Identification of a TMP wood chip refiner with implications for process control

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ABSTRACT

Identification experiments were performed on an industrial primary TMP wood chip refiner. The objective was to make an informed recommendation to the mill regarding the type of control strategy best suited to this particular refiner. The input variables for these tests were dilution water flow rate, indicated chip throughput, and hydraulic pressure applied to the refiner plates. The output variables studied were refiner motor load and pulp blowline consistency. The tests were carried out over one full plate life.

Based on the results of these experiments, the indicated throughput was not recommended for use as a manipulated variable due to the low gain associated with the throughput to motor load and consistency relationships. We also observed that the gain of the hydraulic pressure–to–motor load relationship remained relatively constant over the plate life. Overall, the identification results indicated that a fixed-gain (nonadaptive) controller could be designed to stabilize this refiner.

Application:

This research proposes the use of identification experiments to establish the dynamic relationships between the inputs and outputs of a wood chip refiner process. The results provide useful information for the design of the most appropriate control strategy for each process installation.

A KEY PART OF THE MECHANICAL wood-pulp manufacturing process is the wood chip refiner *(1)*. It is inside the refiner that chips are broken down into fibers. The specific energy, or energy per unit mass of wood fibers, is a major factor in determining the pulp quality. Therefore, the chip feed rate and refiner motor load must be controlled. Pulp consistency (percent solids content of the pulp) is another important variable associated with chip refining, because it determines the quality of the pulp for a given specific energy *(2)*.

Most if not all refiners are volumetrically fed *(3)*. Therefore, it is understandable that variations in chip moisture content and chip bulk density inside the feed screw conveyors are major obstacles in achieving uniform pulp quality. In addition, refining processes are typically two-stage operations, where the pulp from the primary refiner is fed directly into a second stage refiner. In this type of process design, fluctuations in operating and quality variables leaving the primary refiner act as disturbances to the secondary refiner. In fact, experience indicates that these disturbances tend to get amplified by the second stage.

The need for automatic control of chip refining has been appreciated for some time. Rogers *et al. (4)* clearly state the objectives for regulating the refiner process as being (a) to maintain desired levels of motor load, throughput, and discharge consistency by manipulating hydraulic pressure, volumetric feed rate, and dilution water flow rate and (b) to maintain a desired specific energy by adjusting either the motor load or the throughput. The authors also describe the chip refiner process as a nonstationary system. In their study, they observed that as the plates wear, the behavior of the process can change gradually with normal wear or suddenly as a result of a plate clash (metal-to-metal contact between two plates). In their conclusions, the authors pointed out that existing methods for estimating refiner throughput are not adequate and that control improvements could be obtained with an on-line measure of chip mass throughput and moisture content. This assessment remains valid today.

A significant amount of research has been done by Dumont and coworkers *(1, 5-7)* on the problem of controlling the refiner motor load by manipulating the gap between the refiner plates. (The plate gap is actually manipulated by adjusting the hydraulic pressure.) This strategy would maintain a constant motor load, although the problem of throughput measurement and control remains. The controller design problem is difficult to solve since the dynamic relationship between plate gap and motor load is subject to a slow drift due to plate wear and to sudden changes in sign of the gain due to collapse of the pulp pad between the plates. Various advanced control strategies, such as the self-tuning regulator and dual control, have been found necessary to deal with this complicated and unpredictable behavior. Experimental trials reported by Dumont *(1)* were held on a secondary refiner, and the work of Allison *et al. (6, 7)* was performed on a reject refiner.

