

**PERFORMANCE EVALUATION OF PULPER CONSISTENCY
CONTROL WITH DEAD-TIME COMPENSATION¹**

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Application: Dead-time compensation scheme for controlling pulper consistency.

Abstract

In this paper, we study the implementation of a pulper consistency controller for the recycled paper industry. Variations in the weight and the quality of the raw material, i.e. recovered board and paper, are known to cause consistency variations which, in turn, cause variations in the basis weight and the moisture level of the end product, i.e. recycled paper. The first step towards rejecting these consistency variations is to implement a consistency controller in the pulper itself. We propose a combination of feedforward and feedback with dead-time compensation as the paper dissolving process is characterized by a dead time that is large in comparison with the time constant of the process. We describe the implementation of the controller from the pulper modeling phase to the discussion of the experimental results.

1. Introduction

There is a tremendous pressure in the pulp and paper industry when it comes to increasing the profitability of the paper mill. It is therefore of the utmost importance to avoid machine stops due to web breaks in order to maximize production while at the same time producing high quality paper. It is the opinion of the authors that an improved control of the thick stock consistency will ensure a more stable running of the paper production process combined with

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higher quality standards. Recall that consistency is a measure of the solid/fibre content in the stock. Indeed, consistency variations are known to produce web breaks as well as basis weight and moisture level perturbations in the end product. These two parameters are considered to be the main paper quality indicators and it is thus crucial to keep them as constant as possible by avoiding all consistency variations. The first step towards this goal is to reduce the stock consistency variations in the pulper itself as it has consequences for the downstream part of the paper production process.

The paper machine PM7 at Oudegem Papier in Oudegem in Belgium has been used as a test case for pulper consistency control. As the paper dissolving process in the pulper of PM7 is characterized by a dead-time that is large in comparison with the time constant of the process it is necessary to implement dead-time compensation measures. The problem is made more difficult by the fact that the time constant and the dead time associated with the dissolving process are variable with consistency and the quality of the raw material, i.e. recovered paper. This paper describes the design of a robust dead-time compensation controller from the pulper modeling phase to the assessment of the experimental results with the implemented dead-time compensator. As far as we know, it is the first successful implementation of consistency control in the pulper itself in the recovered paper industry.

The paper is organized as follows. The principles behind dead-time compensation are set out in Section 2. Section 3 describes the pulping process. The identification of the system parameters and the pulper modeling are, respectively, discussed in Section 4 and in Section 5. The implementation of the dead time compensator and the discussion of the experimental results can, respectively, be found in Section 6 and in Section 7. We conclude in Section 8.

2. Dead-time Compensation

It is well-known that large process dead times have a destabilizing effect on control loops if not properly compensated for. By large dead times, we mean processes for which the dead time is larger than a half of the main time constant of the process. Because the response to control action is not having effect before the dead time has elapsed, the controller integral action will continue for the duration of the dead time, assuming that the previous action was insufficient to eliminate the error. When the response to the controller is finally seen, the integral action is decreased but that effect is again not seen immediately. The integral action will thus cycle and it may eventually cause instability. It is possible to solve the problem partially by decreasing the controller gain but this results in sluggish controllers. A better solution consists in using dead-time compensation control as suggested by Smith [1]. The idea is to use an internal model (without dead time) of the process. If the model is a perfect image of the process without dead time then it is sufficient to feed the output of the model back to the controller. As a result the dead time is removed from the control loop.

Of course, the model is never a perfect image of the process. Therefore the difference between the measured output and the delayed output of the internal model is also fed back to bring corrective action. This is shown in **Figure 1**. Usually it is sufficient to use a first order model for the internal model. The Smith predictor dead-time compensator is robust to small mismatches between process and model. If the model is less accurate (especially the knowledge of the dead time), the compensation is less accurate and the closed-loop behaviour is degraded.

