Project report:
Multivariable Control of the Grinding Process

Brief version

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Abstract

On-line control of several quality variables of grinding pulp is investigated. Apart from the traditional wood feeding speed also the peripheral speed is used for control. The controlled variables, apart from the traditional freeness, are bulk and Scott bond in carton production, and tear in finer paper production. The effect of the control variables, peripheral and feeding speed, to the controlled variables are experimentally investigated and modelled. The obtained models are used for design of feedback controllers, which are experimentally tested and verified. The feedback control can be used for obtaining more even and expected pulp quality, and finding optimal operating conditions where quality specifications are met and production is as high as possible. That is, more production or alternatively better quality and less energy consumption can be obtained, according to preferences and/or state of the market. The suggested feedback control can be combined with on-line sharpening-of-the-grinding-stone methods without additional efforts or risks. The suggested feedback control methods require investments of adjustable motors, with an expected payback under a year.

1 Introduction

In this report a method for controlling CF and tear in the grinding process is presented, and the sum of squares of the deviations from wanted values (set points) would be minimized (see (1)).

Earlier the process has been controlled by using the CF-value as measure variable, and in most cases without on-line control. The disadvantage of this strategy is that the CF-value doesn't tell everything about the pulp quality. Tear, tensile, light scattering and brightness are also important. For carton producing are bulk and Scott bond also important.

The grinding process (LWC-pulp, SC-pulp, Newsprint pulp and Carton pulp) can be affected by two control variables:

- The wood feeding speed
- The peripheral speed

The peripheral speed can vary between 10-42 m/s and the wood feeding speeds can vary between 0.3-3 mm/s. Furthermore, the pulp quality is affected by wood quality and the properties of the grinding stone.

Traditionally the CF-value has been controlled by the wood feeding speed. If also the peripheral speed is used for control, can other quality variables also be controlled. Of the investigated quality variables, tear correlates best with the peripheral speed and was chosen to the other measure variable besides CF (if it's not carton pulp in question, but e.g. LWC-pulp, SC-pulp, Newsprint pulp, etc.). That is, we are dealing with a multivariable control problem, which can be realized with a multivariable control algorithm or two SISO (Single Input, Single Output)-loops.

- The CF-value and tear will be kept on desired level and the sum of the square deviations will be minimized according to (1), where all quantities are appropriately weighted.

$$(1) \quad \min \sum ((CF-CF_0)^2 + (T-T_0)^2$$

Where CF_0 = set point for freeness
CF = freeness
And T_0 = setpoint for tear
T = tear
And all quantities are appropriately weighted.

When producing carton pulp the most important quality variables besides CF are bulk and Scott bond. These quality variables can also be controlled. The target is to control the carton pulp production by **maximizing** bulk and Scott bond, or alternatively to **control** bulk and Scott bond.

1.1 The Strategy

The CF-value are most affected by the wood feeding speed, higher speeds give higher CF-value. Tear is most affected by the peripheral speed, higher peripheral speed gives lower tear. That is, a sharper stone requires lower feeding and peripheral speeds for obtaining same quality as with a more dull stone. If the CF-value and tear are controlled, feeding and peripheral speeds automatically raises when the stone will be duller, and normal or higher production as a result.

In the control experiments freeness sink due to the dulling to 50, but the controller increased CF to its set point 100, after tree measurements of CF and increasing of the feeding speed (from 0.5 to 1.2 mm/s). By that a higher production and better quality could be reached because the dulling of the stone (See Figure 7). The production (feeding speed) was in this case increased with 140 %. The feeding speed is direct proportional to the production, so increased feeding speed means same increased production (same increased % in tons of the production).

The variations in freeness because sharpening or dulling can be avoided by controlling the process with on-line control. By that can maximal speeds always be kept on target quality (freeness) level. It can be easy to reach 10-20% higher production, especially with adjustable motors and tear control, without risking the pulp quality, even when striving for higher feeding speed. The control should by that be safe.

The advantages of the control strategy can also be motivated with the work of Fagerhed (1990) and the examine work of Lundgren (2001).

- Up to 30-40% better tear
- Better tensile
- Better light scattering and brightness
- Larger production
- Possible savings in bleaching chemicals
- Possible energy savings

1.2 An alternative strategy

You should not strive to bigger production for example due to the demand or the capacity of the paper machine. This can be obtained by increasing the tear set point, which results in lower peripheral and feeding speed. A *lower peripheral speed saves energy,* and a *higher tear saves cellulose*. If higher CF-values are allowed, it is also possible to keep normal or higher production (see Figure 6).