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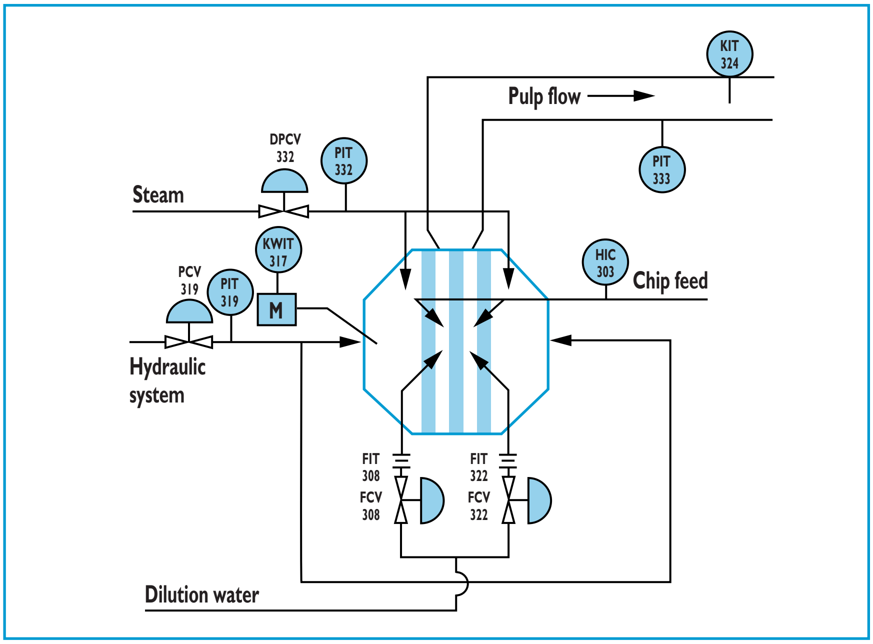
Others have looked at controlling the primary refiner motor load by manipulating the volumetric chip feed rate *(8)*. Evans *et al.* *(9)* have combined this approach with a consistency controller using a consistency measurement made directly in the pulp flow leaving the refiner (i.e., in the blowline) and manipulating the dilution water flow rate. More recently, Roche *et al.* *(10)* have used feed rate to control motor load on the primary refiner and used plate gap to control motor load on the secondary refiner to stabilize pulp quality on a two-stage refiner line. Du and Dumont *(11)* have proposed a multivariable refiner control strategy that regulates refiner motor load and blowline consistency by adjusting three manipulated variables: feed rate, plate gap, and dilution water flow rate.

Much of the focus in the previously mentioned literature has been on the controller design itself. There has been much less emphasis on identifying the process dynamics and how the dynamics behave as a function of plate life. However, this type of information is important when making decisions about the most appropriate control strategy for a particular application.

Our main interest was to study the dynamics of an industrial wood chip refiner over the course of an entire plate life and, in so doing, gain some firsthand knowledge about the characteristics of such a process. The objectives of this study were as follows:

- to identify the dynamic relationships between the refiner inputs (indicated chip throughput, hydraulic pressure, and dilution water flow rate) and the refiner outputs (motor load and pulp blowline consistency)
- to determine any trends in these relationships as a function of plate life.



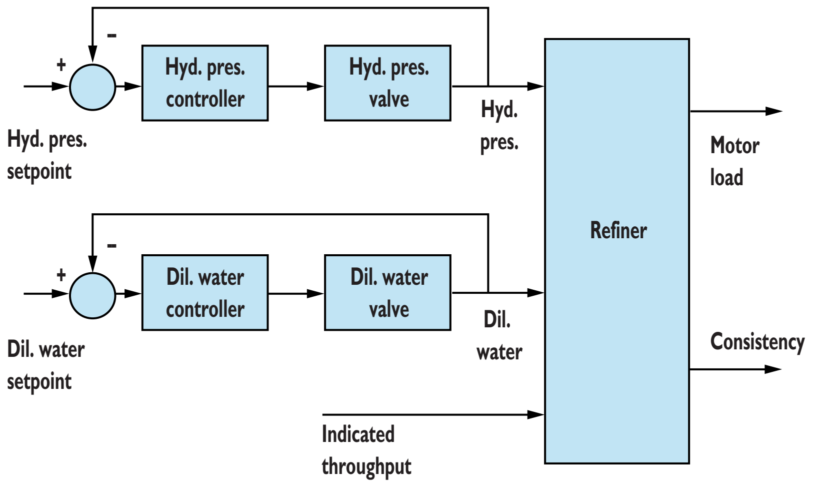
1. Process schematic of the Sprout-Bauer Twin-50 TMP wood chip refiner

This work was performed on the primary refiner of line no. 3 at the Abitibi-Price pulp mill in Beaupré, PQ, during the fall of 1994. Our goal was to make an informed recommendation to the Beaupré mill regarding the type of control strategy that would be best suited to this particular refiner. To our knowledge, these results represent one of the first attempts to study the refiner dynamics as a function of plate life in a systematic way. This work has been presented at two conferences *(12, 13)* and, through interactions within the Government of Canada's Wood-Pulp Network of Centres of Excellence, has prompted similar approaches to studying the refiner process *(10)*. This paper represents a summary of our most important findings, but more details may be found in the literature *(14)*.

