Refiner Optimization and Control Part III: Natural decoupling in TMP refining processes

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KEYWORDS: Refining control, Energy efficiency, fibre distribution, pulp consistency, temperature profile.

SUMMARY: In TMP- refining processes, the stabilization of the fiber pad inside the refining zone requires a new control approach. It is shown that specific energy control tends to be complex and most often affected by a number of disturbances not so well specified in traditional MPC-concepts. To describe the dynamics in such nonlinear processes are difficult, tedious and requires significant maintenance support.

In this paper we will focus on two important issues related to modeling in mechanical pulping processes; measurements of internal states inside the refining zone and particularly natural decoupling to find a model suitable for future process optimization and improved control concepts of complete refiner lines.

As an example of internal state measurements we will use refining zone temperature profiles and estimated distributed consistency in the refining zone.

It is shown that the characteristics of the temperature profile dynamics makes it possible to introduce a decoupling scheme where the anti-diagonal elements in the transfer function matrix describing the process can be eliminated naturally independent on which refiner to be controlled.

In this paper, the idea is to show how this complex process, with serially linked refiners or refining zones, can be modeled and controlled using a simplified process description. It will be shown that the concept hold for different types of refiners. In this series of papers, data from a commercial Twin-refiner and a CD-refiner are available as inputs.

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In this paper we will focus on model descriptions in Thermo Mechanical Pulp (TMP) refiners, which can be seen as one of the most energy demanding non-linear processes in the pulp and paper industry, see Hill et al. (1979) and Karlström and Isaksson (2009).

Based on a number of articles see Hill et al. (1979), Hill et al. (1993), Johansson et al. (1980), Dahlqvist and Ferrari (1981), Oksum (1983), Honkasalo et al. (1989) it was earlier stated that the specific energy, i.e. the relation between refining energy consumption and the assumed production rate, is not sufficient for the control of complete refiner lines.

The reason is that specific energy is an average of the total work distributed along the surface of the refining segment with limited information of the fiber distribution and consequently the local defibration and fibrillation inside the refining zone. Moreover, specific energy as a controlled variable tends to be sensitive for variations in chip feed rate as well as in the chip properties.

Even though using specific energy as a measure and controlled variable is associated with several weaknesses this is still very common in control concepts on the market due to the lack of measurements of physical variables inside the refining zones, see Sikter et al. (2007).

Karlström and Eriksson (2014a,b,c,d) showed that modeling of the refining process, using internal state measurements like the temperature profiles in a full-scale CD-refiner, gives valuable information about the refining zone dynamics. As model inputs, the temperature profile together with traditional external variables such as motor load, dilution water added, plate gaps and inlet- and outlet pressures measurements were used.

Karlström and Eriksson (2014a,b,c,d) also introduced a new concept called “fiber energy efficiency” to focus on the defibration and fibrillation work obtained when the fibers and fiber bundles interact with the refining bars. It was shown that the fiber energy efficiency differs from the total refining energy efficiency as the latter includes also the thermodynamical work. Hence, the model can be seen as soft sensor for estimating a number of “hidden” internal states like the forces acting on the refining segment bars, residence time and velocities in the refining zone.

In this paper the focus is on decoupling of processes. The extended version of the entropy model, derived by Karlström and Eriksson (2014a), will be used for distributed consistency estimation along the refining segment length.

This is the third in a series of four consecutive papers and the idea is to broaden the discussion on how to use the temperature profile to set a convenient decoupled control concept with maximized uptime, process stabilization in order to reach the full refining optimization potential.

Fundamentals

The pulp and paper industry is always seeking new opportunities to become more energy efficient. Fuel switching is one such opportunity for those facilities that use more than one form of energy or fuel. Maximizing the overall energy efficiency at a facility may often lead to net reductions in one form of energy (*e.g.*, natural gas, fuel oil or coal) with simultaneously increased consumption of another (*e.g.*, electricity). How to model these options and thereafter optimize a complete mill is a challenging task.

From an energy balance perspective a simplified model can be formulated and dynamic considerations are best described by differentiating the electrical consumption in the mill, W_{TOT}, with respect to time and the vector u containing the elements P, representing the production rate of pulp in the refiners, h, the hydraulic pressure applied on the refiner discs[1] and D the dilution water feed rate, see further description in Karlström and Hill (2014a,b).

$$\begin{gathered} W_{TOT} = f(u) \quad ; \quad B_{TOT} = g(u) \quad ; \quad u = [P, h, D]^T \\ \frac{\partial}{\partial t}(W_{TOT}) = \frac{\partial}{\partial u}(W_{TOT}) \cdot \frac{\partial}{\partial t}(u) \quad ; \quad \frac{\partial}{\partial t}(B_{TOT}) = \frac{\partial}{\partial u}(B_{TOT}) \cdot \frac{\partial}{\partial t}(u) \end{gathered} \tag{1}$$

In order to describe the differentiated forms of W_{TOT} and B_{TOT} with respect to the vector u, material and energy balances from the TMP must be derived. Dynamic changes in the vector elements in u can be seen as measurable inputs to an overall optimizer and therefore are straightforward to handle.

