REDUCTION OF MATERIAL LOSS DURING GRADE CHANGE PREDICTIVE CONTROL IN A PAPER MACHINE.

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Abstract: In this contribution, the dynamical behavior of a paper-making system is presented and an advanced controller is developed to minimize the amount of recycled paper used in the paper making process. The advanced controller is a model based control strategy, and therefore, a model is developed in order to evaluate the loss of paper during the transition between two points of operation. The wastage model is adapted to be used in the cost function of an *in-house* developed predictive control algorithm. Performance evaluation is described and the corresponding results are presented.

Keywords: Paper industry, Predictive control,nonlinear model, constraints, optimal, robust, wastage paper

1. STATE OF THE ART

Grade change on a paper machine is a transition from one set of operating conditions to another. During the transition, without proper coordination and control, the entire process could have radical fluctuations and produce significant amounts of off-specification paper or even cause sheet break. The production loss and the efforts to recycle off-spec waste are very costly (Murphy T. F., 1999). For machines which need to make frequent grade changes in order to produce a wide variety of paper grades, they often spend a significant portion of their production time making off-specification products through grade change transitions. Definitely, there is a strong need to improve the operation of grade change transitions. The research of improving control of grade change transitions has been mostly focused on process modeling, as in (Chen, 1992) and (Menani, 1998). Although some work on grade change control has been done, as in (McQuillin, 1994) and (Ihalainen, 1996). The basic process of making paper is preparing the stock, forming the paper web, drying the sheet, and applying coatings and additives.

This paper is organized as follows. In the section 2 the objectives are presented and esplained. Section 3 presents the model and the variables involved. In section 4 the model of waste is explained and the cost function of the predictive controller is designed. The results obtained with the proposed controller are presented in the section 5, also the controller is tested under unmeasured disturbance. Finally, in section 6 the conclusions are presented.

2. CONTROL TASK

The main objective of this investigation is to design a predictive controller that minimizes the amount of paper wasted in the papermaking process. This paper will be referred to as *wastage paper*. The paper produced during the transition from one kind of paper to another (depending on customer's specifications) is considered lost, since in this case the paper does not fulfill the technical specifications required by the client. Therefore, it can only be sold at lower price or not sold at all - producing wastage. However, there is a possibility to recycle this paper, but this process uses extra energy in order to transform the paper into pulp.

3. MODEL OF THE PLANT

Making paper requires a complex procedure, with different input variables. In the model only some of the most important inputs have been considered as manipulated variables.

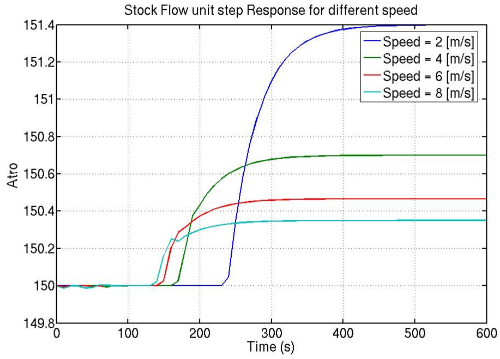

Fig. 1. Atro response in open loop, when applied a unit step in the Stock Flow input variable, for different speed.

These variables are *stock flow, speed and pressure* (*www.paperonweb.com*, 2006). The other inputs are considered constant parameters, such as: consistency of the pulp, the temperature and width of the paper. The model has two output variables, the *Atro* and *Moisture*:

<u>*Moisture*</u> (or water content in %)content is complementary to the Consistency indicator.

$$Moisture = \frac{M\_water}{M\_matter\_dry + M\_water} \cdot 100$$

<u>*Atro*</u> (or grammage or dry weight)represents the mass of dry matter reported to the surface.

$$Atro = \frac{M\_matter\_dry}{surface} \left[\frac{g}{m^2}\right]$$

More details of the process and the model of the plant was presented in (Melo, 2006). One of the most challenging characteristics of the process is the variable time-delay in the output variables. The variable time-delay depends on the speed of the machine. Figure 1 shows the output variable Atro response when a unit step is applied in the Stock Flow for different speeds of the machine. The faster the machine works, the smaller the time-delay in the output variable response.