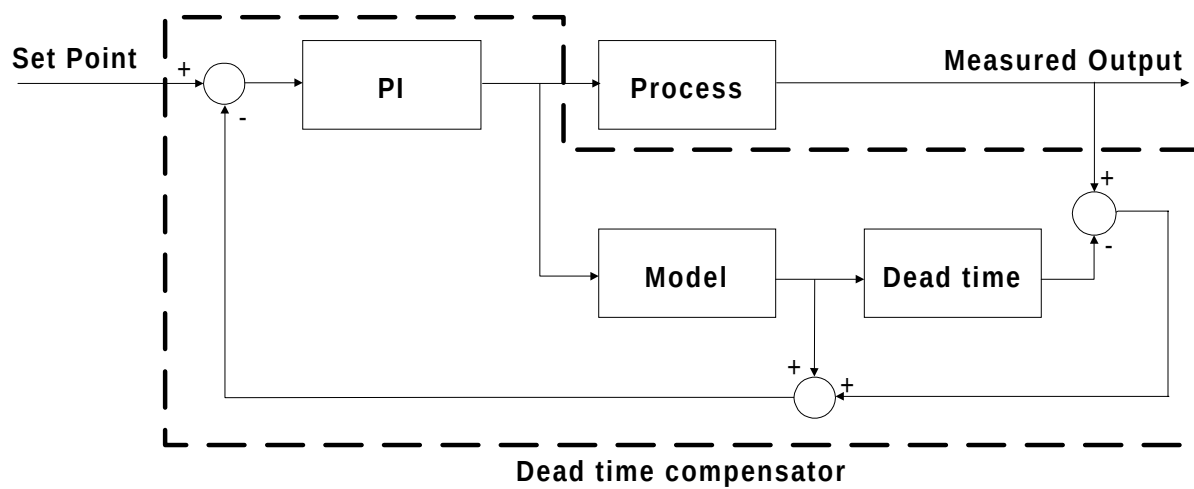


Figure 1. Smith predictor for dead time compensation.

Before implementing a Smith predictor, alternative control strategies such as a wait-and-see controller [2][3] and a PI controller have been considered. The three methods have all been tested for their tracking and disturbance rejection behaviour as well as for their robustness using a Simulink model of the pulper. A Smith predictor was finally selected for pulper consistency control.

3. Process description

A conveyor belt brings the raw material into the pulper. The conveyor belt is activated by setting a run time and a pause time, i.e. at each cycle period the belt is running for a time corresponding to the run time and subsequently pausing for a time corresponding to the pause time. Equivalently, one can set a run time and a cycle period. The stock is continuously withdrawn from below through a screen. The raw material is mainly composed of recovered paper and board which arrives at the mill compressed into bales that vary in weight between 300 kg and 700 kg. The waste paper and board is fed into the pulper while adding water to maintain the pulper level at a given set point, usually 55%. A toothed rotor driven at high speed produces a swirling action which breaks down the waste paper and eventually separates the individual fibres from each other. The dissolving of paper into fibres and its effect on consistency (solid content) is roughly a first order process with time constant T and a dead time τ . Adding water has an almost immediate effect on consistency. The pulper level and consistency and the pulper output flow are measured and used for feedforward/feedback purposes. (See **Figure 2.**)

The aim of the optimisation exercise is to control the consistency as tightly as possible at a prescribed set point, usually 4%. This allows a downstream control of consistency to about 3.5%. Indeed, the remaining disturbances are removed downstream by adding the required amount of water. It goes without saying that this is only possible if the consistency is maintained above 3.5% in the pulper itself.

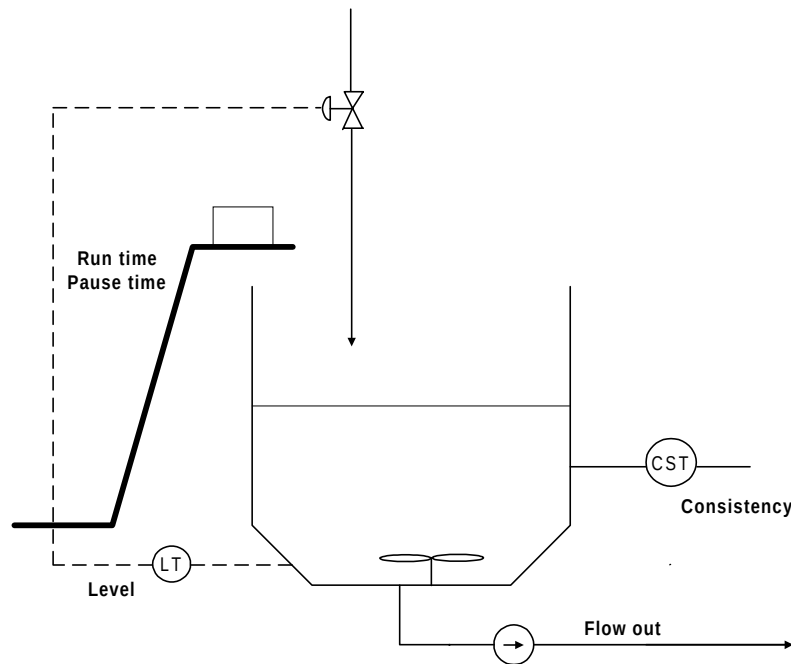


Figure 2. Pulping process.