The major part of W_{TMP} is associated with the energy consumption in the refining processes, i.e. $W_{TMP} \approx \Sigma W_R$ where W_R is the electrical consumption in each refiner.

As the modeling of the refiners is an essential step towards a better understanding of the process, the reader is referred to Karlström et al. (2008) and Karlström and Eriksson (2014a,b,c,d) where the extended entropy model is described in details. It is important to mention that the entropy model is a physical non-linear model which still can be used in on-line applications at sampling rates down to one second if the DCS can provide enough computer capacity.

A common TMP process configuration has two serially linked refiners in each production line and the final pulp quality is dependent on the operation of each refiner.

The refiner control strategy differs from one mill to another. Refining is well known to be a complex process with many disturbances and interactions. In some cases, refiners have an internal interconnection, in terms of piping from the outlet to the inlet, which makes control even more challenging.

From a control engineering perspective we start with a simplified description where all disturbances have been excluded, see *Fig.* 1.

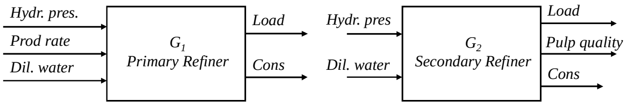

Fig. 1: System description for two serially linked refiners.

In more complex systems two refining zones can be implemented in one refiner, such as the CD-refiner described by Karlström and Eriksson (2014a) but that does not affect the common description.

The production (wood chip feed rate), dilution water feed rate and plate gap (hydraulic pressure for closing the refining zone) forms the inputs. As outputs, the external variables[2] like motor loads and blow line consistencies are often considered together with pulp quality. Hence, in its simplest form we have five inputs and at least five outputs[3] to handle.

The production rate is related to the wood chip feed rate to the initial refining zone. It is thereby, according to *Fig.* 1, considered as an input while the motor load W_R is an output.

In many applications the specific energy, i.e. the ratio of the motor load to the production rate, is controlled. The motor load is normally seen as an output while the production rate, i.e. the chip feed rate to the refiner line is an input. Therefore, from a control engineering perspective the specific energy control concept is questionable.

Moreover, the motor load is the integral of the distributed work inside the refining zone which means that local fluctuations that affect the final pulp quality sometimes are difficult to capture. The nature of specific energy control is even more difficult to describe in details as the production rate is an average estimation affected by disturbances in the feeding screws, see Karlström and Eriksson (2014a,b,c,d). However, today specific energy control is the most common concept for refining control and we prefer to start the system description according to *Fig.* 1, by the time-invariant model structure.

$$y = \begin{bmatrix} W_{R_1} \\ C_1 \\ W_{R_2} \\ C_2 \\ Q \end{bmatrix} = Gu = \begin{bmatrix} g_{11} & g_{12} & & & g_{15} \\ g_{21} & g_{22} & & & g_{25} \\ g_{31} & g_{32} & g_{33} & g_{34} & g_{35} \\ g_{41} & g_{42} & g_{43} & g_{44} & g_{45} \\ g_{51} & g_{52} & g_{53} & g_{54} & g_{55} \end{bmatrix} \begin{bmatrix} h_1 \\ D_1 \\ h_2 \\ D_2 \\ P \end{bmatrix} \tag{2}$$

Hence, the motor loads W_{Ri} are in focus in this output vector y together with C_i, which represents the consistency in the blow-lines from each refiner, and Q which denotes the pulp quality. The G is the transfer function matrix describing the process dynamics.

The subscript 1 corresponds to the primary refiner and the subscript 2, the secondary refiner (or equivalently the flat zone and CD-zone in a CD-refiner). The input vector u in *Eq 1* and *Eq 2* contains the hydraulic pressure h, as an element which is equivalent to the plate gap S if the distance between the refining segments is available.

In some TMP-lines the elements $\{g_{13}, g_{14}\}$ and $\{g_{23}, g_{24}\}$ cannot be neglected as in *Eq 2*, due to internal

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[1] In many TMP refiners, plate gap sensors are implemented and can be used instead of the hydraulic pressure if the measurements are reliable.

[2] In this context, external variables are related to measurements outside the refining zone while internal variables are measured inside the refining zone.

[3] The pulp quality can be described by at least three variables but normally only one of these is the prime candidate in control concepts.

interconnections (piping) between the primary and secondary refiners. This calls for special attention when only using external variables as outputs.

The simplified system description in *Eq 2* is useful in many aspects and it is obvious that the anti-diagonal elements must be handled with care in traditional MPC-concepts. However, the knowledge of the dynamics in these elements, has turned out to be difficult to implement due to inherent nonlinearities. Therefore alternative concepts based on measurements of internal states to reduce the nonlinear impact and reach natural decoupling have been proposed see Karlström and Isaksson (2009)[4].

To fully understand the need to cope with complex dynamics in terms of decoupling in refining systems, the reader is referred to Appendix for details. The natural decoupling is best defined by following a physical description.

