Harmonizing your paper machine operation: Getting all the loops to work in concert

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Abstract: The papermaking process is highly interactive. Disturbances in one part of the plant propagate to other process areas in many ways. Part of the problem stems from the fact that we try to control a very complex, multivariable process with single variable control loops. Today, modern measurements and multivariable controls are providing superior performance both during a grade run and, more significantly, during highly upset conditions where traditional methods have not performed well.

Traditionally, paper machine quality-control systems comprised dry end scanners and their feedback loops. Today paper machine quality control is being extended back up the process to include the wet end and stock preparation areas. The reason for this shift in focus is simple. As measurements in the wet end improve in both quality and quantity, it is becoming increasingly obvious how much of the instability in the wet end imprints itself on the final product at the reel.

With the advent of modern machine technology, such as dilution headboxes, short-term MD (machine direction) and residual variability are becoming dominant [1]. To achieve improved runnability and even lower levels of variations demanded by papermakers, machine vendors have recognized that the feed to the machine has to be stabilized. Accordingly, radical new designs for the stock preparation and stock blending process have been developed, such as Metso’s OptiFeed [2].

THE HIGH COST OF INSTABILITY
An unstable wet end exacts a high price from a paper machine operation. In addition to product quality issues, it has a major effect on machine efficiency. Since the web breaks at the weakest point, it is not average value of pulp properties but the extreme values that adversely affect runnability. Stabilizing the wet end through, for instance, white-water consistency control moves these extremes away from the danger zone. Retention control has repeatedly shown improvements in paper quality accompanied by faster start-ups and grade changes and by dramatic reductions in the frequency of wet end breaks [3-5]. Often the real payback from quality improvements comes from these runnability gains.

Improving wet end stability will also lead to better profiles. For dilution headboxes, changes in the incoming flow or solids retention will change the gain of the basis weight profile control, and thus create profile disturbances [6]. Wet end stability seems to determine a level beyond which CD controls cannot go. Only after wet end stability is improved can CD variability be reduced.

Control based on dry-end scanning measurements is necessary since these signals represent final product quality. However, the limitation imposed by the location of the scanner means that the lowest MD and CD variability could only be achieved if disturbances can be prevented from reaching the machine in the first place. The ideal strategy would combine both wet end and dry end measurements to achieve the best control.

Figure 1 shows a power spectrum of basis weight: MD variability with notes showing major causes of variability at different frequencies. For a typical machine, the scanner at the dry end can control only cycles having periods of ~20 minutes and longer [7]. Controls using information from wet-end sensors would be able to reduce this cutoff period to ~2 minutes. Further improvement would require process changes to achieve better mixing in chests and of different fibres, fillers and additives.

COMMON DISTURBANCE SOURCES
Based on case studies Metso Automation has performed on many paper machines, a number of disturbance sources are often seen [6].

1. Consistency control strategy;
2. Disc filter operation;
3. Dosing of additives close to the headbox;
4. Broke handling and proportioning; and
5. Level controllers.

These disturbance sources arise from the process and automation equipment commonly used. In addition, there are interactions inherent in the forming process between the paper furnish components. Figure 2 shows how dry weight, paper ash content and white-water consistency are affected when stock flow, filler flow and retention aid flow are increased. The process is highly coupled. Each manipulated flow causes changes in all of the controlled variables. Additionally, all of them also cause moisture upsets. Figure 2 can be thought of as a matrix showing how these variables interact. Scanner feedback and retention controls, implemented as separate single-variable control loops, employ only the information from the diagonal elements in this matrix. The interactions between different variables (the off-diagonal elements in Fig. 2) are ignored by traditional control systems.
In short, the stock preparation and wet end of a paper machine is subject to disturbances from many causes. There are many mechanisms whereby a disturbance in one area can propagate to other parts of the process. Typically, the process is controlled by a number of separate, single-variable PID loops for flows, levels, consistencies, etc. In the design of the control system, little attention has been paid to minimize inter-variable interactions and disturbance propagation mechanisms.

