 Upper
Match Score	0.0511	
Correlated Signals	CH11-β Gauge	CH06-Duo#1 Lower
Match Score	0.0803	
Correlated Signals	CH11-β Gauge	CH012-Machine Chest
Match Score	0.0796	
Correlated Signals	CH11-β Gauge	CH013-Soft Wood
Match Score	-0.098	
Correlated Signals	CH11-β Gauge	CH014-Hardwood
Match Score	-0.1565	
Correlated Signals	CH11-β Gauge	CH15-Blend Chest
Match Score	0.33	
Correlated Signals	CH11-β Gauge	CH16-Blender
Match Score	-0.336	

III. Correlation coefficients of basis weight β gauge signal to other signals of the problematic run data.

	Channel Name	
Correlated Signals	CH16-Blender	CH15-Blend Chest
Match Score	-0.2959	
Correlated Signals	CH15-Blend Chest	CH04-Stuff Box
Match Score	0.603	

IV. Correlation coefficients of the consistencies of blender, blender chest, and stuff box of the problematic run data.

	Channel Name	
Correlated Signals	CH11-β Gauge	CH01-P Inlet
Match Score	-0.0096	
Correlated Signals	CH11-β Gauge	CH02-P Outlet
Match Score	0.005	
Correlated Signals	CH11-β Gauge	CH03-Flow
Match Score	-0.0418	
Correlated Signals	CH11-β Gauge	CH04-Stuff Box
Match Score	-0.0511	
Correlated Signals	CH11-β Gauge	CH05-Duo#2 Upper
Match Score	-0.0116	
Correlated Signals	CH11-β Gauge	CH06-Duo#1 Lower
Match Score	-0.095	
Correlated Signals	CH11-β Gauge	CH012-Machine Chest
Match Score	0.074	
Correlated Signals	CH11-β Gauge	CH013-Soft Wood
Match Score	-0.075	
Correlated Signals	CH11-β Gauge	CH014-Hardwood
Match Score	-0.0665	
Correlated Signals	CH11-β Gauge	CH15-Blend Chest
Match Score	-0.0257	
Correlated Signals	CH11-β Gauge	CH16-Blender
Match Score	-0.0042	

V. Correlation coefficients of Basis Weight β gauge signal to other signals of the consistent run data.

	Channel Name	
Correlated Signals	CH16-Blender	CH15-Blend Chest
Match Score	-0.0139	
Correlated Signals	CH15-Blend Chest	CH04-Stuff Box
Match Score	0.0831	

VI. Correlation coefficients of the consistencies of blender, blender chest, and stuff box of the consistent run data.

and stuff box for the consistent formation as shown in **Table VI**. As can be observed from the tables, all match scores are close to zero, which means for the consistent formation case, none of the previously mentioned factors affect the output basis weight directly. At the same time, the consistency in blender also does not affect the consistency of the stuff box.

CONCLUSIONS

We have studied the large amount of information gathered in two separate runs on the same paper machine. The benefit of analyzing two sets of mill data is to confirm that some of the findings are generic and system dependent, such as the pressure pulsation attenuator performance. The most significant aspect of this work is to present a systematic approach to tackle the mill data and extract from a wealth of information packed in the signals the most important aspects of the improvement of both system performance and future system designs. In conclusion, we have made the following observations:

1. Synchronization (taking into consideration the time lags) is important to analyze the low frequency range signals, yet not needed for the analysis of high frequency range signals.
2. The pressure pulsation attenuation device is effective for frequencies higher than 1 Hz (as illustrated in Fig. 7), and the transfer functions obtained from the inlet and outlet pressure pulsations are characteristics of the particular pressure pulsation attenuator and the headbox recirculation line.
3. Regardless of certain high, medium, and low frequency range variations, both runs were stable (as illustrated in Figs. 2, 3, 4, and 5).
4. The use of a stuff box stock flow control valve does significantly improve the CD basis weight variation (as illustrated in Figs. 8 and 9).

The analysis procedures and the developed software can be used to study the long-term, multichannel signals of other process variables, such as retention aids and fines. **TJ**

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We chose this topic for research because it is an important and relevant process control study with immediate application for streamlining and improving the operation of paper mills. In comparison with a 1998 report documented in IPST Member Company Reports, this study has a specific focus on key correlation between ß gauge and approach flow units such blender, blend chest, and stuff box, as well as the transfer function between the pressure attenuator inlet and outlet.

Wang

Guo

The most difficult aspect of this research was an overwhelming amount of data, which made it difficult to be disciplined and focused in identifying the key information. The most interesting lesson learned from this exercise is to stay focused and disciplined, because crucial useful information is often hidden among vast amounts of data.

The in-house developed software employed in this research will be used to monitor and study data and provide relevant recommendations with direct impact on mill operations. Our next step is to implement the same study for a few other mills and to add a graphic user interface to our data analysis software.

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