PROCESS DESCRIPTION

The chips used in the Beaupré pulp mill are a combination of approximately 20% black spruce and 80% fir. Prior to refining, the chips are presteamed for 30–45 min. The chips are then transported via a plug screw to the primary refiner. The refining process consists of two Sprout-Bauer Twin-50 refiners in series. The pulp produced from the primary refiner is transported to a steam recovery cyclone prior to entering the secondary refiner. Dilution water is added with the chips/pulp at the eye of both the primary and secondary refiners. Finally, the pulp leaving all three secondary refiners enters a common latency chest.

A schematic of the no. 3 line's primary refiner is given in **Fig. 1.** The Twin-50 consists of a double-faced disc centrally mounted on a rotating shaft. The operator sets the desired dry chip mass feed rate, which is then converted to a plug screw speed using a constant factor (HIC-303). Each of the dilution water lines has its own dedicated flow transmitter (FIT-308 and -322) and control valve (FCV-308 and -322). Changes in the dilution water flow rates are made via their respective setpoint values (FIC-308 and -322). Hydraulic pressure (PIT-319) is applied to the plates to decrease the plate gap. Differential steam is also injected behind the plates to help stabilize them and prevent warping. A differential pressure of 60 kPa is maintained between the casing pressure



2. Block diagram of the refiner process

Plate life, h	Motor load setpoint, MW	Indicated throughput, Metric tons/ day	Dil. water flow rate setpoint, L/min	Sensor cons., %	Test tag ref.
225	7.6	215	35	45	PIT1
385	8.5	230	50	45	PIT2
525	8.2	225	43	50	PIT3
825	8.0	220	46	38	PIT4

I. Refiner operating points for identification experiments

(PIT-332) and the blowline pressure (PIT-333). A consistency probe is located in the blowline (KIT-324). A motor load controller (KWIC-317) has also been implemented as the master controller of a cascade control strategy that has as its output the setpoint for the hydraulic pressure controller (PIC-319). When this cascade controller is in automatic mode, the operator enters only a motor load setpoint.

For our study, an Andritz Sprout-Bauer optical consistency sensor was installed in the primary refiner blowline. An earlier study *(14)* was performed to assess the performance of this probe prior to its use during the identification experiments. The main conclusions were that the probe was adequate for measuring changes in consistency within the normal operating range and that the variations in the consistency signal contained significant high-frequency noise.

PROCESS IDENTIFICATION

Identification experiments were performed on the primary refiner to determine models for the dynamic input-output relationships and to establish the time dependence of these models with respect to plate life. The input variables used were (a) hydraulic pressure applied to the refiner plates, (b) dilution water flow rate introduced into the refiner, and (c) indicated chip throughput. The output variables were the refiner motor load and blowline pulp consistency. The identification tests were repeated periodically over one plate life. One plate life is typically 600–800 hours, depending on the frequency and intensity of plate clashes and process operating conditions such as chip species.

Identification methodology

Separate open-loop step tests were performed on the hydraulic pressure setpoint, both dilution water setpoints (simultaneously) and the indicated chip throughput. The motor load and consistency responses were measured. A block diagram of the refiner process is shown in **Fig. 2.** The magnitude of the hydraulic pressure setpoint step changes was 400 kPa, the dilution water setpoint steps were 10 L/min, and the throughput steps were 10 metric tons/day. These magnitudes represent the maximum allowed by production personnel.

Input-output data were collected at a sampling rate of 0.25 seconds using appropriate anti-alias filtering. A period of approximately 5 min was allowed between each input step change at the request of the mill operators. The use of random binary test signals as opposed to step tests may have been preferred due to the significant amount of noise present in the output signals. However, mill personnel did not permit this type of test. The tests were always centered on the refiner's operating point at the time of the experiments. This feature of the experiments is significant, since the operating point shifts during the refiner plate life to maintain pulp quality.

Table I lists the nominal operating point, plate age, and reference name for each set of experiments. **Figures 3–5** give samples of the type of input-output data collected during these experiments. Shown in Figs. 4 and 5 are the measured values of dilution water flow rate and hydraulic pressure resulting from the step changes made in their respective setpoint values. Step response models were estimated from the collected input-output data using a new methodology based on the frequency sampling filter (FSF) model *(15)*.