Some of the problems arise from, or are exacerbated by, the complex network topology of the conventional process design [1]. For these cases, re-design of the process is required for a complete solution. However, much can be done short of this drastic course of action.

**FIXING THE BASICS**

Between the high-density stock tower and the paper machine, the stock is diluted several times by consistency regulators, where a PID controller receives the consistency signal and outputs directly to a dilution water valve. This simple scheme has several problems.

As has been studied theoretically [8] and observed at many mills, the use of a common dilution water header for several dilution loops leads to propagation of disturbances. A broke chest consistency upset might pull more dilution water, thus decreasing the header pressure and therefore the dilution flow after the blend chest. Effectively, this bypasses the chests, thus invalidating some of the mixing benefit that the chests were designed to achieve. This is an example of how disturbances can propagate through shared services.

However, the simple regulator has a more insidious problem. Often a tuning that gives good results at high production rates becomes unstable as the flow of the diluted stream decreases. The reason for this behaviour is that the process gain is an inverse function of the total flow after the mixing point [6].

A simple improvement is shown in Fig. 3. Here both the main and dilution water flows are measured and the consistency signal is used to supervise their ratio. With this design, process gain is a function only of incoming consistency, thus making tuning much easier [9, 10]. This scheme also compensates for changes in dilution header pressure, tank level and throughput in a feedforward manner making consistency regulation faster and more precise.

In several of the machines studied, significant variability in the final product was coming from varying operation of the disc filter. An interesting illustration of how extraneous paths can create problems was a case where oscillation of the broke chest level caused increased paper variability, even though broke consistency remained quite stable. The mechanism in this case was as follows: broke chest level variations lead to cyclic thickener operation, which in turn upset the disk filter. In this process, the disk filter recovers about 60-80% of the filler in the machine stock (before adding fresh filler). This filler is sent to the blend chest as an un-metered stream through a path parallel to the main process flow. Not surprisingly, variability in quality (particularly in ash content) is created in the short circulation, and therefore in the paper.

While this case occurred on an SC machine, similar phenomena will occur whenever low-retention materials form a significant fraction of the sheet (e.g., fines in newsprint) [11].

Modern wet end process designs such as OptiFeed avoid this problem because the recovered solids are returned to one of the stock systems, where variations can be measured and compensated. For the existing process in this case, retuning the blend chest level control to be less aggressive and make more use of the surge capacity of the chest resulted in improved paper uniformity.

In many cases, simply retuning existing controls while considering the process as a whole can make significant improvements. Dosing of chemical additives has often caused increased sheet variability [6]. In many cases, careful retuning of the chemical flow, dilution and pressure regulation loops has improved performance.

**COORDINATING CONTROL OF STOCK PREPARATION**

To borrow a concept from control theory, the design of the wet end and stock preparation process could be described as not very “robust.” In steady-state everything is fine. However, when upsets occur, the many recycle flows and other disturbance propagation paths can amplify a simple upset into a major “ringing” of the wet end. Such a case is shown in Fig. 4. The broke flow changes cause an oscillation in paper ash and dilution water consistency that lasts for hours!

Broke handling is a difficult issue on a paper machine for many reasons. It is impossible to predict web breaks that will cause rapid filling of the broke tower. After a break, broke tower level should be returned quickly to a minimum level where mixing is effective and full capacity of the tower is available. Typically, broke flow is changed in steps having a certain size...
depending on the mill policy. However, as Fig. 4 shows, they are still often too rapid. Operator education and better operating practices such as more frequent but smaller changes, or the use of ramps to limit the speed of changes, can reduce the upsets. A better alternative to this simple operating practice change would be to incorporate broke flow as a feedforward disturbance input into the design of the control system.

Another prominent feature of the wet end of the paper machine is the existence of several large chests in series. These are intended to reduce variability through stock mixing. When this mixing functions correctly, it has a major stabilizing influence on the process. Too often, problems like that shown in Fig. 5 are seen where a sticky blend chest level valve causes level cycles. Interactions with other level controls cause this disturbance to be amplified as it propagates upstream.