4. Determination of the system parameters

Some parameters crucial for the design of the dead-time compensator were determined from experiments performed on the actual pulper. Siemens' Millwide Information Management System (MIMS) was used to collect and archive the test data. The goal of the experiments was to determine the time constant and dead time associated with the dissolving of the paper. During the testing period, the stock output flow was stopped and a bale was fed into the pulper. The influence on the consistency was monitored and archived using MIMS. This test was repeated 8 times in order to minimize the stochastic effects. An example of the data collected during a typical experiment is shown in **Figure 3**. The Matlab/Simulink package was used to estimate the first order model with dead time that best fits the data.

We concluded that the dead time associated with the dissolving of the paper is $\tau = 100 \pm 40$ seconds and that the associated time constant is $T = 142 \pm 20$ seconds. The large variation of the dead time can be explained by the fact that the dead time varies with consistency, i.e. it is larger for higher values of consistency.

An experiment with a pulper level set point change (i.e. adding water) confirmed our hypothesis that the effect of adding water on consistency is virtually instantaneous.

Other parameters such as the average capacity of the conveyor belt and a typical range for the stock output flow were estimated from historical data. The belt capacity was estimated at 46 kg/second and the stock output flow ranged between 7000 and 12000 l/min. These two parameters were used to construct a model matching the actual pulping process as closely as possible.

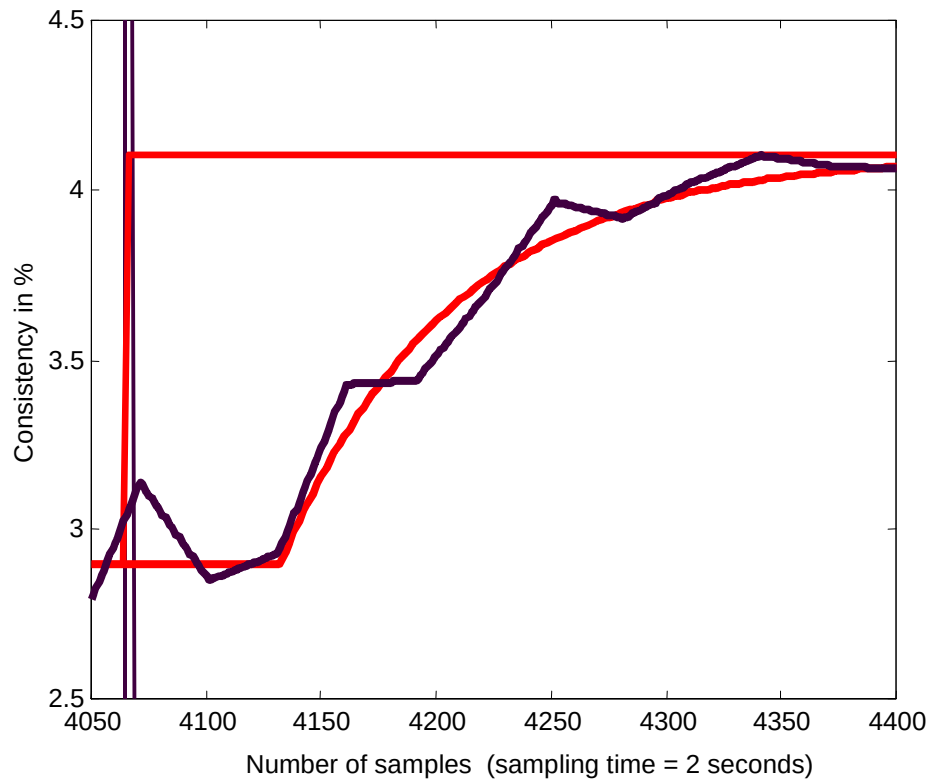


Figure 3. *Determination of the time constant and the dead time associated with the dissolving of the paper.*

5. Pulper model

A model of the pulper was implemented in Matlab/Simulink. This model proved to be very useful for fine tuning the controller and testing its robustness under different scenarios. The upper part of **Figure 4** shows a global overview of the model implemented in Matlab/Simulink.