Identification results

Throughput to motor load. The results for this particular input-output pair indicate that the signal-to-noise ratio was too low and/or the input signal did not have sufficient frequency content. However, we were able to conclude that the process gain was on the order of 0.01 MW/metric ton/day. Therefore, our step changes of 10 metric tons/day would have produced a motor load response within the noise band. Much larger throughput step changes would be required during the identification experiments to develop a more accurate model.

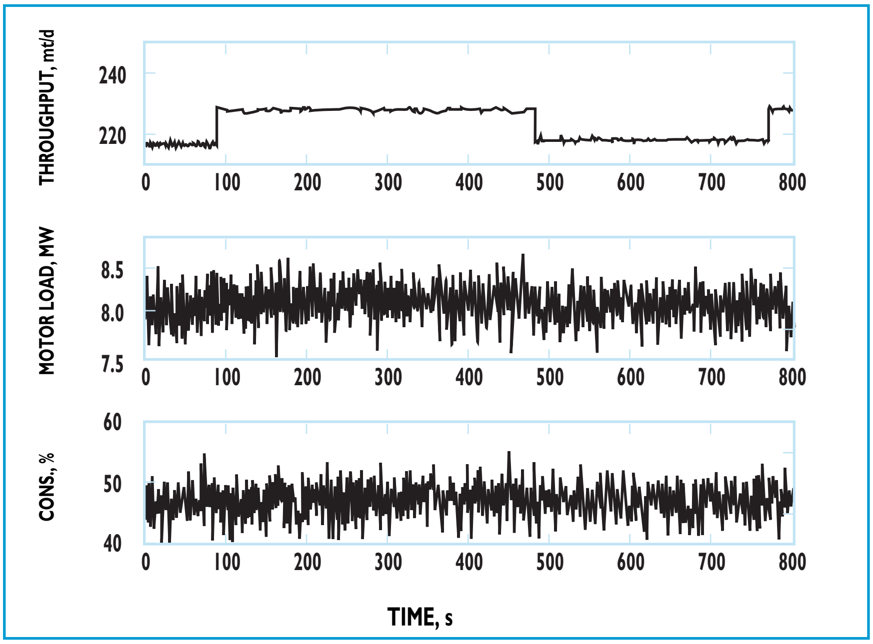
Throughput to consistency. The conclusions for this input-output pair are very similar to those obtained for throughput to motor load. In this case, the gain was on the order of 0.05% consistency/metric ton/day.

Dilution water setpoint to motor load. The unit step response model shown in **Fig. 6** exhibits an underdamped response with a negative gain. The magnitude of the gain increased by approximately 100% at the end of the plate life (see **Fig. 7**). The negative gain confirms previous work, which states that as the consistency in the refiner drops, the specific energy will decrease *(16)*. The underdamped behavior of this input-output pair is felt to be related to interactions between the motor load and the consistency.

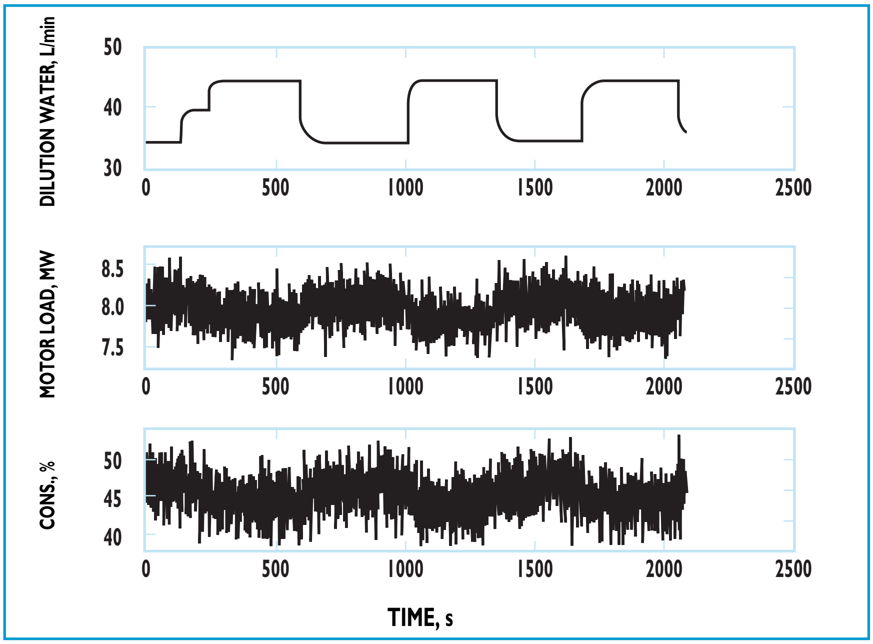
Dilution water setpoint to consistency. The unit step response between these variables is overdamped with a negative gain (see **Fig. 8**). In this case, the magnitude of the process gain increased by approximately 40% at the end of the plate life, as shown in **Fig. 9**.