Natural decoupling: The flow pattern in a refiner is complex, with three physical states (chips, water and vapor) to be handled simultaneously. The steam/fibers generated in the refining zone are commonly assumed to be saturated, i.e. the pressure is a function of the temperature and vice versa. Steam is evacuated both forwards (towards the periphery of the segments) and backwards (towards the inlet), with a stagnation point at some radius in between, see Berg and Karlström (2005). This point is assumed to be marked by the maximum temperature (or pressure), since this peak implies zero pressure gradient $\partial p/\partial r=0$. The maximum can also be described by its temperature (T_{max}) and radial position (r_{max}). A typical temperature profile and pressure gradient is shown in *Fig. 2*.

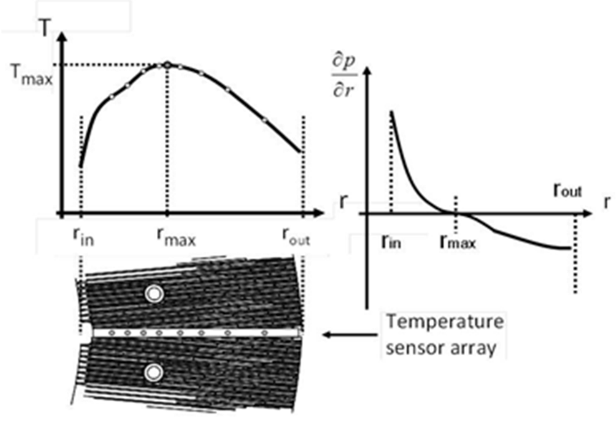

Fig. 2: A typical temperature profile, and corresponding pressure gradient, from a primary refiner where a sensor array is placed between two refining segments. The white dots on the black lines showing the temperature profile indicate the positions of temperature sensors T_1 to T_8.

As outlined by Karlström and Eriksson (2014a,b) it is important to control the maximum temperature as it sets the gradients for the refining zones. If the gradients are varying too much and not controlled, the fiber residence time will be affected and thereby the final pulp properties.

As shown by Karlström and Eriksson (2014d), the segment pattern will also have an influence. This is unfortunately not considered in traditional refiner control concepts which often use empirical models for estimating e.g. consistency and pulp quality variables like mean fiber length, freeness and shives in the blow-line.

Other nonlinearities, like refining segment wear also occur and introduce many problems in traditional MPC-control concepts based on the system description in *Eq 2.*

However, when the temperature profile is available and thereby the maximum temperature in *Fig. 2*, a new control concept based on natural decoupling can be introduced. This is best illustrated by studying the low-frequency gains K_{ij} obtained from a Twin refiner, see *Fig. 3*.

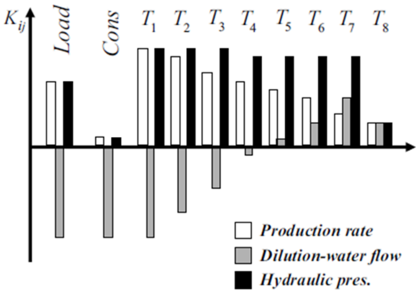

Fig. 3: Low-frequency gains from a primary refiner for different elements in a 10x3- system.

As described, the temperature sensors T_4 and T_5 as process outputs will give small gains from the dilution water feed rate *D*, while the other temperature sensors lead to larger gains.

As seen in *Fig. 3*, the effect on consistency *C* is small when changing the plate gap (hydraulic pressure, *h*) and the production rate. Changes in the production rate can affect the outlet consistency considerably, for example, input consistency typically changes a lot when changing raw materials. Altogether, this identifies the hydraulic pressure as a good input candidate.

The information given in *Fig. 3* is valuable and constitutes the idea with natural decoupled systems based on internal measurements. Note that the external variables motor loads (or the specific energies) in *Eq 2* are in this case replaced by the maximum temperature in the refining zones, which results in a clear system description useful for control at low maintenance cost.

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[4] Later studies show that even more rudimentary control structures can be introduced if the temperature profile is measured in the refining zone, see Eriksson et al. (2010).

$$y=\begin{bmatrix}T_{\max_1}\\C_1\\T_{\max_2}\\C_2\\Q\end{bmatrix}=Gu=\begin{bmatrix}g_{11}&&&&\\&g_{22}&&&\\&&g_{33}&&\\&&&g_{44}&\\g_{51}&g_{52}&g_{53}&g_{54}&g_{55}\end{bmatrix}\begin{bmatrix}h_1\\D_1\\h_2\\D_2\\P\end{bmatrix} \qquad (3)$$

An MPC- concept can be used also for this system but it is questionable if it is necessary. Simplicity is sometimes to be preferred and traditional PID-controllers are often robust enough with excellent uptime. This will be shown in future research papers in this series.

Normally, the aim is to keep the production as stable as possible. Any disturbance in production is captured by the temperature profile measurements and by these measurements the refining zone conditions are well reflected in terms of pulp quality variations. As a result, the complexity can be reduced even further, see Eriksson (2005), Eriksson and Karlström (2009), Karlström and Isaksson (2009), Eriksson (2009), Eriksson et al (2011), Eriksson and Karlström (2011) and Karlström (2013).

In case of large intentional changes in production rate, a feed forward controller can be implemented as well but the result of such changes will be detected by the temperature profile and therefore not included in *Eq 3*.