The “Paper dissolving” block keeps track of the amount of waste paper that has been dissolved into individual fibres at any given time. The time constant and the dead time associated with the process as well as the belt capacity can be perturbed from their nominal value to check the robustness of any designed controller in extreme situations without having to actually implement it on the actual physical pulper.

The level of the pulper is modeled by integrating the difference of the flows coming in and out the pulper. It is kept to its prescribed set point by the level controller. Again, it is possible to modify the level set point and the stock output flow to check the behaviour of any given consistency controller.

The “Consistency measurement” block keeps track of the incoming (after dissolving) and outgoing (stock output flow) fibres and is in turn used to compute the consistency in the pulper.

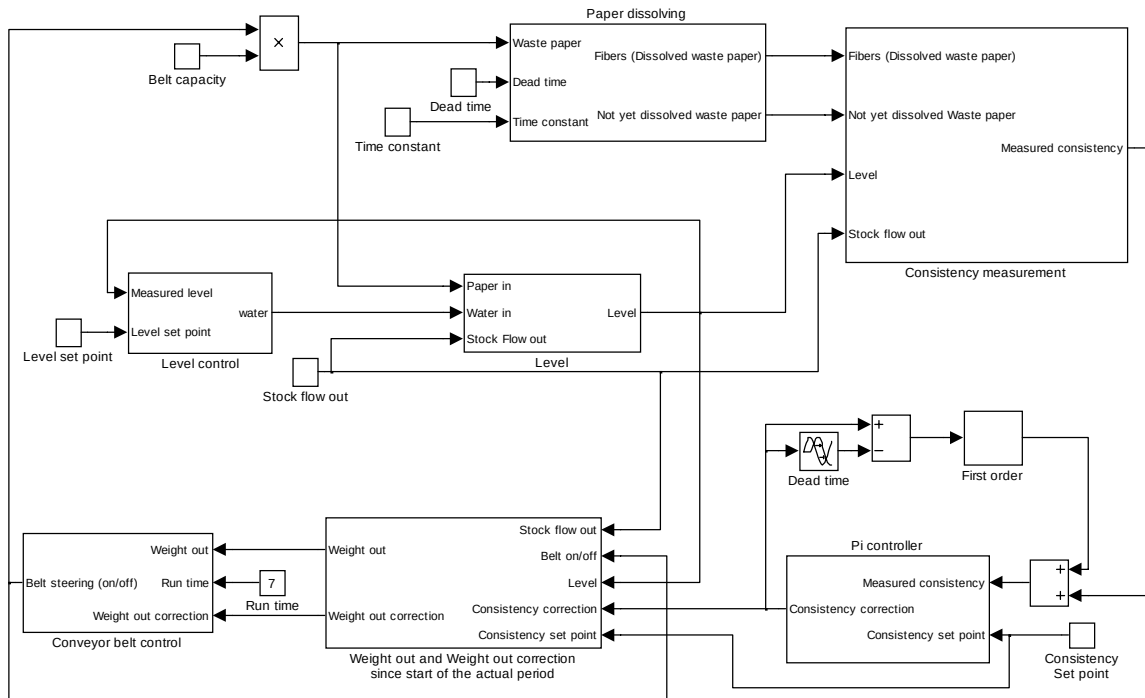


Figure 4. Pulper model (upper part) and dead time compensation controller (lower part) implemented in Matlab/Simulink.

6. Implementation

To optimize the control of pulper consistency, there is only one solution, i.e. to control consistency by adjusting the amount of waste paper entering the pulper. Indeed, the alternative, controlling consistency by adding water in the pulper, is impractical as large quantities of water have to be added to modify consistency by a small percentage. Also, this type of control would bring along large variations in the pulper level.

As the dead time associated with the dissolving of paper is large in comparison with the time constant of the process, special care has to be taken for its compensation.

The stock output flow from the pulper is acting as a varying perturbation on the consistency control loop. As this perturbation is measurable, it is natural to compensate its effect before it creates control errors; this control paradigm is called feedforward. The idea is that the stock is replaced almost instantaneously by water by the level control loop. One can therefore precompute the amount of paper necessary to bring the amount of water entering the pulper to the appropriate consistency. This amount of paper is then corrected by feedback, i.e. by the Smith predictor. The combination of feedforward and feedback results in a faster control (feedforward) system, more insensitivity to process variations and good stability properties despite the large dead time (feedback, dead-time compensator).

