

Dynamic modeling of agitated pulp stock chests

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ABSTRACT: The chief purpose of agitated pulp stock chests is to reduce high-frequency variability in mass concentration, freeness, and other quality factors. These chests behave as low-pass filters to complement the action of control loops, which only control low-frequency variability. Dynamic tests made on industrial and scale-model stock chests show non-ideal flows such as channeling, recirculation, and stagnant zones. These flows reduce the degree of upset attenuation at frequencies higher than the cut-off frequencies of paper machine control loops. We have developed a dynamic model of agitated pulp stock chests, incorporating these non-ideal flows. In this paper, we explore the excitation design required to estimate the model parameters and the effect of process variables on disturbance attenuation. The variables examined include the impeller speed, pulp feed and exit location, fiber mass concentration (consistency), and pulp flow rate through the chest. Test results show that the location of the input and output in the chest significantly affects the percentage of channeling and the degree of disturbance attenuation. We found that at higher pulp flow rates through the chest and fiber mass concentration greater than 3% the system is prone to a high percentage of channeling and a low degree of upset attenuation.

Application: Identification of the type and degree of non-ideal flow in a pulp stock chest allows mills to take corrective measures to improve uniformity in downstream processes.

Agitated pulp stock chests affect all areas of pulp and paper manufacture. They act as a buffer between processes and reduce variability in fiber mass concentration, freeness, and other quality factors. From the standpoint of variability reduction, stock chests provide means for reducing high-frequency disturbances [1]. This filtering complements the action of control loops, which can only control low-frequency variability [2]. It is important to ensure these chests are properly designed to achieve the desired overall degree of upset attenuation.

Industrial data show that non-ideal flows such as channeling, recirculation, and stagnant zones exist in agitated pulp stock chests [3]. These non-ideal flows should be avoided since they decrease the performance of the chest. **Figure 1** shows the measured response of an industrial stock chest to a step input change at $t = 200$ s (private communication, Bill Bialkowski, 2001). The upper curve is the input signal and the lower curve is the output response. The chest response is clearly not ideal. The output shows an initial bump (at about $t = 300$ s) that is due to short-circuiting (channeling) within the chest. The response also shows a series of first order exponential responses, each one getting progressively smaller. From this we conclude that a portion of stock is recirculated within the chest. The theoretical

residence time for this chest is 14 min. Since the real time constant obtained from the step response is 5.8 min., we concluded that stagnant and/or dead zones exist inside the chest [4].

Figure 2 shows the plotted frequency responses calculated for this industrial stock chest and for a perfectly mixed chest having the same volume and flow rate [3]. The degree of upset attenuation for the industrial stock chest is considerably worse than that of the perfectly mixed chest, especially for frequencies from 0.01 to 0.1 rad/s. These frequencies are higher than the cut-off frequencies of paper machine control loops, which are usually between 0.002 and 0.005 rad/s [2]. Therefore, disturbances at these frequencies would not be attenuated and would affect paper quality and machine runnability.

No information is available on the effects of non-ideal flow on the dynamic behavior of stock chests, although studies have been made on ideal chests [1, 5-10]. Since ignoring non-ideal flows can lead to errors in system design [11], it is necessary to study the dynamic behavior of stock mixing under realistic (less-than-ideal) mixing conditions. The objective of this work is to incorporate process dynamics in the design criteria so that mills can attain good mixing with a predictable dynamic response profile.

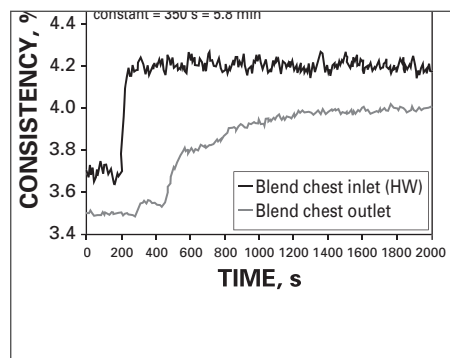
EXPERIMENTAL SETUP

Figure 3 shows a schematic diagram of the experimental setup. Pulp suspension is pumped from the feed tank to the stock chest and from this to the discharge tank. The stock chest is rectangular and equipped with a side-entering impeller. To study the dynamic response of the stock chest, we injected a saline solution through a computer-controlled solenoid valve into the pulp feed. The conductivity variations in the input and output streams are measured with flow-through conductivity sensors. The details regarding this experimental setup are discussed by Ein-Mozaffari et al. [3].