Hydraulic pressure setpoint to motor load. The unit step response for this input-output pair is overdamped with a positive gain. **Figure 10** shows that the gain remained relatively constant over the plate life, although we were unable to collect the necessary data at the late plate life conditions for this input-output pair.

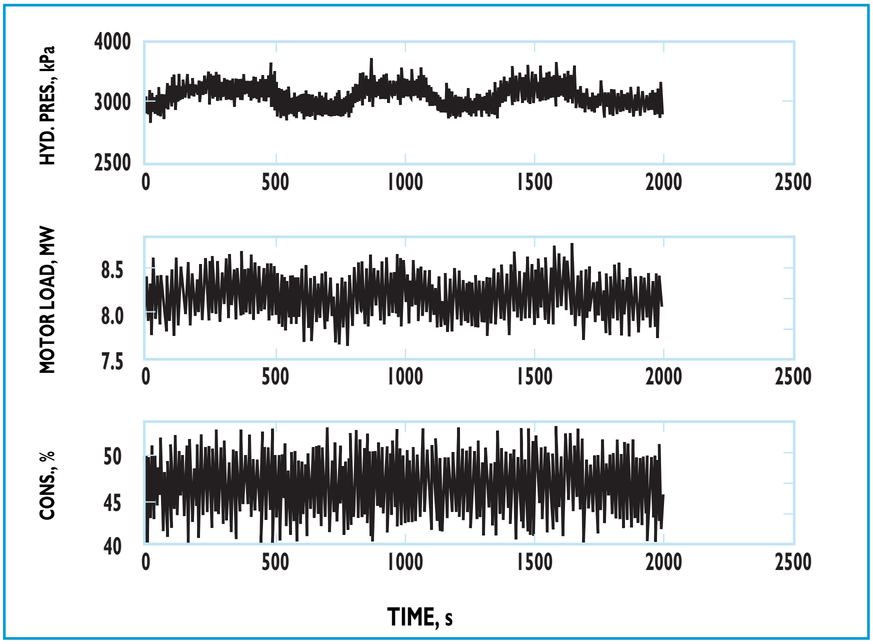
Hydraulic pressure setpoint to consistency. The conclusions for this input-output pair are very similar to those obtained for the throughput results. In this case, the gain was on the order of 1×10^{-3} % cons./kPa. Again, it was felt that larger changes in hydraulic pressure setpoint would be required to improve the model accuracy, but this would have brought about unacceptably large changes in motor load.



3. Sample input-output data. Input variable: indicated throughput.



4. Sample input-output data. Input variable: dilution water flow rate.



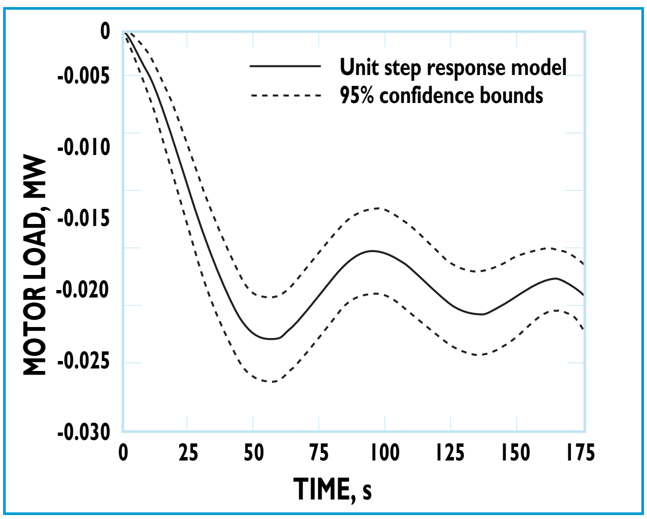
5. Sample input-output data. Input variable: hydraulic pressure.