There are two ways to implement this combination of feedforward and feedback. The first method is to vary the run time and to keep the cycle period constant; see **Figure 5**. The second method is to adapt the cycle period while keeping the run time fixed; see **Figure 6**.

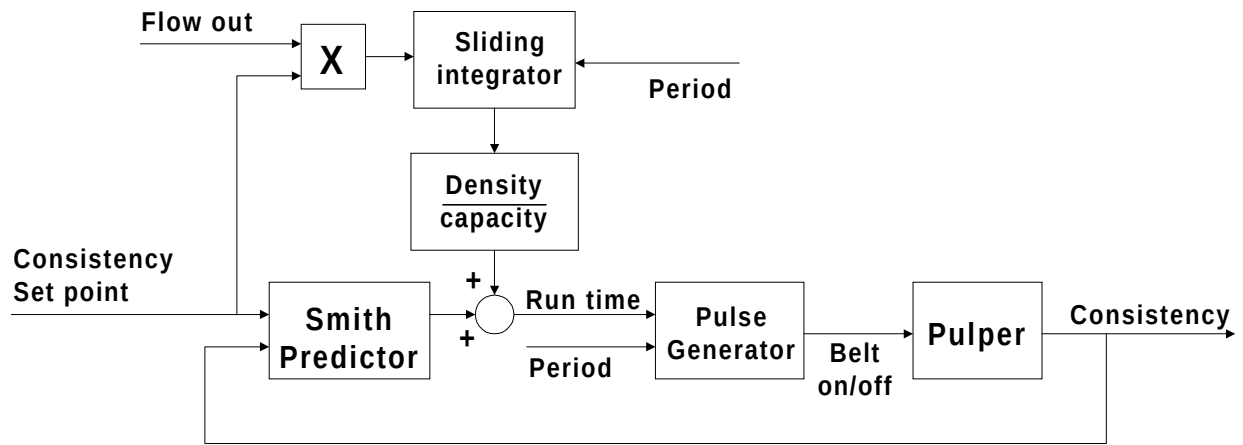


Figure 5. Combination of feedforward and dead-time compensation feedback with varying run time and fixed cycle period.

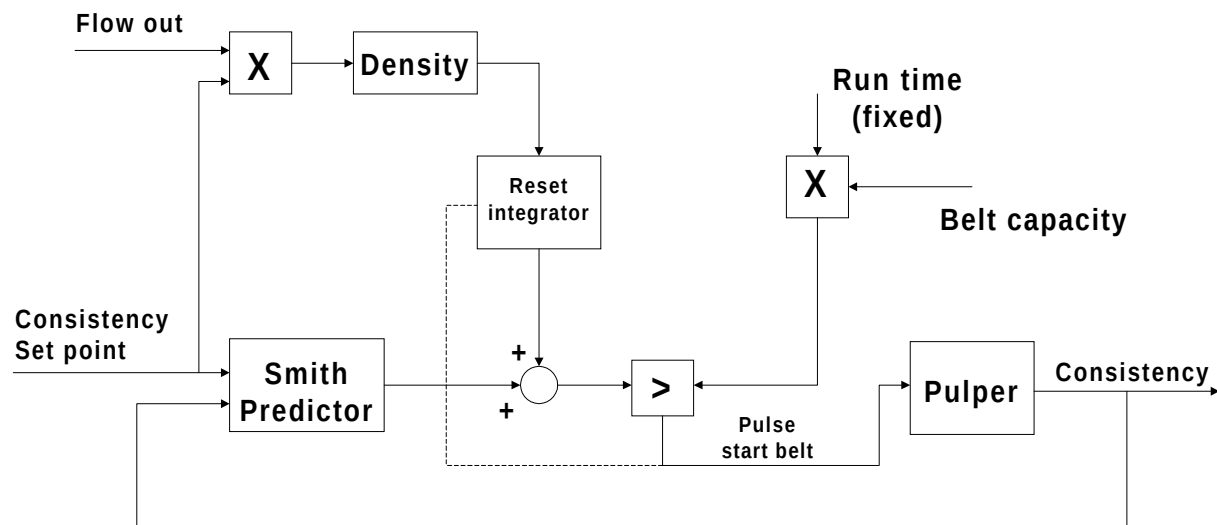


Figure 6. Combination of feedforward and dead time compensation feedback with fixed run time and varying cycle period.