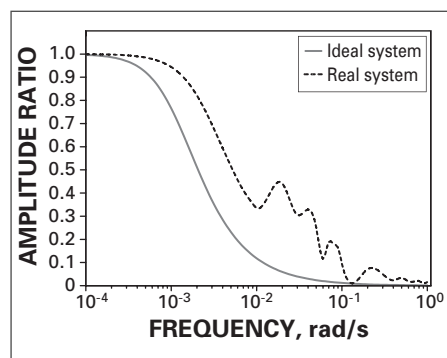
DYNAMIC MODEL

Figure 4 shows a simple continuous-time dynamic model that represents the observed behavior of the industrial and scale-model chests. We built this model using basic principles where the system parameters have a physical interpretation. In this figure, f is the portion of the stock bypassed (channeled) in the mixing zone and R is the portion of the stock recirculated within the mixing zone. G_2 is the first order transfer function for the agitated zone. Since a limited amount of mixing occurs in the short circuit flow, it also has a first order transfer function (G_1). τ_1 and τ_2 are the time constants for the channeling and agitated zones.

PULP FLOW MODELING



1. Step response of an industrial stock chest.



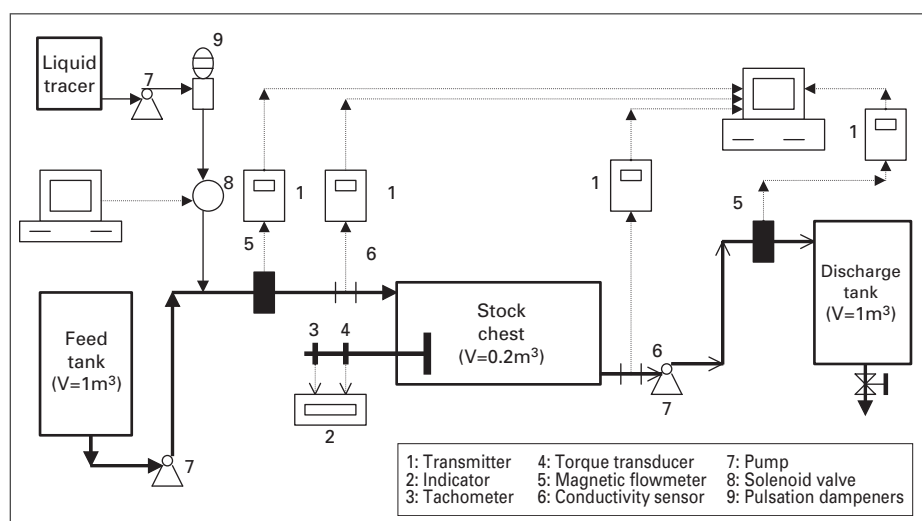
2. Frequency response measured for the industrial chest compared with its ideal response.

where: $\rho_1 = f(1-a_p)$, $\rho_2 = -f(1-a_p)a_2$, $\rho_3 = (1-f)(1-R)(1-a_2)$, $\rho_4 = -(1-f)(1-R)(1-a_2)a_1$, $\rho_5 = -fR(1-a_p)(1-a_2)$, $\rho_6 = -a_1a_2$, $\rho_7 = a_1a_2$, $\rho_8 = -R(1-a_2)$, $\rho_9 = Ra_1(1-a_2)$, $a = e^{-ts/\tau}$, $d = 1 + T/t_s$, $d_2 \geq d_1$, and t_s and q^{-1} are sampling time and backward shift operator.