In both cases:

- ❑ The production increase strategy
- ❑ The energy saving and cellulose saving strategy

$ The payback for the investment should be under one year and the productivity should be 10-30% better than without investment.

2 The goals

The goals can be striving to *higher production* (up to 30%) according to the strategy in section 1.1.

Or

Striving to *save energy* and *cellulose* with *same* or *bigger* production according to the alternative strategy in section 1.2

In both cases the saving and production increase means up to **0.25 billion** € in a perspective of 10 years.

For the whole plant including the paper machine and the final paper product it means **0.5-1.5 billion** € better result depending on paper quality, which means **together 1.8 billion** € if there are energy and cellulose savings. The **1.5** billion comes because the final product price is 3 times higher than expected price of ground wood pulp and the amount is up to 2.5 times the pulp amount because filling material and cellulose.

Check the profitability calculations in the appendix of the enclosed project report (the last page).

3 The Control Theory

3.1 The Model

The used model is linear, with possible static nonlinearities.

(3) $y_i = a_{i,1}u_1 + a_{i,2}u_2 + b_i$

Where y_i is dependent variable (e.g. CF) and u_1 and u_2 are independent variables (the peripheral speed and wood feeding speed). Static nonlinearities are obtained received by transforming these variables, for example by logarithming all variables the following model is obtained:

(4) $y_i = b_i u_1^{a_{i,1}} u_2^{a_{i,2}}$

The model (4) is similar to equations found in the literature (Bergström 1957, Paulapuro 1976, Fagerhed and Lönnberg 1988). The parameters of the model can be estimated from the experiments by linear regression.

3.2 The Controller

The models above can be used for development of a controller. It's assumed that the measurement delay is so long (on-line measurements takes about half an hour) that other considerably faster dynamics can be neglected. By that the dynamic model is the following.

(7) $\mathbf{y}(t+1) = \mathbf{A}\mathbf{u}(t) + \mathbf{b}$

The parameters of the model are here collected in a matrix **A** and a vector **b**. The dependent variables y_i have been collected in a vector **y**, and the independent variables u_1 and u_2 are collected in a vector **u**. The following input nonlinearities were used

(8) $$\mathbf{u} = \begin{bmatrix} v_p^2 \\ \sqrt{v_n} \end{bmatrix}$$

The role of the controller is to control the dependent variables using the independent variables. In this context dependent variables are denoted output-signals and independent variables are denoted input-signals.

It was found beneficial to filter the measurement values, which reduce the effect of the measurement errors. A first order filter was used, in this case the filtered measurement value y_f is given by the following equation:

$$y_f\,(t+1) = 0.5\ y(t+1) + 0.5 y_f(t)$$

With two input-signals two output-signals be controlled freely, at least in principle. That is, freeness and tear can be controlled using wood feeding speed and peripheral speed. The control is only limited by the limits of wood feeding speed and peripheral speed.

The controller was designed to minimize the following Linear Quadratic (LQ) perfomance objective, which is a more applicable version of (1):

(9) $$\sum_t (\mathbf{y}(t)-\mathbf{r}(t))^T(\mathbf{y}(t)-\mathbf{r}(t)) + (p\Delta\mathbf{u}(t))^T(p\Delta\mathbf{u}(t))$$

Here **r** is set point, $\Delta\mathbf{u} = \mathbf{u}(t)-\mathbf{u}(t-1)$, and p is a factor which is used to damp variations in the inputs. An LQ-optimal controller can be calculated off-line, and on-line optimization is not necessary. The tolerance against model errors was increased using a Glover-McFarlane robustification, which allows lower p-values and faster controllers. This works better than robustification using only the p-value.

3.2.2 Control of three output-signals

When producing carton pulp we are interested of the CF-value, bulk and Scott bond. With two input-variables it isn't possible to contol three output-signals freely. A suggested strategy is to control freeness according a desired set point, and maximise bulk and Scott bond. This strategy requires an on-line optimising controller. In this case, the optimisation problem can be simplified due to the scalar dynamics. One degree of freedom is used to control CF, and the other degree of freedom is used for maximisation of bulk and Scott bond. This strategy doesn't need on-line measurements of bulk and Scott bond, only of the CF-value.

The alternative strategy is to use a controller which do a least-square-compromise, where all three output-signals can be controlled. This strategy is easier and clearer from the control aspect than the maximizing strategy above, but it needs on-line measurements of bulk and Scott bond.