Results and discussion

As described above, the simplest form, the maximum temperature and the consistency in *Eq 3* can be used for process control in a SISO-system structure for most of the serially linked refiners. Moreover, as stated by Berg et al. (2003) and Karlström and Eriksson (2014a,b), the consistency can be estimated by the entropy model as a soft sensor based on the temperature profiles.

There are two types of refiners where the system description in *Eq 3* cannot be used directly, namely the CD-refiner and the Hymac Jumbo refiner.

In this paper we focus on the CD-refiner, see *Fig. 4*, to figure out how the structure in *Eq 3* should be modified in order to apply the decoupling concept also for these types of refiners.

Consider the following system description for a CD-refiner where the pulp quality is not included[5]

$$y=\begin{bmatrix}T_{\max FZ}\\C_{FZ}\\T_{\max CD}\\C_{CD}\end{bmatrix}=Gu=\begin{bmatrix}g_{11}&g_{12}&g_{13}&g_{14}\\g_{21}&g_{22}&g_{23}&g_{24}\\g_{31}&g_{32}&g_{33}&g_{34}\\g_{41}&g_{42}&g_{43}&g_{44}\end{bmatrix}\begin{bmatrix}S_{FZ}\\D_{FZ}\\S_{CD}\\D_{CD}\end{bmatrix} \qquad (4)$$

where the subscripts FZ and CD corresponds to the flat zone and conical zone, respectively.

In CD-refiners plate gap sensors, *S*, are most often available as standard measurements and they are also used for refiner control. If the dynamics between the hydraulic system or other mechanical actuators and the actual plate gap are negligible we can replace *h* in *Eq 2* and use the plate gap instead.

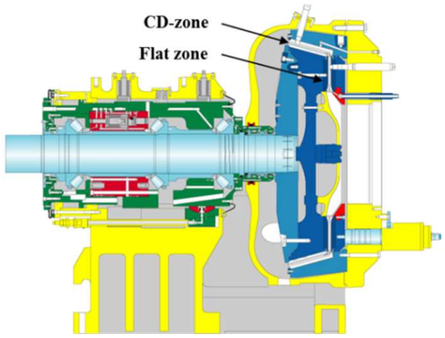

Fig. 4: A schematic drawing of a CD-refiner. The vertical flat zone is directly linked to the CD-zone via an expanding point where dilution water to the CD-zone is added.

According to the concept of natural decoupling outlined above we are searching for a simple way where:

- T_{maxFZ} is controlled by the FZ gap, S_{FZ}.
- C_{FZ} is controlled by the FZ dilution water, D_{FZ}.
- T_{maxCD} is controlled by the CD gap, S_{CD}.
- C_{CD} is controlled by the CD dilution water, D_{CD}.

This calls for a system description where the elements

$g_{12}= g_{13}= g_{14}=g_{21}= g_{23}=g_{24}= g_{31}=g_{32}= g_{34}=g_{41}= g_{43}\approx 0$.

Finding all elements, g_{ij}, can be seen as a tedious procedure but some simplifications can be performed without too much efforts.

Basic considerations: The diagonal elements, g_{ii}, where $i=\{1,\ldots,4\}$ are obviously not negligible as the input variables are essential for the entire control concept. Moreover, according to Karlström and Eriksson (2014a,b) it is concluded that refining conditions in the CD-zone have minor impact on the refining conditions in the flat zone and this means that we can set $g_{13}=g_{14}=0$ and $g_{23}=g_{24}=0$. The difference compared with serially linked single-disc refiners is that the flat zone and the CD-zone cannot easily be separated into two uncoupled SISO loops as the total amount of water added to the CD-zone[6] is necessary to know. This means that the element $g_{42}\neq 0$.

Nevertheless, using the temperature profiles together with the extended entropy model described in Karlström and Eriksson (2014a), the consistency in the flat zone C_{FZ} can be estimated and this will be commented on below.

Hence, from this initial discussion we can conclude that $g_{13}=g_{14}=g_{23}=g_{24}=0$ and $g_{42}\neq 0$.

Temperature profile response in the CD-zone - when changing plate gap and dilution water added to the flat zone: When studying CD-refiners it is not obvious that

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[5] In this description the dynamics in pulp quality are excluded. This dynamics will be described in more details later on in this series of papers.

[6] The obstacle to split the motor load into actual work in the flat zone and CD-zone is not relevant when having access to the temperature profiles in each zone see further Karlström and Eriksson (2014b).

changes in plate gap, S_{FZ}, and the dilution water, D_{FZ}, in the flat zone have a minor impact on the temperature maximum, T_{maxCD}, in the CD-zone.

Moreover, it is not clear that the consistency, C_{CD}, will be affected by S_{FZ} or the plate gap in the CD-zone, S_{CD}, and this call for plant tests.

Consider the step changes in S_{FZ} and D_{FZ} according to *Fig. 5* maintaining stable plate gap, S_{CD}, and dilution water, D_{CD}, in the CD-zone.