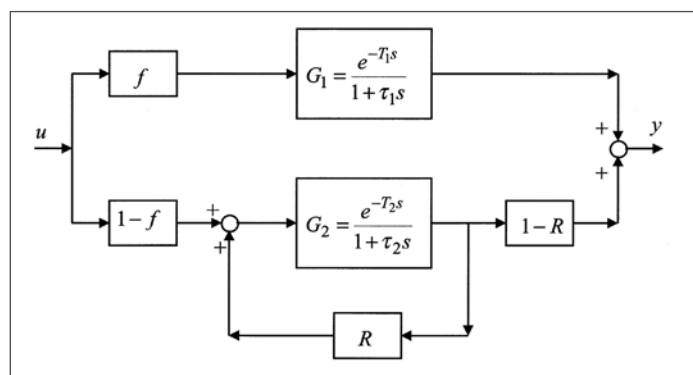
By measuring the input-output response of an agitated pulp stock chest, the above dynamic model parameters can be estimated using a numerical method developed by Kammer et al. [12].

DYNAMIC TESTING PROCEDURE

The identification experiment was performed by exciting the system and observing the input and output conductivities over a time interval. We recorded these signals in a computer to estimate dynamic model parameters. The excitation provided in the dynamic experiments was limited to binary sequences because the input signal was controlled by an on-off solenoid valve. The process of model identification required two experiments. In the first experiment, the input signal was a rectangular pulse (Fig. 5), which allowed the estimation of an approximate model (gray line in Fig. 5) used to design the excitation for the second experiment. The excitation energy



3. Schematic of experimental setup.



4. Continuous-time dynamic model of the stock chest.

The step response signal also shows the possibility of transport delays in both paths, which we also incorporated into the model. T_1 and T_2 are the time delays for the channeling and agitated zone, respectively.

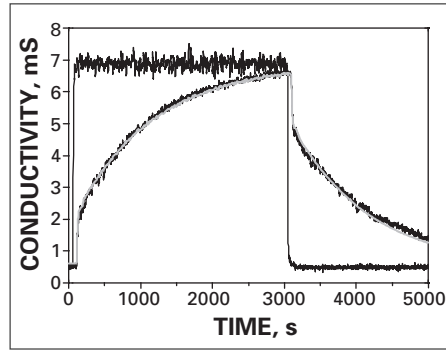
Since the data are measured at fixed time intervals, the continuous model is initially transformed into a simple discrete-time model [12]:

$$\hat{G}(q) = \frac{\rho_1 q^{-d_1} + \rho_2 q^{-(d_1+1)} + \rho_3 q^{-d_2} + \rho_4 q^{-(d_2+1)} + \rho_5 q^{-(d_1+d_2)}}{1 + \rho_6 q^{-1} + \rho_7 q^{-2} + \rho_8 q^{-d_2} + \rho_9 q^{-(d_2+1)}}$$

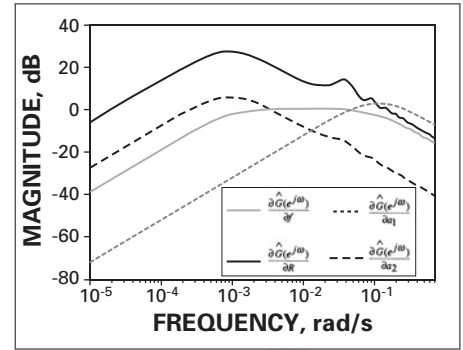
for the second experiment encompasses frequencies where the magnitude of the Bode plot was sensitive to parameter variations [13]. For this purpose, the magnitude of the Bode plot for the partial derivatives of the model with respect to model parameters (f , R , a_p , and a_2) are calculated and shown in Fig. 6. From this figure the frequencies at which the magnitudes are maximum are obtained: $w_f = 0.05 \text{ rad/s}$, $w_R = 0.0009 \text{ rad/s}$, $w_{a1} = 0.15 \text{ rad/s}$, and $w_{a2} = 0.001 \text{ rad/s}$. Therefore, the excitation energy for the second experiment was concentrated at frequencies from 0.0009 rad/s to 0.15 rad/s.