The experiments with three outputs are presented and interpretated in Section 5 in the project report.

4 Why a new control method and how was this done earlier?

The advantages of the new control method were discussed already in the introduction:

- Bigger production
- Better quality (better tear, tensile, brightness and light scattering)
- Energy savings
- Cellulose savings

$$$ These points mean definite saving of money or extra dollars from higher production

Besides that the control can give safer production, when it is known what quality is produced and that the controller steers the quality in a wanted direction.

Earlier freeness was measured only once per day or once per week and whatever could happen in the quality between the measurements, which was repaired with a lot of cellulose. Alternatively can the wood feeding speed be kept low, and the production could be up to 50% lower than it could be. (See the feeding speed in figure 7.)

4.1 Sharpening

The presented control method can be combined with an on-line stone sharpening method. On-line sharpening can be considered as feed forward control, knowledge of a disturbance (dulling of the stone) is compensated with sharpenings. However, the effect of the sharpening cannot be exactly known, and the dulling of the stone is not the only source of disturbance, so such a feed forward technique should in principle always be combined with feedback control. Measurements of the controlled variables can be fed back to a controller, which automatically adjusts peripheral and feeding speeds until wanted quality is obtained.

5 Experiments

The Åbo Akademi grinder (Fagerhed 1987) was used in the experiments. The grinding zone is 40 mm x 40 mm and the length of the feeding chamber is 500 mm. A hydraulic cylinder feeds the wood pieces against the grinding stone. The feeding speeds can vary between 0-3 mm/s. The peripheral speed of the grinding stone can be chosen between 0-50 m/s. The pressure can be chosen between 0-5 bar, and the maximal temperature of the shower water is 150 °C.

The quality measurements was done with a Pulp-Expert analyzer. The correlation coefficient r (the correlation between laboratory measurements and Pulp-Expert measurements) was 0.903 for tear. The standard deviation between laboratory measurements and Pulp-Expert measurements was 11% for tear. The CF measurements were considered more exact than the tear measurements, and only the CF-level were adjusted according laboratory measurements.

5.1 Experiment results

The experiment results are based on experiments done with the 2-variable controller (5) for the SC, LWC and Newsprint processes, and the 3-variable controller (6) for the carton process.

The results are presented in figures 5-12 in the enclosed project report where the result is deeper analyzed.

As a summary can be said that both the 2-variable controller and the 3-variable controller worked well in different conditions . The 2-variable controller in both atmospheric pressure and 2.5 bars pressure with target freeness levels from 70-200 ml and the target set points could be reached in 3 steps (measurements/samplings). The tear control is a bit slower (of safety reasons), but the important is that strategic advantages can be reached (energy saving cellulose saving and reched possibilities to larger production compared with constant peripheral speed.)

Tear could be raised with 30-40% with lower peripheral speed and by that can cellulose and energy be saved (see the appendix to the project report).

The 3-variable controller for carton worked also well in different conditions (variations in sharpness, different freeness levels).

But the most important was that wanted goals could be kept (target freeness level, a minimum scott bond level, a necessary bulk level) and from that could the economy be optimized, see figures 11 and 12 and the profitability calculations in the appendix of the project report.

6. Economical aspects

The economy of the method is shown in the goals in sections 1.1 , 1.2 and 2. And in the appendix and section 6 in the project report.

The savings and production increasings can go up to 0.25 billion (€) for the grindery and 1.5 billions because increased production of the end product.

7. Conclusions and recommendations

My recommendation is that a company with possibilities and a suitable grindery which is willing to develope its activity both technically and economically should applie the presented control methods. Maybe first only using freeness control without motor update, and then verify the advantages with one new motor (economically supported by ABB). And, if these industrial-scale results also are satisfactory, continue with the rest of the grindery.

8. Summary

The grinding process was investigated, and the possibilities for multivariable control of the process were studied. The economical benefits were also considered.

As a result it was found that the process could be controlled by a multivariable controller, according to obtained models, experiences with on-line measurement, and laboratory-scale control experiments.

A 2-variable controller was designed for the SC, LWC and Newsprint processes, and a 3-variable controller for the carton process. Suitable and reliable controllers were developed in all cases.

We are satisfied with the obtained results. The pulp quality variables in the grinding process are somewhat difficult to measure accurately, but they are otherwise simple to control due to the simple dynamics of the process. Much work has been put on safety and reliability, and the controllers are ready for application in industrial-scale processes.

The economically advantages are not the only reasons for an application of this control strategy, and this opportunity is also given to your competitors.

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