IMPLICATIONS FOR REFINER CONTROL STRATEGY DESIGN

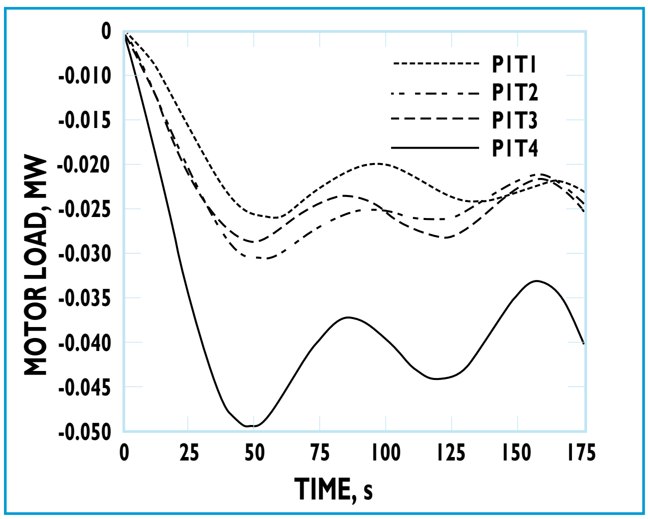
The objective of a refiner control strategy, as stated previously by Rogers *et al. (4),* is twofold: (a) regulation of motor load, throughput, and discharge consistency and (b) maintenance of the desired specific energy. The former "regulation" objective deals with stabilizing the refiner operation, and the latter "maintenance" objective for specific energy reflects the traditional thinking in the industry about how to control the produced pulp quality.

Researchers at Paprican *(16)* have more recently identified the concept of refining intensity as an important variable in determining pulp quality that can be adjusted via refining consistency. The existing control configuration for the refiner studied in this paper consists of a motor load controller with the hydraulic pressure setpoint as the manipulated variable. The indicated throughput and the dilution water flow rates are held constant for long periods of time. The specific energy is not monitored or controlled, primarily because there is no means to calculate an accurate mass throughput. Therefore, it is expected that pulp quality fluctuates due to variations in the incoming wood chip quality and periodic changes in production rate made by production personnel.

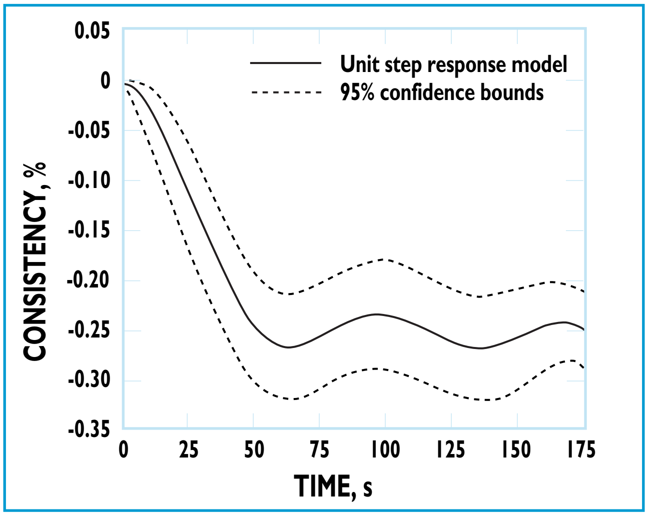
To make recommendations for an improved control strategy for this particular refiner, the use of throughput as a manipulated variable was considered. Shortly after the successful application of a simple motor load control strategy via direct manipulation of the plug screw speed at another Abitibi-Price mill *(8)* but prior to this study, a similar approach was attempted on the no. 3 line's primary refiner at the Beaupré mill. These trials were unsuccessful because they resulted in an unacceptable ramping-type behavior in the screw speed. As many mills use the screw feeder speed to set the desired production rate, automatic manipulation of the screw speed would ultimately have to be constrained about the desired production rate in some manner *(11).* Our identification results for the throughput–to–motor load relationship