Figure 7 shows the procedure for designing a frequency-modulated random binary input signal for the second experiment. First, a zero-mean white-noise signal is filtered by a band-pass filter with cut-off frequencies obtained from Fig. 6. Then the filtered signal is converted into a binary sequence. Since such a conversion can change the spectrum of the signal, we checked its spectrum to see if it was acceptable [13]. The signal designed by this method was then applied to the injection valve. Preliminary dynamic test results showed that the designed signal was too fast for this system. The high cut-off frequency ($w_{a1} = 0.15 \text{ rad/s}$) for the band-pass filter was obtained at the maximum value of the partial derivative of the model with respect to a_p , which corresponds to τ_i in continuous-time domain. Because a very limited amount of mixing occurs in the channeling zone, the value of τ_i is very small

(a few seconds) for the scale-model chest and should be ignored when designing the input signal. Therefore, the high cut-off frequency for band-pass filter was reduced from $w_{a1} = 0.15$ rad/s to $w_f = 0.05$ rad/s. The low cut-off frequency for band-pass filter (0.0009 rad/s, corresponding to the period $T = 2\pi/w = 6981$ s) was higher than the maximum length of the experimental data (5500s, determined by the feed tank capacity and pulp flow rate through the chest). Therefore, it was not necessary to consider the low cut-off frequency when designing the input signal. **Figure 8** shows the final input signal and its spectrum. We applied this signal to the injection valve. **Figure 9** shows the input, measured output, and model output signals obtained from one of the dynamic tests made on the scale-model chest.



5. Chest input and output signals in black lines and model output in gray line.



6. Magnitude Bode plot of partial derivatives of the model.

RESULTS AND DISCUSSION

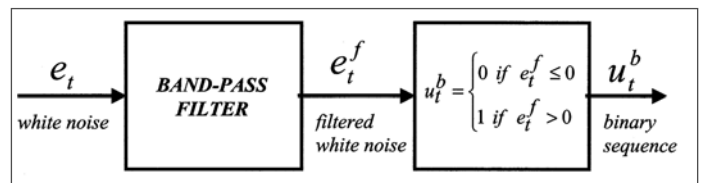
We studied the effects of operating conditions on the dynamic behavior of the stock chest by varying the impeller speed (700-1750 rpm), fiber mass concentration (2.1%-3.3%), and pulp flow rate through the chest (7.9-37.1 L/min). In this study, we tested the effect of pulp feed and exit location for two configurations (C1 and C2) shown in **Fig. 10**. Since C1 is widely used, we focused on the dynamic response of this configuration and explored how changing the operating conditions improves the dynamic response. At the end, we compare the dynamic behaviors of both configurations.

The effect of impeller speed

Figure 11 shows the input and output responses for a series of tests where the flow rate into the chest is fixed and the impeller speed (N) changed. At $N = 1127$ rpm, which is above the criteria of complete surface motion used to size the chest, the output response follows the input signal, indicating complete channeling in the vessel. Channeling decreases abruptly when the impeller speed reaches a critical value and then progressively decreases as the impeller speed is increased. **Figure 12** shows the effect of impeller speed on channeling at different pulp flow rates. This data show that channeling decreases as impeller speed increases. At higher impeller speeds, the fiber/fiber network is disrupted further from the impeller, leading to improved mixing by eliminating non-ideal flows. **Figure 13** shows the effect of impeller speed on frequency response of stock chest. As can be seen, the degree of disturbance attenuation can be improved by increasing the impeller speed. For example, at $N = 1724$ rpm the dynamic response is very close to an ideal response, which has a simple first order transfer function. That means that increasing the impeller speed eliminates the effect of non-ideal flows such as channeling and stagnant zones.

The effect of pulp flow rate

At higher flow rates, the system is prone to a high percentage of channeling (**Fig. 12**), even at impeller speeds above the criteria of complete surface motion used to size the chest. At lower flow rates and higher impeller speeds, decreasing the flow rate does not have a significant effect on the channeling. However, the degree of upset attenuation is improved by decreasing the pulp flow rate through the chest (**Fig. 14**). A decrease in pulp flow rate increases the time constant of the mixing zone.