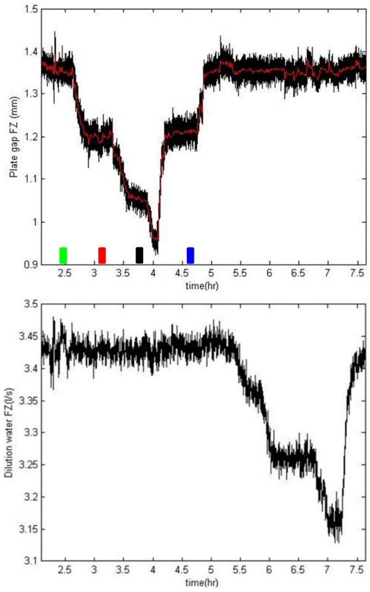

Fig. 5: Step changes in plate gap and dilution water feed rate to the flat zone (FZ) in a CD-refiner (red line corresponds to the filtered plate gap) maintaining stable plate gap and dilution water in the CD zone. Coloured dots are introduced to distinguish the temperature profiles in *Fig. 8*.

As can be seen in *Fig. 6*, which shows temperature responses in the CD-zone when changing the plate gap and dilution water to the flat zone, only minor changes occur. Therefore, it is natural to assume $g_{31}\approx0$ and $g_{32}\approx0$ as well as $g_{41}\approx0$ and $g_{43}\approx0$ and this is vital as it opens up for a number of unexpected simplifications regarding the design of future control strategies for CD-refiners.

It is important to stress that all sensors along the entire radius are covered in the plots to see if some local fluctuations can be significant when changing other refining zone conditions. The local fluctuations are often overlooked as refiners normally have limited measurement devices mounted in the refining zones.

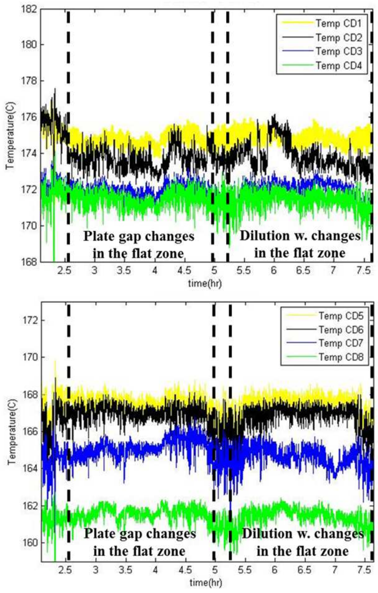

Fig. 6: Temperature responses in the CD-zone when performing step changes in plate gap and dilution water feed rate to the flat zone according to Fig. 5.

Temperature profile response in the flat zone - when changing plate gap and dilution water added to the flat zone: When it comes to the dynamic responses in the flat zone it is easy to see that both plate gap and dilution water feed rate will have an impact on the temperature profile.

In *Fig. 7* the positions for the sensors in the flat zone are visualized. FZ1 gives the sensor position near the centrum of the refining zone and FZ8 the sensor at the periphery of the refining segment.

The expected temperature maximum in the flat zone of a CD-refiner will be located close to the periphery under normal operating conditions. However, when changing the plate gap the position for the temperature maximum can change. This is shown in *Fig. 8*.

Note the temperature profile is only given for the flat zone sensors, which have been shifted 3 mm consecutively to get a better visualization of the temperature responses.

The information given in *Fig. 8* is maybe even better shown in *Fig. 9*, where the temperature maximum is moved from the position defined by FZ8 inwards the segment to the position given by FZ7, i.e. almost 40 mm. Moreover, the fiber packing degree increases also inward the refining zone as indicated by FZ1 – FZ6 in *Fig. 8*, *Fig. 9* and *Fig. 10*.

Fig. 7: Sensor array with eight temperature sensors mounted between two refining segments in the flat zone of a CD-refiner.

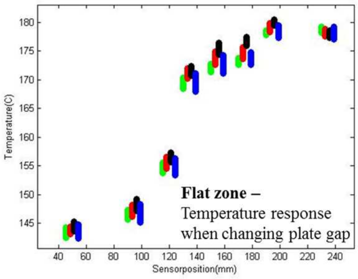

Fig. 8: Temperature profile in the flat zone according to the pulp sampling – Each sampling period is shifted 3 mm to get better readability. The colors indicate the period when changing the plate gap according to *Fig. 5.*

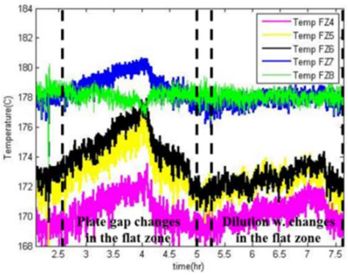

Fig. 9: Temperature response in FZ4-FZ8, see *Fig. 7.*

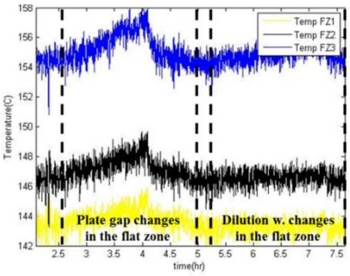

Fig. 10: The first temperatures (FZ1 to FZ3) measured by the sensor array mounted in the flat zone.

Temperature profile response in the CD-zone - when changing plate gap and dilution water added to the CD-zone: As seen in *Fig. 11*, the assumption that $g_{34}\approx 0$ will be possible to include for normal step changes in dilution water feed rate to the CD-zone.