Figure 5 shows a schematic implementation of the control system with fixed period and varying run time. The output of the sliding integrator block provides the integral of the product stock flow times consistency set point over the cycle period that has just elapsed at any given time, i.e. the fiber mass that is necessary to bring the water added over the elapsed period to the consistency set-point. This output is then further multiplied by the stock density and, finally, divided by the band capacity. This results in the feedforward part of the run time. This time is a measure of the time that is needed by the conveyor belt to bring enough raw material to compensate for the stock that has been replaced by water over the cycle period that has just elapsed. This time is then adjusted by the feedback part of the control system to produce the actual run time. This run time is read into the pulse generator once at the end of each cycle period.

Figure 6 shows a schematic implementation of the control system with fixed run time and varying cycle period. The conveyor belt is started once the fibre mass that is necessary to bring

the water that has entered the pulper over the current cycle period to the prescribed consistency plus the corrective action brought by the dead-time compensation scheme has exceeded the mass that can be fed into the pulper during a run time. It is stopped after the fixed run time. The fibre mass that is necessary to bring the water added over the current cycle period to the consistency set-point is computed using a reset integrator.

Both strategies were implemented and compared in Matlab/Simulink in various situations, i.e. varying belt capacities, time constant, dead time, stock flow and pulper level. Extensive simulations have shown that the implementation in Figure 5 gives the best results. These simulations also show that the dead-time compensation controller is robust to the changes in dead time and time constant that have been predicted experimentally and can be expected on the actual system.

Figure 7 shows simulation results with the fixed period implementation of the dead-time compensator. We have used the following parameters to simulate extreme situations:

- Belt capacity: random variations between 35 and 55 kilograms per second.
- Stock output flow: random variations between 153 and 167 liters per second.
- Time constant: random variations between 120 and 160 seconds.
- Dead time: random variations between 60 and 140 seconds.
- Level set point: change from 55% to 60% at time $t = 3$ hours.

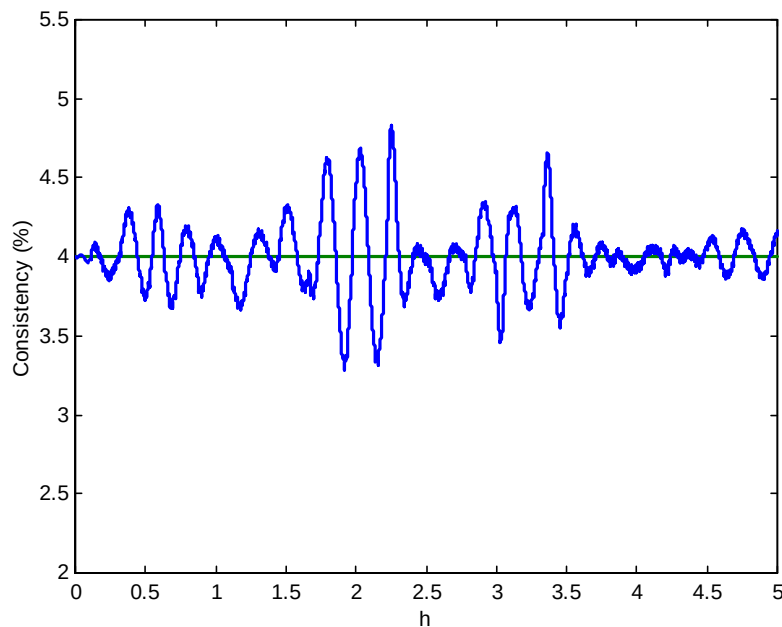


Figure 7. Simulation of the designed dead-time compensator in an extreme situation to test its robustness.

It follows from Figure 7 that the implemented dead time compensator is fully robust in situations that are likely to occur in real life situations.

7. Results

The dead time compensator with fixed cycle period was finally implemented on the actual pulper. **Figures 8 and 9** show the actual variations of consistency before (manual control) and after dead-time compensation. Notice that the consistency deviations have been roughly divided by three. More precisely, the average consistency with manual control is 3.49% with a standard deviation of 0.69%. The figures after dead-time compensation are, respectively, 3.65% and 0.29%. Also the minimal value of consistency is around 3.5%. This will allow an improved downstream control of consistency at 3.5%.