7. Input signal design procedure.

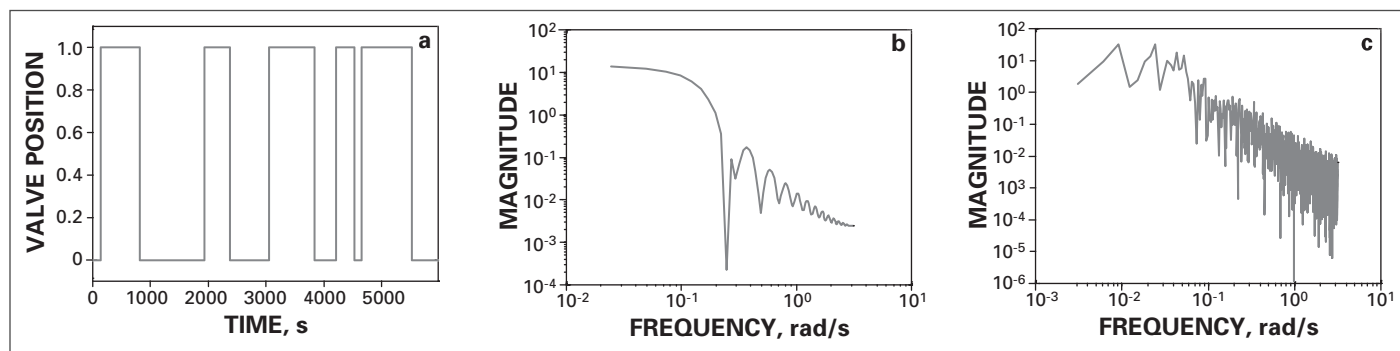
The effect of fiber mass concentration

As the fiber mass concentration increases, the number of fiber-fiber interactions increases, which increases network strength. Because of this rheological behavior, the effect of non-ideal phenomena such as channeling and stagnant regions increases with an increase in fiber mass concentration. **Figure 15** shows the effect of fiber mass concentration on channeling. At fiber mass concentration greater than 3%, a high percentage of channeling exists, even at impeller speeds greater than the speed required for complete surface motion. At fiber mass concentrations smaller than 3%, full channeling does not occur, even at impeller speeds equal to that required for complete surface motion. This phenomenon can cause problems when the fiber mass concentration inside a chest (designed for lower fiber mass concentration) increases during operation due to disturbances. In this situation, the system can shift to the full channeling with a low degree of attenuation. **Figure 16** shows the effect of fiber mass concentration on the chest performance in the frequency domain. In this graph, the comparison has been made at the beginning of complete motion through the chest for different mass concentrations. These data show that the degree of attenuation decreases with an increase in fiber mass concentration. Although the whole suspension inside the chest is in motion, no significant attenuation occurs at 3.3%. However, when the fiber mass concentration decreases to 2.1%, the degree of upset attenuation is significantly improved. Therefore, chests designed using the criterion of the onset of complete motion do not necessarily lead to a fully mixed system, especially at fiber mass concentration greater than 3%.

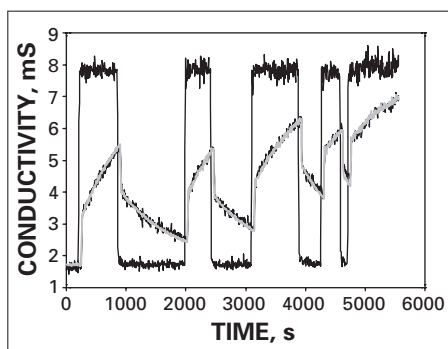
The effect of pulp feed and exit location

Dynamic tests showed that the pulp feed and exit locations significantly affect the degree of upset attenuation due to channeling. Based on results presented in previous sections of this paper, the degree of disturbance attenuation increases by increasing the impeller speed and decreasing the pulp flow rate and fiber mass concentration for the first configuration (C1).