4. CONTROLLER DESIGN

This section describes a mathematical model for evaluating the amount of lost paper during grade transitions. The model was adapted for discrete time and was used in defining the cost function of an *in-house* predictive controller (De Keyser, 2003).

4.1 A Model for the Wasted Paper

The first step in the design of the controller is to model the amount of wastage paper. The length of the transition is the time needed to change the production between two production/operation points. A point of operation must be defined for setting the quality standards of the paper (customer-based tailoring). The length of a grade transition is defined by two time instants (t_1 and t_2). The speed of the machine determines the amount of paper produced per unit of time. In order to obtain the amount of lost paper (mass) per unit of time, is necessary to multiply the width of the paper by the speed and the Atro output. This product has unit of grams per second $[\frac{g}{s}]$. Calculating the integral of this product in the interval time from t_1 to t_2, gives the amount of waste during the transition. Equation (1) shows the model for lost paper (LP).

$$LP = W \int_{t_1}^{t_2} A(t)\, v(t)\, dt \qquad (1)$$

where:

LP :	Paper Loss $[g]$.
W :	Width of paper $[m]$.
$A(t)$:	Gramage $[\frac{g}{m^2}]$.
$v(t)$:	Speed $[\frac{m}{s}]$.
t :	Time $[s]$.
t_1 :	Start time of transition
t_2 :	End time of transition

It is possible to convert the continuous model of wastage in a discrete model by approximating the integral of the equation (1) in a sum; notice that the term of the time now becomes the sample time. The discrete model for wastage paper becomes:

$$LP \approx W\, \Delta t \sum_{k=k_1}^{k_2} A(k)\, v(k) \qquad (2)$$

where:

$A(k)$:	Gramage $[\frac{g}{m^2}]$.
$v(k)$:	Speed $[\frac{m}{s}]$.
Δt :	Sample time $[s]$
$k_1 = \frac{t_1}{\Delta t}$:	Start time of transition
$k_2 = \frac{t_2}{\Delta t}$:	End time of transition

This discrete model allows us to write a new cost function that includes the LP in the optimization procedure of the predictive controller.

4.2 The Cost Function

One of the most common cost functions is defined as the square error between the output of the system and the desired reference trajectory. In this investigation, a term which describes the amount of LP in a finite horizon of prediction is included. The cost function used is defined by (3). The function $\delta\,(t+k|t)$ predicts if the paper is into the allowed region of tolerance. This function has only two values: 0 when the paper produced is into the region of tolerance; and 1 when the paper produced is out of the tolerance's region (=wastage paper). The principal role of the function $\delta\,(t+k|t)$ is to predict the limits of the transition (k_1, k_2) for (2) at each sample time, because the values of the N_{1L} and N_{2L} are fixed in the cost function (3).

4.3 Constraints

The calculation of the input variables considers the physical/technical constraints of the paper machine. The nominal range considered was: for the stock flow from 200 to 700 $[\frac{l}{s}]$; for the speed from 2 to 10 $[\frac{m}{s}]$ and for the pressure from 2 to 8 $[Bar]$. In the calculation of the control inputs, the restrictions in the outputs were not considered (un-constrained).

4.4 The Optimizer

The cost function (3) is non-linear and for this reason the optimization algorithm iterates in order to obtain the optimal control value. The paper machine model is also non-linear, and therefore, the prediction of the system output used the step response calculated at each sample time. The reduction of the LP presents a difficulty, because when the algorithm minimizes the speed, it produces an increase in the variable time-delay, as depicted in the Atro response in figure 1. The increase in time-delay is predicted by the function $\delta\,(t+k|t)$. In other words, when the speed of the machine is decreased, the length of the transition increases. Therefore, there is a compromise between the prediction of the speed and the delta function in the cost function (3).