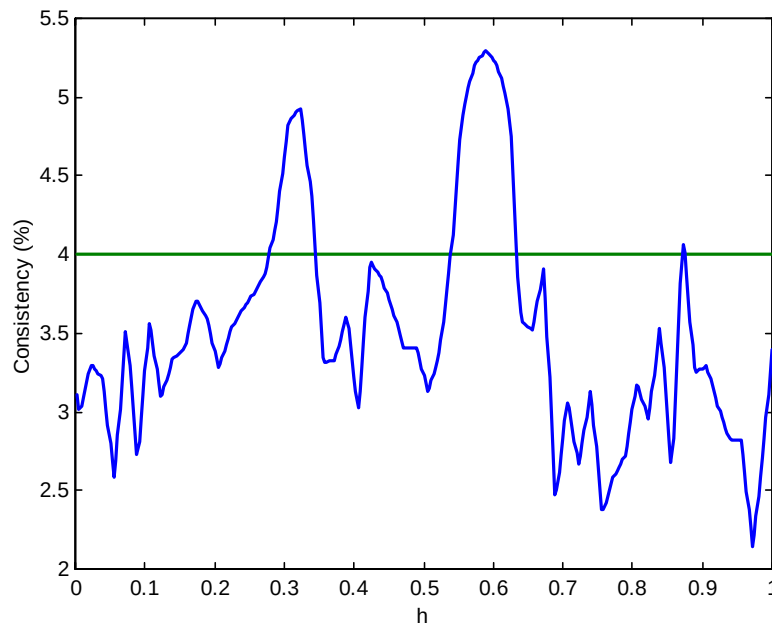


Figure 8. Consistency variations without dead-time compensation (manual control).

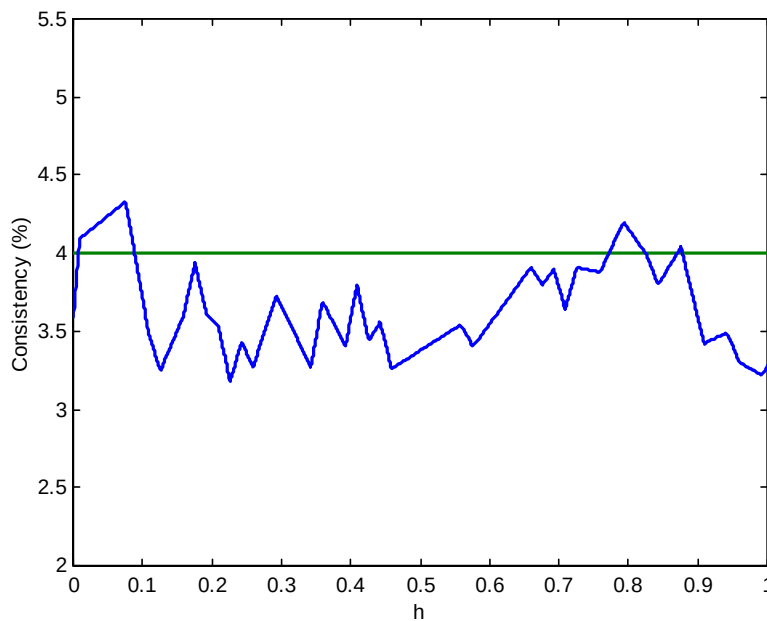


Figure 9. Consistency variations with dead-time compensation.

Also, the potential exists of producing stock with a higher consistency (for example 4.5%) without running the risk of having consistency variations above 5.5%. A consistency above 5.5% with a pulper level of 55% constitutes the limit for the rotor motor to be able to spin the stock at an appropriate speed. Note that a reserve of thick stock at 4.5% constitutes a higher fibre storage capacity when compared with thick stock at 4%.

8. Conclusions

In this paper we have shown that dead-time compensation allows an excellent first control of consistency in the pulper. Indeed, consistency variations in the pulper have been divided by three when compared with manual control. This subsequently allows an improved downstream control of the thick stock flow. A first advantage is an amelioration of the quality of the end product as the disturbing effects of consistency variations are decreased. This advantage is achieved using an automatic controller which, in turn, saves on manpower. A second advantage is the possibility of producing thick stock with a higher storage capacity.

The combination of collecting data for parameter identification and white box modeling allowed us to test the robustness of any designed controller before actually testing it on the pulper.

9. References

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