Such behaviour is almost inevitable in that the levels of these chests are usually controlled using independent PI controllers. For most practical tunings, both disturbance rejection and setpoint following responses will exhibit overshoot [6]. The next tank upstream responds to these overshoots by over-compensating in turn so the original disturbance is amplified as it propagates upstream.

The amplification of flow disturbances can generally be avoided by using feedforward connections. Changes to the outlet flow of a chest are added to the flow into the tank. In effect, the control strategy is now based on the steady state mass balance of the process. If dry fibre demand increases, all flows increase to match. The PI controller is used to calculate a level correction to eliminate level deviations from setpoint, possible offset errors caused by flow calibrations or unmeasured flows to the tank. A conventional and modified scheme is shown in Fig. 6.

The modern OptiFeed design has gone even further in addressing these issues. The blend and machine chests have been replaced by overflow controlled dosing chests and a mixing reactor, thus eliminating level variation as a disturbance source near the machine. Consistency and stock flow control are integrated and even greater use is made of feedforward connections [12]. With this approach a more stable process with much lower process volumes is achieved.

**MULTIVARIABLE MACHINE DIRECTION CONTROL**

Wet end analyzers measuring headbox and white-water total and ash consistency have been available and on control for almost 15 years [1]. The most common application has been to measure total white-water solids and control retention aid flow. More recently, the headbox ash consistency signal has been used to control filler addition during breaks, and thick stock ash has been measured and used as a feedforward ash control. As mentioned previously, these controls have achieved remarkable results in both improved product quality and better machine runnability [3-5].

The results from these single-variable loop controls were very promising, but this approach ignores the process interactions of Fig. 2. Interactions like these can easily cause the wet end and dry end loops to fight each other. Unfortunately, optimal tuning of each separate loop DOES NOT result in optimal performance of the process as a whole.

In practice, a skilled control engineer will slow down the closed loop response of one or more loops to achieve an acceptable compromise for the over-all behaviour of the multivariable system. For instance, single variable loops for ash and retention control cannot be tuned in same frequency band, i.e., one (usually the white-water consistency) has to be about one decade slower than the other to avoid oscillation. Because of this, the separate loops are not delivering their full potential. If the single-variable loops are replaced with an optimal multivariable controller, you don’t have this restriction in the controller tuning. By minimizing a performance index that includes the key interactive papermaking variables, the multivariable controller will move the manipulated variables as much as is
required and as fast as possible (and/or desired), so as not to hurt the other controlled variables. Unlike the SISO case, optimization is simultaneous and not serial. As a result, you can also control the white-water consistency aggressively during strong disturbances.

Metso Automation has been developing multivariable model-based predictive control systems since the early 1990s. The technical details have been described elsewhere [14], so this paper will focus on some of the results.

Comparing the performance of different control strategies in an industrial context is difficult. Traditional before and after figures are really only valid if there have not been too many changes to the process in between.

Figure 7 shows such a case where control was implemented in a step-by-step manner on an SCA machine. Initially, only scanner-based control was in use. The variability levels at this point are represented by the whole “pie” in Fig. 7. The next step was to add wet end measurement and single-loop control of white-water consistency. The variability reduction from single-loop retention control is shown as the darker unexplored “slice.” Step three was to combine feedback ash and retention control into a 2x2 multivariable MPC controller. The exploded “slice” shows additional variability that the multivariable control was able to remove over what the single-variable loops were able to accomplish.

Note that weight and moisture were not included in this multivariable controller but at each stage; stabilizing the wet end leads to a more uniform weight and moisture in the final product. Clearly, the multivariable controller was able to achieve better results due to its optimal coordination of the filler and retention aid addition.

These results have been typical. In another mill making wood-free copy paper, multivariable control of filler and retention aid was implemented in one step. The 2-sigma variation of paper ash and white-water consistency were reduced by 27% and 58% respectively, with 30% reduction in the use of retention aids.

In this mill, the operators reported that the new control handled major upsets much better than the previous SISO scanner-only control scheme. This was particularly important for them as this machine had to process large amounts of coated broke from other lines in the mill. Since both the old and new strategies were present, a direct comparison test was made, Fig. 8. In this test, paper ash setpoint was changed by 1% and then restored to normal. This was a bigger change than the operators would normally have made in a single move, and so was a good test of disturbance rejection of the two strategies.