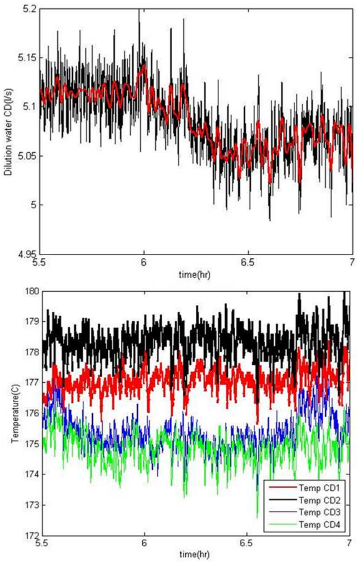

Fig. 11: Upper: Step change in dilution water. Lower: Temperature responses when doing the step change in dilution water added to the CD-zone.

We have already concluded that it will be necessary to cope with the element $g_{42}\neq 0$, i.e. the consistency in the flat zone, as it affects the consistency in the CD-zone. This results in a system description that is quite reasonable to handle by all system engineers.

By using the extended entropy model described by Karlström and Eriksson (2014a,b,c,d) the consistency out from the flat zone will be possible to estimate and this is vital for the concept and form a natural use of the extended entropy model as a soft sensor.

$$y=\begin{bmatrix}T_{\max FZ}\\ C_{FZ}\\ T_{\max CD}\\ C_{CD}\end{bmatrix}=Gu=\begin{bmatrix}g_{11}&&&\\ &g_{22}&&\\ &&g_{33}&\\ &g_{42}&&g_{44}\end{bmatrix}\begin{bmatrix}S_{FZ}\\ D_{FZ}\\ S_{CD}\\ D_{CD}\end{bmatrix} \tag{5}$$

In summary: All anti-diagonal elements can be neglected in the 4x4 system matrix described in *Eq 5* except the element g_{42}. The consistency in the blow line (out from the CD-zone) in *Eq 5* does not necessarily have to be measured as it is estimated from the extended entropy model. Actually, the consistency can be predicted as a vector for the entire refining zone including both the flat zone and the CD-zone as the dilution water feed rates to the zones are known. Moisture variations in the chips are handled as an input to the extended entropy model and Karlström and Eriksson (2014a) showed good agreement with manually measured blow line consistency, see *Fig. 12*.

The natural decoupling of the system, by measuring internal states inside the refining zone, gives a simplified system description which can be used for refining process optimization. This is not possible to achieve using only motor load or specific energy control where the anti-diagonal elements must be specified to cope with the essential dynamics in the system.

In this paper we have only scratched on the surface of all possibilities offered by using the temperature profile as the maximum temperature has been in focus as an output in the system description. This statement is based on the fact that the temperature profile also constitutes a possibility to develop a pressure gradient control concept which indirectly set the fiber residence time, see Karlström and Eriksson (2014a).

As indicated in *Eq 3* the pulp properties are affected by all changes in the input vector $u=\{S_{FZ},D_{FZ},S_{CD},D_{CD},P\}^T$ and therefore it is important to handle as well when considering the refining process from an optimization perspective and this will be described in more details in later papers in this series.

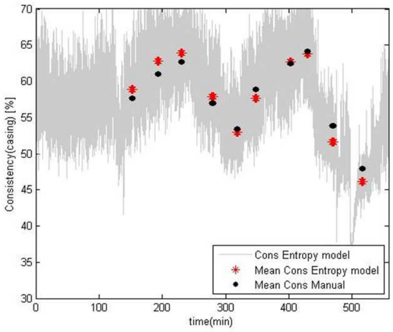

Fig. 12: Consistencies obtained in a CD-refiner at variable plate gap and dilution water feed rate, see Karlström and Eriksson (2014a).

Conclusions

In this paper it has been shown how the implementation of temperature sensor arrays in the refining zones of a CD-refiner system can accomplish a rather simple system description. It is concluded that only minor changes have to be inserted to get an almost decoupled system where the plate gaps and dilution water flow rates in the flat zone and CD-zone are the primary inputs. As output variables, the maximum temperatures and the consistencies in the flat zone and the CD-zone are used. Using the temperature profile, it also possible to estimate the consistency vector in the flat zone using the extended entropy model outlined in Karlström and Eriksson (2014a). All these features when using temperature measurements in the refining zone outperform most system descriptions based on e.g. motor load or specific energy as the main output target.

Besides the natural decoupling, the pressure gradient is easily derived from the temperature profile. The pressure gradient has an impact on the fiber residence time in different parts of the refining zone. Knowing the maximum temperature in the flat zone and the CD-zone, the backward and forward steam pressure gradients are possible to control which results in an improved fiber pad stabilization.

The motor load and consequently the specific energy are averages of the total work distributed along the surface of the refining segment with limited information of the fiber distribution and consequently the local defibration and fibrillation inside the refining zone. When using specific energy control, it is necessary to estimate the dynamics in all the anti-diagonal elements in the system description given in this paper. This is a tedious approach and calls for several updates over time due to the non-linearities in the refining process.