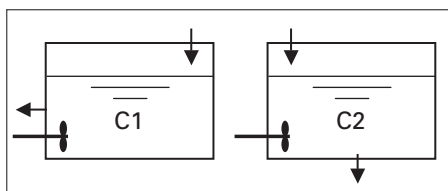
PULP FLOW MODELING



8. Input signal (a); its spectrum (b); and its periodogram (c).



9. Chest input and output signals in black lines, model output in gray line.



10. Input-output configurations studied (C1 = configuration 1, C2 = configuration 2).

However, the higher impeller speed requires higher installed power and can cause more air entrainment in the suspension. Decreasing the pulp flow rate and the fiber mass concentration also reduces the production capacity of the chest. The dynamic tests made on a scale-model chest showed that the dynamic

performance for C1 could be improved by changing the feed and exit locations to that of the second configuration (C2). Figure 17 shows the effects of pulp feed and exit locations on channeling for the two configurations shown in Fig. 10. For C1, the system is susceptible to a higher percentage of channeling compared to that of C2. Under identical operating conditions, C2 can provide greater attenuation and approaches an ideal response (Fig. 18).

Sufficient motion is needed at the pulp exit location to prevent dewatering of stock before it enters the discharge pump. Therefore, the exit port cannot be located at the impeller opposite wall where insufficient motion is induced by the impeller. In both C1 and C2, sufficient motion exists at the pulp exit locations. However, C1 is widely used in industry due to the ease of mechanical installation and maintenance.

CONCLUSIONS

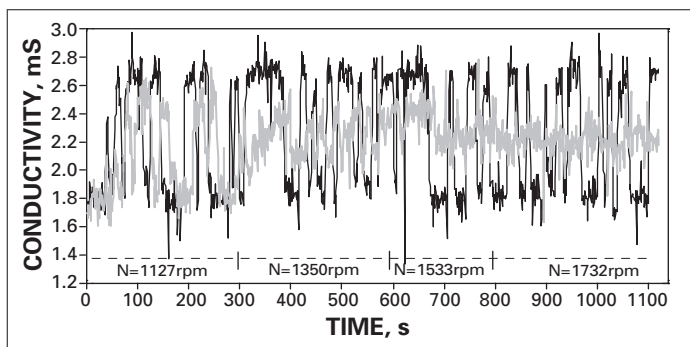
Industrial data and dynamic tests made on the scale-model chest confirm the existence of non-ideal flows such as channeling, recirculation, and dead zones. Since these non-ideal flows reduce the degree of upset attenuation, we factored them into the dynamic modeling of the chest. Dynamic tests showed that the pulp feed

percentage of channeling and a low degree of attenuation. Under these circumstances, the degree of attenuation could be improved by either reducing the pulp flow rate through the chest or increasing the impeller speed. In industrial situations, a decrease in pulp flow rate is not possible and changes in impeller speed must be considered. We found that chests designed using the criterion of the onset of complete motion do not necessarily lead to a fully mixed system, especially at fiber mass concentration greater than 3%. **TJ**

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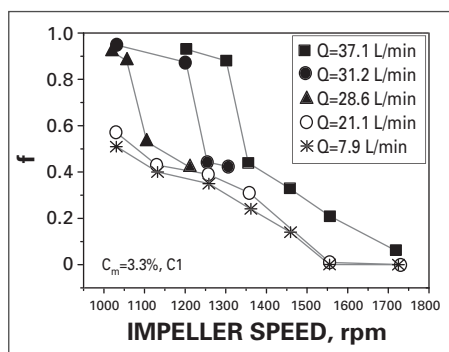
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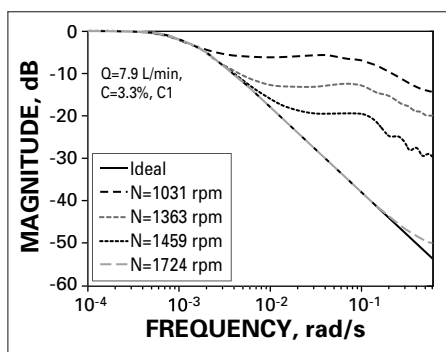