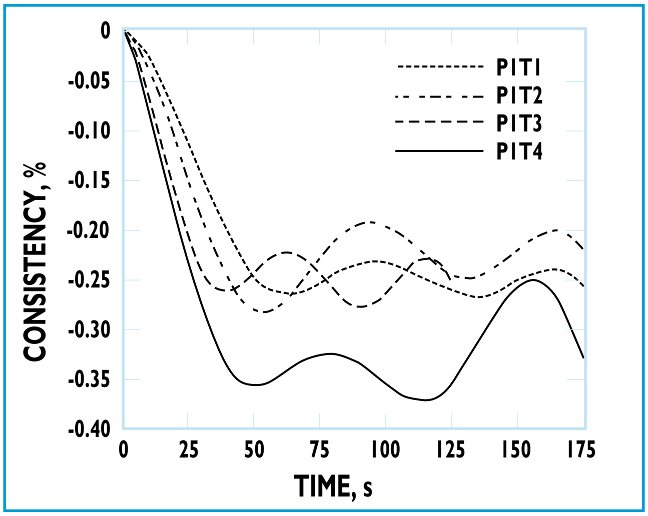
6. Sample step response of motor load to a unit step in dilution water setpoints, PIT1



7. Effect of plate life on unit step response models between dilution water setpoints to motor load



8. Sample step response of consistency to a unit step in dilution water setpoints, PIT1

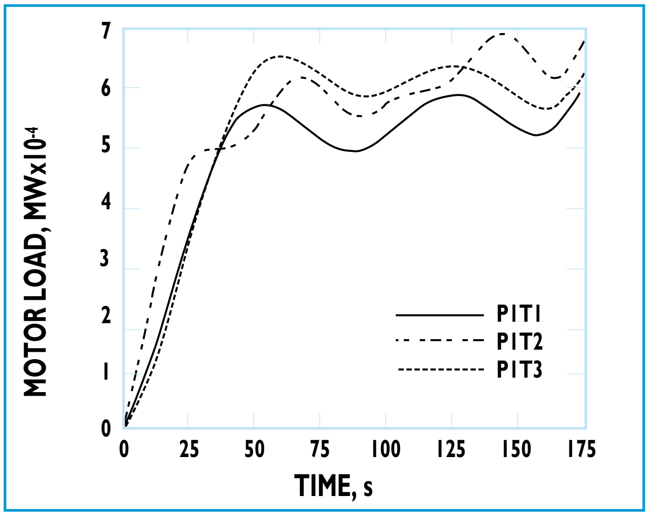


9. Effect of plate life on unit step response models between dilution water setpoints and consistency

found a very small gain for this input-output pair, on the order of 0.01 MW/metric ton/day. A small process gain means that a controller for this refiner would have to change the indicated throughput considerably in order to bring about a noticeable change in the motor load, as reflected in the earlier control work. Therefore, use of the indicated throughput was not recommended for this refiner.

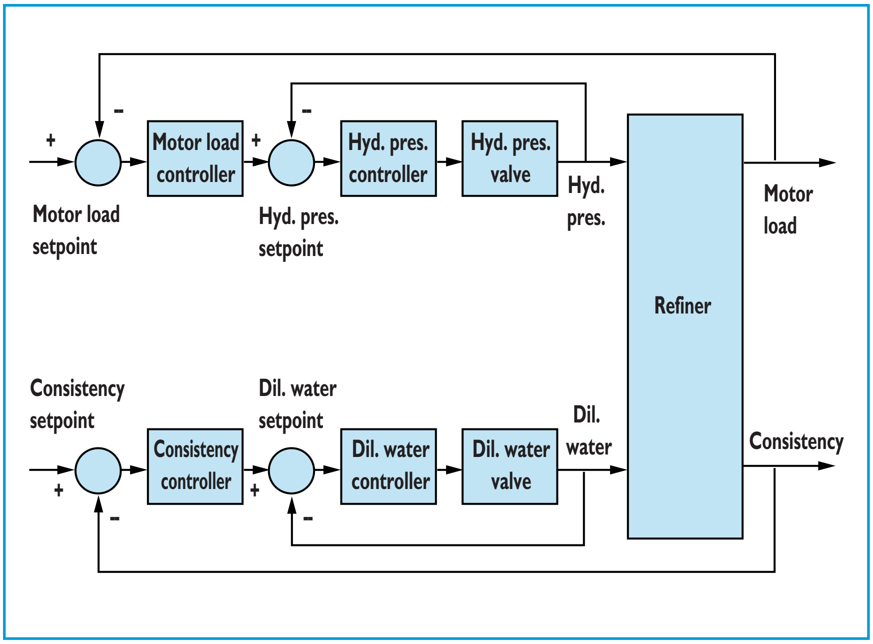
This conclusion reduces the refiner to a two-input (hydraulic pressure setpoint and dilution water flow rate setpoints), two-output (motor load and consistency) system. A simple relative gain array analysis *(17)* suggests that the best control pairing for a multiloop control strategy would be attained with the motor load controlled by the hydraulic pressure and the consistency controlled via the dilution water flow rates (**Fig. 11**). The relative gain value of 1.46 implies that there would not be significant interactions between two such control loops. In our identification experiments, the high-frequency variations in the consistency signal essentially masked the effect of the 400 kPa hydraulic pressure changes made to the system. Since sudden changes on this order of magnitude are fairly infrequent, a decoupler to compensate for this interaction would probably not be required. However, a decoupler is recommended to address the dilution water flow rate-to-motor load interaction. The idea of using a one-way decoupler has been suggested in earlier work by Evans *et al. (9)* and is supported by the identification results obtained in this study.