Acknowledgments

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Appendix

Consider, for simplicity, the following 2x2-system

$$Y = \begin{bmatrix} W_R \\ C \end{bmatrix} = GU = \begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix} \begin{bmatrix} h \\ D \end{bmatrix}$$

One of the major drawbacks with this process description is that both the hydraulic pressure, *h*, and the dilution water feed rate, *D*, will affect the motor load, W_R, and thereby the specific energy. This means that the interaction element, i.e. the transfer functions on the anti-diagonal in the *G* matrix, must be known. This calls for a methodology to find model parameters like, for instance, gain and time constants as described in *Fig. 13.* The controllers C_{i_x} are defined together with the decoupling filters P_{ij_x}, see *Fig. 14.* In an MPC-concept the anti-diagonal elements must be described in order to cope with the main dynamics in the diagonal elements and we use the decoupling scheme to describe the need to handle the anti-diagonal elements.

An optimal situation would be if the filters P_{12} , P_{21} and the transfer functions g_{12} , g_{21} could be set to zero as the antidiagonal elements thereby are negligible.

In this specific 2x2-system the filter *P* must be chosen so that the transfer function matrix *S*=*GP* is diagonal and non-singular. The system is then said to be dynamically decoupled

$$P = G^{-1}S \quad \text{where} \quad S = \begin{bmatrix} S_{11_x} & 0 \\ 0 & S_{22_x} \end{bmatrix}$$

i.e. an infinite number of *S* will be available and we propose the following decoupling filter

$$P_x = \begin{bmatrix} 1 & P_{1_x} \\ P_{2_x} & 1 \end{bmatrix}$$

which gives only two filter elements to design i.e.

$$Y_x = \begin{bmatrix} y_{1_x} \\ y_{2_x} \end{bmatrix} = \begin{bmatrix} g_{11_x} & g_{12_x} \\ g_{21_x} & g_{22_x} \end{bmatrix} \begin{bmatrix} 1 & P_{1_x} \\ P_{2_x} & 1 \end{bmatrix} \begin{bmatrix} w_{1_x} \\ w_{2_x} \end{bmatrix} =$$

$$= \begin{bmatrix} \dfrac{g_{11_x} g_{22_x} - g_{12_x} g_{21_x}}{g_{22_x}} & 0 \\ 0 & \dfrac{g_{11_x} g_{22_x} - g_{12_x} g_{21_x}}{g_{11_x}} \end{bmatrix} \begin{bmatrix} w_{1_x} \\ w_{2_x} \end{bmatrix} =$$

$$= \begin{bmatrix} \mathrm{S}_{11_x} & 0 \\ 0 & \mathrm{S}_{22_x} \end{bmatrix} \begin{bmatrix} w_{1_x} \\ w_{2_x} \end{bmatrix} = \mathrm{S}_x \mathrm{W}_x \quad \text{here} \quad \begin{cases} P_{1_x} = \dfrac{-g_{12_x}}{g_{11_x}} \\ P_{2_x} = \dfrac{-g_{21_x}}{g_{22_x}} \end{cases}$$

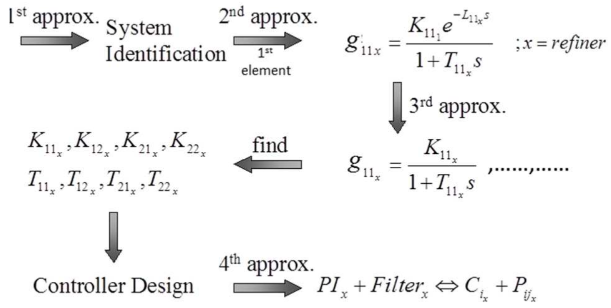

Fig. 13: Schematic procedure to find parameters in a 2x2-system.

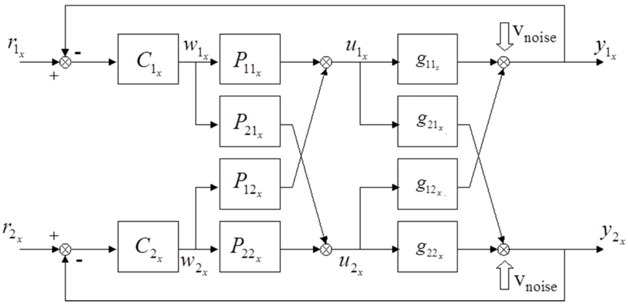

Fig. 14: Complete control concept including controllers and filters for decoupling.

It is worth mentioning that the procedure, described in *Fig. 13*, is rather tedious and sometimes difficult to follow in real processes[7] as the refiners run within a wide range of operations where new parameters must be found for each operating point.

Another weakness when formulating control concepts based on this concept is that the motor load is affected by a number of process variables besides the two mentioned above which makes it difficult to pre-specify an optimal operating window. As an example, the motor load will always be related to the integral of the force distribution along the radius in the refining zone and it will not give any information about the spatial energy consumption. It is clear, from this aspect alone, that the motor load provides limited information about the local process conditions which affect the final pulp quality.

Additional non-linear problems exist as well and one to be mentioned is that traditional control concepts do not handle natural variations caused by e.g. plate wear, fluctuations in fiber pad distribution etc.