11. The effect of impeller speed on the degree of attenuation.

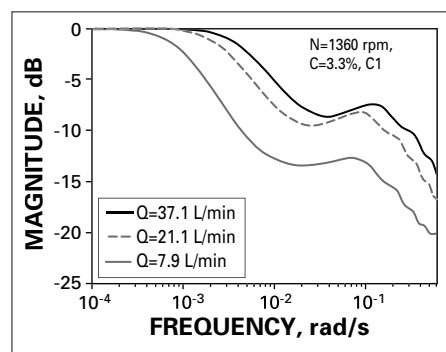
and exit locations have a significant effect on the degree of upset attenuation, although the exit must be located in a zone of sufficient agitation to prevent dewatering. For suspension mass concentrations greater than 3%, the system was prone to a high



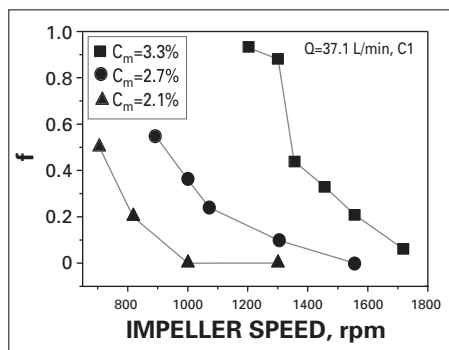
12. The effect of impeller speed and pulp flow rate on channeling.



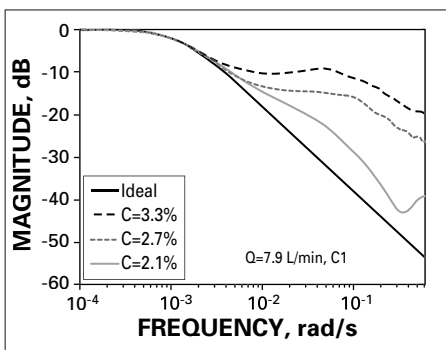
13. The effect of impeller speed on the degree of disturbance attenuation.



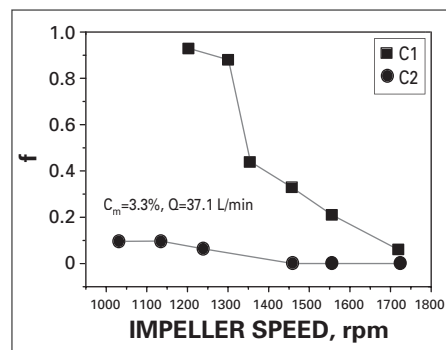
14. The effect of pulp flow rate on the degree of disturbance attenuation.



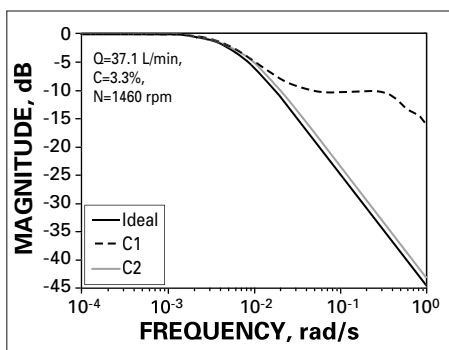
15. The effect of fiber mass concentration on channeling.



16. The effect of fiber mass concentration on the degree of disturbance attenuation.



17. The effect of input-output location on channeling.



18. The effect of input-output location on the degree of disturbance attenuation.

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INSIGHTS FROM THE AUTHORS

Little information was available about the effects of non-ideal flows on the dynamic behavior of pulp stock chests. In this study, we developed a dynamic model and used it to study flow non-idealities in a scale-model pulp agitation chest over a wide range of operating conditions.

We learned that to approach ideally mixed conditions in a stock chest requires considerably more power than is normally installed at mills, based on current design practices.

In certain pulp processing situations the attenuation of process fluctuations is critical. This paper shows the extent of non-ideal flows in pulp agitation systems and how changes in process variables can reduce their effects and improve dynamic response.

In future work we will expand our examination of pulp mixing dynamics to cover a wider range of process conditions. Research will be directed at developing criteria to design chests for a known dynamic performance and to find effective ways to improve the dynamic response of existing chests.

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