5. SIMULATION RESULTS

The performance of the controller was tested with different kinds of paper (grade-changes). The first aim was to prove the controllability of the system in closed-loop. The second aim was to compare the response of the controller for different values of the tuning parameters and evaluate the amount of wastage paper in each case. In order to make a comparison, the tolerance used in the test was the same for all kinds of paper: for the Atro the tolerance was $T_{A1} = T_{A2} = \pm\, 2\ [\frac{g}{m^2}]$ and for the moisture it was $T_{M1} = T_{M2} = \pm\, 1$ [%].

5.1 First Test

The first test used an Atro reference which changed from 80 to 150 $[\frac{g}{m^2}]$ while the moisture reference was maintained constant in 4.5 %. In this test, three different values of tuning parameters λ_2 have been used to compare the effect of the third term in the cost function (3). Figure 2 shows the result of this simulation.

The amount of lost paper was evaluated with the expression (2) for different values of the tuning parameter λ_2 and the result is shown in table 1.

The controller with $\lambda_2 = 0.4$ has produced less amount of lost paper. It is possible to obtain a reduction of the wastage paper equal to 28 % with respect to the case with $\lambda_2 = 0$, due to the advantage of using a model for the lost paper.

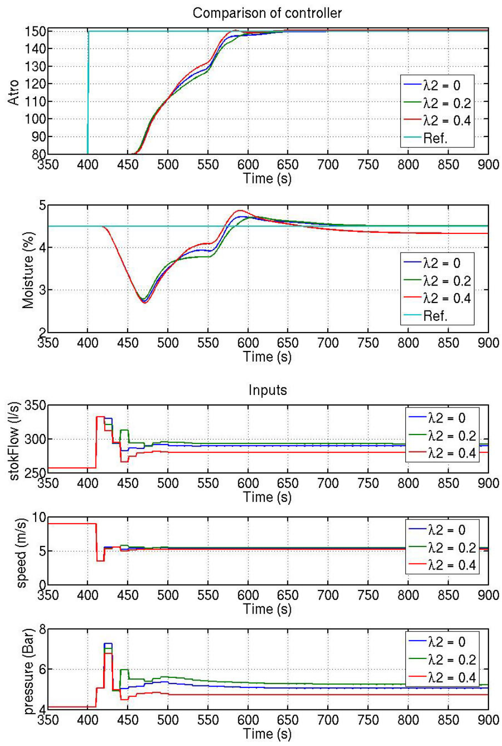

Fig. 2. Behavior of the controller for three different values of λ_2 tuning parameter.

Table 1. Result of the test 1

λ_2	range of time [s]	LP [kg]	reduction [%]
0	[448 609]	527	0
0.2	[447 592]	464	11.95
0.4	[447 573]	376	28.65

5.2 Second Test

An analysis of controller's behavior has been performed when a disturbance was introduced in the consistency of the pulp, while it was unknown in the prediction model. The controller compares the output variables of the process and the model.

In this test we have employed a step change in the consistency of the pulp from 1.4 to 1.3 [%] as disturbance at time 400 [s]. The filter of the estimator for perturbation used $n(t+k|t) = n(t),\ \{k = 1, .., N2\}$.

$$J(t) = \sum_{k=N_{1A}}^{N_{2A}} \left[A(t+k|t) - R_A(t+k|t)\right]^2 + \lambda_1 \sum_{k=N_{1M}}^{N_{2M}} \left[M(t+k|t) - R_M(t+k|t)\right]^2$$
$$+\lambda_2 \sum_{k=N_{1L}}^{N_{2L}} A(t+k|t)\ v(t+k|t)\ \delta(t+k|t) \quad (3)$$

$$\delta(t+k|t) = \begin{cases} 0 & \text{if } [\text{abs}(A(t+k|t) - R_{A1}) < T_{A1}] \text{ and } [\text{abs}(M(t+k|t) - R_{M1}) < T_{M1}] \\ & \text{or} \\ & [\text{abs}(A(t+k|t) - R_{A2}) < T_{A2}] \text{ and } [\text{abs}(M(t+k|t) - R_{M2}) < T_{M2}] \\ 1 & \text{in other case} \end{cases} \quad (4)$$