Figure 8 makes it clear that multivariable control is faster and has minimal overshoot compared to the scanner-only feedback control. Since the time of these tests, weight and moisture have been added into the multivariable controller for even better coordination.

By the end of 2003, Metso’s multivariable control has started up on 15 paper machines. Improved steady-state uniformity has been a consistent result. However, as the experience base grows, it seems that the real added benefit of multivariable MPC over the traditional SISO is best seen during periods of machine upsets, e.g., start-ups, grade changes and recovery from breaks. Many of the installations are new machines or significant rebuilds, making before and after comparison difficult. The evidence is largely anecdotal, but mills with multivariable MPC control have been telling a consistent story.

Stefan Fors, production line manager of UPM-Kymmene’s AKTI line in Kunsankoski, Finland, was surprised at how easily the machine starts up after the rebuild when the multivariable control was installed. Karl-Heinz Hannen, production manager PM3 in UPM-Kymmene’s Augsburg mill, reports: “After a long break, the sheet basis weight is within 1 g/m². Moisture and ash are also close to target.” Stora Enso Langerbrugge PM4, the world’s largest newsprint machine, started up in May 2003. Recently, Gert Wütinck, production manager, said: “Before the paper is on the reel we know it is on target. That limits the rejects during start-ups.” He estimates that no more than 10 tons of paper has been lost at start-ups from May to October. Lief Alfredsson, manager of the news line, adds: “We have run for five days without a break. The runnability is fantastic.”

Anecdotal or not, such statements by experienced papermakers suggest that multivariable MPC with its unique ability to combine wet end and dry end measurements and optimally coordinate stock, filler retention aid and steam pressure represents a step change improvement over traditional paper machine quality controls.

**CONCLUSIONS**

In order to meet the higher stability levels required by papermakers, wet end stabi-
elimination is essential. Experience on many paper machines points to similar problems again and again. Consistency control, disc filter operation, additive dosing and level controllers cause variability problems in many mills.

One reason for this is the complex topology of the traditional process design, which allows many paths for the propagation of upsets from one place to another. The ultimate solution will involve redesign of the process, but much can be done with the existing plant configuration.

One of the keys is to increase awareness of how interconnected the process actually is. One has to emphasize to mill-instrument personnel the need to look at over-all process performance rather than just a single variable when tuning controls. Simple operational changes such as ramping broke flows rather than sharp steps will help. Ratio-based consistency control and incorporating feedforward elements into tank level controls can increase wet end and stock prep stability.

The papermaking process shows strong interactions between weight, ash content, retention chemical and moisture content. To meet the challenge, a new multivariable MPC controller has been proven itself in many mills. This MPC concept integrates dead-time-dominated quality variables from scanning sensors with the highly interactive wet end measurements and coordinates the manipulation of stock, filler, retention aid and steam valves.

Improved steady-state results have been reported. More significantly, the real added benefit of multivariable MPC over the traditional SISO has been seen during periods of machine upsets, e.g., start-ups, grade changes and recovery from breaks. The ability of multivariable controller to eliminate the tuning compromises that have been necessary with single-variable loops is leading to much superior performance during these difficult conditions when traditional SISO techniques have often not worked well.

**LITERATURE**


Résumé: Le processus de fabrication du papier est très interactif. Les perturbations dans une partie de l’usine se propagent à d’autres secteurs de la fabrication de plusieurs façons. Une partie du problème découle du fait que nous essayons de contrôler un processus multivariable très complexe à l’aide de boucles de contrôle à une seule variable. Aujourd’hui, des mesures et des contrôles multivariables modernes permettent d’obtenir un rendement supérieur lors du passage d’une catégorie de papier sur machine et, encore plus important, pendant les fortes perturbations où les méthodes traditionnelles n’ont pas bien fonctionné.


**Keywords:** PROCESS CONTROL, CONTROL SYSTEMS, PAPER MACHINES, VARIABLES, PERFORMANCE EVALUATION.