Hence, if it is possible to find alternative control concepts, which are not significantly affected by changing the operating points, the controllability of the process can be improved significantly from a pulp quality perspective.

It is worth mentioning that if the system description needs to be extended to a 3x3-system the decoupling becomes much more complex. Suppose that we are looking for a decoupled system with

$$S_x = \begin{bmatrix} S_{11_x} & 0 & 0 \\ 0 & S_{22_x} & 0 \\ 0 & 0 & S_{33_x} \end{bmatrix}$$

As S_x can be chosen differently, there is theoretically an infinite number of filters which make the system perfectly decoupled.

In our case the filter is proposed to be

$$P_x = \begin{bmatrix} 1 & P_{12_x} & P_{13_x} \\ P_{21_x} & 1 & P_{23_x} \\ P_{31_x} & P_{32_x} & 1 \end{bmatrix}$$

which gives six filter elements to be realized.

$$y_x = \begin{bmatrix} y_{1_x} \\ y_{2_x} \\ y_{3_x} \end{bmatrix} = \begin{bmatrix} g_{11_x} & g_{12_x} & g_{13_x} \\ g_{21_x} & g_{22_x} & g_{23_x} \\ g_{31_x} & g_{32_x} & g_{33_x} \end{bmatrix} \begin{bmatrix} 1 & P_{12_x} & P_{13_x} \\ P_{21_x} & 1 & P_{23_x} \\ P_{31_x} & P_{32_x} & 1 \end{bmatrix} \begin{bmatrix} w_{1_x} \\ w_{2_x} \\ w_{3_x} \end{bmatrix}$$

One drawback with such filters, P_{ij_x}, besides their complexity see below, is that the order of the transfer function elements increases. For practical reasons approximations would be performed when applying it to industrial processes.

Even though the filter can be designed, a more robust solution should always be considered since e.g. time-varying aspects can affect the control robustness, see Berg and Karlström (2003).

Several attempts have been made to create advanced mill-wide control systems in TMP to produce a more homogeneous pulp quality. Unfortunately, as concluded by Lidén (2003), about 90% of all the installed software-based control systems are not used properly and one reason for this might be the difficulty involved in formulating a reliable control approach for each refiner.

The most optimal solution would be to find a transfer function matrix, *G*, which have zeros, or at least almost negligible elements, in its sub-diagonals and design a robust controller without decoupling filters. In refining processes with limited instrumentation this is most often impossible but if measurements from internal states in the refining zone, like the temperature profile, are available new possibilities for designing decoupling filters exist.

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[7] The same procedure must be followed also in MPC-concepts to describe the elements in the complete transfer function matrix.

$$P_{12_x} = \frac{a}{\Delta_{22_x}} = \frac{-g_{12_x} g_{33_x} + g_{13_x} g_{32_x}}{g_{11_x} g_{33_x} - g_{13_x} g_{31_x}}$$

$$P_{13_x} = \frac{b}{\Delta_{33_x}} = \frac{g_{12_x} g_{23_x} - g_{13_x} g_{22_x}}{g_{11_x} g_{22_x} - g_{12_x} g_{21_x}}$$

$$P_{21_x} = \frac{c}{\Delta_{11_x}} = \frac{-g_{21_x} g_{33_x} + g_{23_x} g_{31_x}}{g_{22_x} g_{33_x} - g_{23_x} g_{32_x}}$$

$$P_{23_x} = \frac{-g_{11_x} g_{23_x} + g_{13_x} g_{21_x}}{g_{11_x} g_{22_x} - g_{12_x} g_{21_x}}$$

$$P_{31_x} = \frac{g_{21_x} g_{32_x} - g_{22_x} g_{31_x}}{g_{22_x} g_{33_x} - g_{23_x} g_{32_x}}$$

$$P_{32_x} = \frac{-g_{11_x} g_{32_x} + g_{12_x} g_{31_x}}{g_{11_x} g_{33_x} - g_{13_x} g_{31_x}}$$

and

$$y_x = \det(G_x) \begin{bmatrix} \frac{1}{\Delta_{11_x}} & 0 & 0 \\ 0 & \frac{1}{\Delta_{22_x}} & 0 \\ 0 & 0 & \frac{1}{\Delta_{33_x}} \end{bmatrix} \begin{bmatrix} w_{1_x} \\ w_{2_x} \\ w_{3_x} \end{bmatrix}$$

By using the temperature profile for control purposes in both primary and secondary refiners several of the earlier problems can be tackled.

In all cases studied so far the shift in the low-frequency gain, when changing the dilution water feed rate, coincide with the position where the maximum temperature T_{max} is located see *Fig. 3*. All this, is clearly valuable when attempting to introduce natural decoupled systems (without decoupling filters) by using new measurement techniques to minimize the undesired interaction between input and output elements. The simplified description above become

$$Y = \begin{bmatrix} T_{\max} \\ C \end{bmatrix} = GU = \begin{bmatrix} g_{11} & \approx 0 \\ \approx 0 & g_{22} \end{bmatrix} \begin{bmatrix} h \\ D \end{bmatrix}$$

for each refiner which makes it easy when formulating different control concepts.