Where:

$A(t+k\|t)$:	Prediction of Atro $[g/m^2]$
$R_A(t+k\|t)$:	Atro reference $[g/m^2]$
$M(t+k\|t)$:	Prediction of Moisture [%]
$R_M(t+k\|t)$:	Moisture reference [%]
λ_1, λ_2:	Tuning parameter
$v(t+k\|t)$:	Prediction of speed $[m/s]$
$\delta(t+k\|t)$:	Prediction function (binary)
N_{2A}, N_{1A}:	Horizon range for Atro
N_{2M}, N_{1M}:	Horizon range for Moisture
N_{2L}, N_{1L}:	Horizon range paper loss
R_{A1}, R_{A2}:	Atro ref. for paper 1 and 2 resp.
R_{M1}, R_{M2}:	Moisture ref. for paper 1 and 2
T_{A1}, T_{A2}:	Atro tolerance for paper 1 and 2
T_{M1}, T_{M2}:	Moisture tolerance for paper 1 and 2

Figure 3 shows the output of the process and Table 2 shows the result of the second test, when a disturbance was introduced in the consistency.

Table 2. Result of the test 2

λ_2	range of time [s]	LP [kg]	reduction [%]
0	[450 548]	393	0
0.2	[451 552]	405	-3.08
0.4	[451 545]	373	5.14

All controllers maintain stability when a disturbance unregistered in the prediction model is applied to the process. However, the reduction of LP was not guaranteed. This kind of behavior is due to the difference between the model and the process produced for the disturbance.

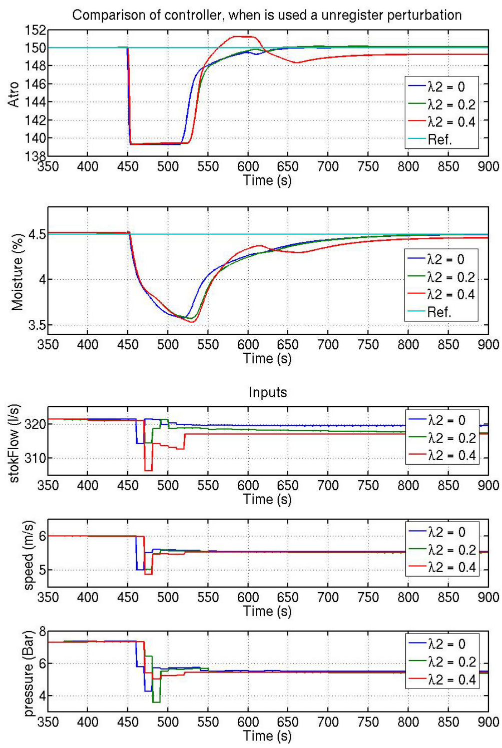

Fig. 3. Behavior of the controller when an unmeasured perturbation was applied in the consistency of the pulp from 1.4 % to 1.3% for three different values of λ_2 tuning parameter.

6. CONCLUSIONS

A model was developed for evaluating the amount of lost paper during the transition between two kind of paper qualities, depending upon the process variables.

The continuous model of the wastage paper was used to design a term of the cost function in the predictive controller. The cost function used the square error between output of the process and the reference, as the classic model predictive control. However, the waste paper model was also included as a new term in the cost function.

The relationship between the operation point in the production process and the length of the transition was included in the wastage paper model of the cost function. The results of the predictive control with the lost paper model were successful when compared with a predictive controller with classic cost function. The use of the lost paper model in the cost function reduces the waste during the transition between two operating points. The controller presents good results for disturbance rejection in the process, but the performance of the controller depends highly on the tuning parameters. At this moment there is not an automatic system for tuning parameter. Although there is an interesting subject for future studies.

Concluding, the use of the wastage model in a predictive controller reduces the amount of paper that is recycled in the paper industry, leading to a decrease in the energy employed in the transformation process from paper to pulp and then to paper again.

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