The relationship between hydraulic pressure and motor load has always been the prime motivation for using adaptive control for wood chip refiners due to the gain drift associated with plate wear and the change in sign of the gain due to the pad collapse. However, the identification results for this particular refiner indicate that the gain and the overall dynamics of the hydraulic pressure-to-motor load relationship are relatively time invariant over a significant portion of the plate life (see Fig. 10). Unfortunately, we were unable to collect data at the late plate life (825 hours) to see if this relationship may have changed more substantially. However, work within our own group *(18)* has shown that, for this same refiner, the pulp quality deteriorates significantly when the plates become very worn (approx. 800 hours), and therefore operation beyond this point is not recommended. These results indicate that adaptive control may not be necessary for this refiner and perhaps other primary refiners, as confirmed by Roche *et al. (10)*.



10. Effect of plate life on unit step response models between hydraulic pressure setpoint and motor load

To determine whether an adaptive controller or a simpler fixed-parameter (nonadaptive) control strategy is needed for this process, we must not only consider the expected variations in a single element in this 2×2



11. Block diagram for multiloop control strategy

system (e.g., the hydraulic pressure-to-motor load relationship) but must also consider the expected variations in every element and take into account the fact that these input-output relationships are coupled in some way. Skogestad and Postlehwaite *(19)* provide some analysis tools for studying this problem.

To design a fixed-gain (nonadaptive) controller for this refiner process, one might start by taking an "average" model of the system on an element-by-element basis from results obtained from the identification experiments. Then this average model (G) would be used for controller design, and the identified models as a function of plate age (P1T1, P1T2, and P1T3) would be treated as expected perturbations from this average model (call these G_1, G_2, and G_3).

For a stable process with an equal number of inputs as outputs, if the eigenvalues of the matrices $G_1(0)G(0)^{-1}$, $G_2(0)G(0)^{-1}$, $G_3(0)G(0)^{-1}$ are positive, then it is possible to design a controller with integral action such that the closed-loop system is stable for G_1, G_2, and G_3 *(20, 21),* where G(0), $G_1(0)$, etc. denote the steady-state gain matrices. These eigenvalues were calculated from the identification results, and it was found that all of the eigenvalues were positive, indicating that a fixed-gain (nonadaptive) controller could be designed to stabilize this process and ensure zero steady-state control errors. Of course, this result says nothing about the resulting dynamic performance, and it is on this basis that a final decision would have to be made regarding whether an adaptive control strategy would be warranted.

With constant mass throughput and constant chip quality, the proposed motor load and consistency control strategy would be capable of maintaining the pulp quality. However, this control strategy is in fact unable to recognize chip quality changes and/or mass throughput fluctuations and therefore could not guarantee constant pulp quality. One potential enhancement to this controller design would be to add a supervisory controller for pulp quality. The feasibility of such a strategy would rely on either obtaining an accurate measure of the dry pulp mass throughput or obtaining a fast on-line pulp quality measurement. This supervisory controller would then adjust the motor load and consistency setpoints, in an optimal fashion, to maintain the target pulp quality while minimizing the energy required to refine the wood chips.

CONCLUSIONS

A systematic identification study of the dynamics of a primary wood chip refiner over one plate life has been performed. The first conclusion is that indicated throughput is not recommended for use as a manipulated variable in a control strategy due to the low gain associated with the throughput-to-motor load and consistency relationships. A second conclusion is that the hydraulic pressure-to-motor load gain remained relatively constant over the plate life. This would suggest that an adaptive controller is not required for this system. It is important to point out that the above conclusions must be confined to the refiner under study (primary refiner, double-disc design). However, these results illustrate that these types of experiments provide useful information when selecting the most appropriate control strategy for a particular refining process. **TJ**

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