SHEET THICKNESS CONTROL SYSTEM OPTIMIZATION THROUGH MATHEMATICAL MODELLING AND SELF-LEARNING PUMP MAPS

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ABSTRACT

Well performing sheet thickness control systems allow for significant raw material savings in fibre cement production and reduce tool costs and dust generation in sheet finishing. State-of-the-art thickness controls measure the layer thickness early in the process and incorporate felt speed and slurry density control. Density disturbances in the board machine feeding can be minimized by pilot felt speed control, backed up by mathematical process models being continuously calculated as a process simulation in the programmable logic controller (PLC).

A general problem with sheet thickness control is the linked structure of the various controllers involved for tank filling levels, slurry throughput, felt speed and slurry density. Time lag and mutual dynamical influences lead to increased sheet thickness tolerances under certain operating conditions such as plant start-up or e.g. in the event of process disturbances by changes in flocculation efficiency or increasing pipe clogging.

Here considerable improvements can be achieved by the application of characteristic map based controls for the involved slurry pumps. During regular plant operation, the relationship between pump rotor speed and slurry flow can continuously be evaluated by the PLC. As an add-on to the existing standard controllers, self-adjusting pump maps can be utilized to instantaneously set pump speeds as a pilot control. This shortcuts time lags and allows for more consistent slurry densities during compensation of process disturbances.

In addition to optimising the sheet thickness tolerance, dynamic pump maps can furthermore be utilized to monitor the equipment maintenance status and to increase plant availability.

KEYWORDS:

sheet thickness control; centrifugal pump; flow control; control engineering; Hatschek machine

INTRODUCTION

The creation of uniform product thicknesses in the manufacture of fibre cement boards is desirable as it allows for significant raw material and energy savings in the sheet production, dust reduction in the product post-processing and better product performance in its application.

Basis for the production of consistently thick product on Hatschek-type fibre cement machines is a stable water and slurry circulation with a well-controlled and consistent slurry feeding into the process. This control shall on one hand operate stably and evenly when the process is in equilibrium, but shall on the other hand react quickly and targeted when process disturbances occur.

An earlier paper entitled “Sheet thickness control system optimisation by mathematical modelling and simulation” (Becker, 2018) describes how feed density and felt speed can simultaneously be utilized as control variables for fast- and long-term system response. Furthermore, it explains feed-forward pilot felt speed control and its function to compensate undesired feed slurry density deviations by time adapted felt speed adjustments. The mentioned elements can be found in **Figure 1**, showing the architecture of the overall sheet thickness control system setup in Wehrhahn fibre cement production plants.

This article focusses on methods to optimize the feeding pump flow controller as the central element in Wehrhahn sheet thickness control systems, marked with a blue frame in **Figure 1**. It explains how a mathematical model of the system can be used to achieve more steady overall production conditions by generating an as much as possible consistent feed density in the homogenizer tank and consequently a minimization of compensatory adjustments by the felt speed controller at the sheet production machine.

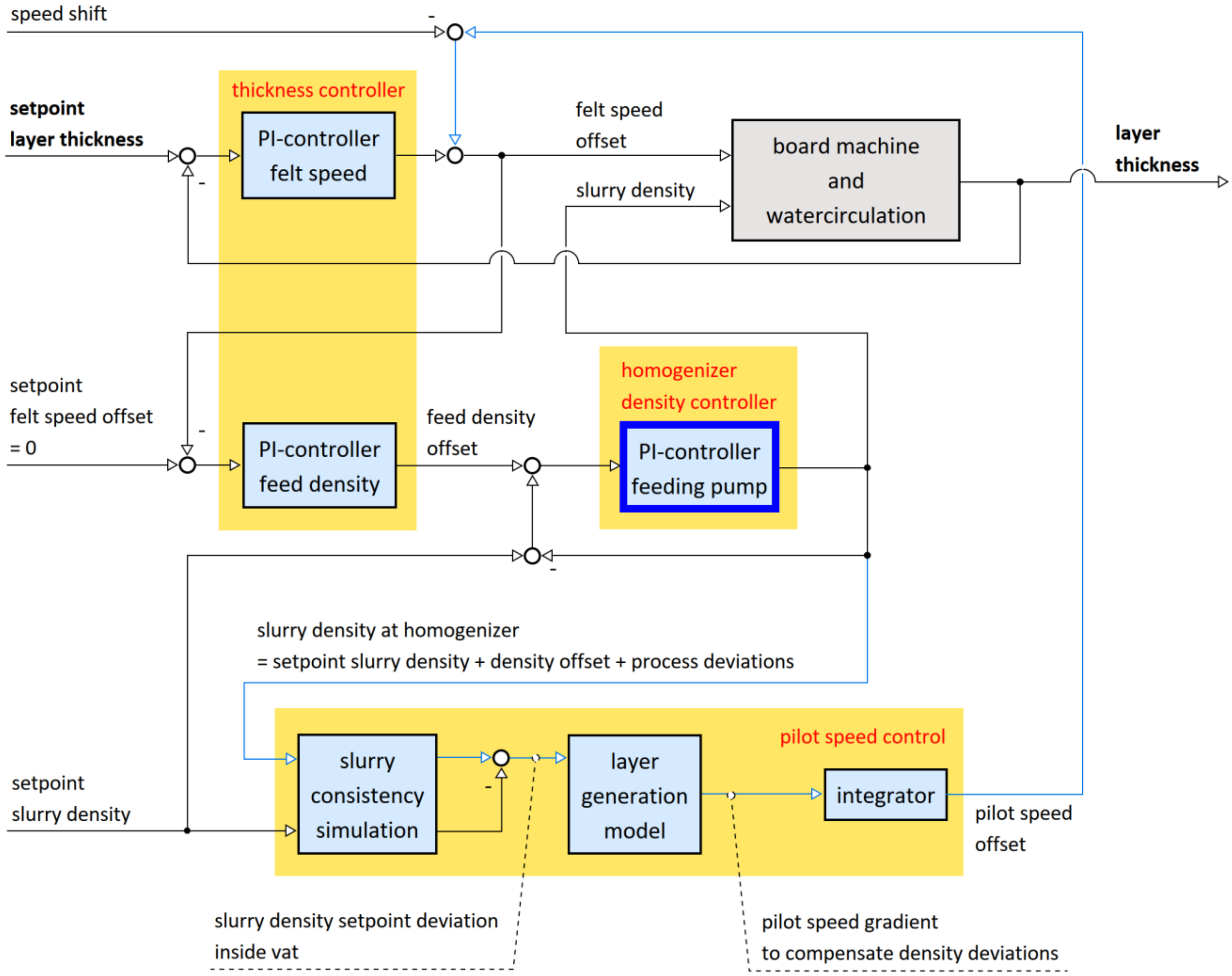

Figure 1 – Wehrhahn sheet thickness control system setup

FEED DENSITY AT HOMOGENIZER TANK AND FRESH SLURRY FEEDING PUMP CONTROL

Feeding pump target flow rate calculation

The homogenizer tank is a continuous mixer, typically receiving three main slurry flows: the *backwater flow* from the board machine, the *recuperator return slurry flow* and the *fresh slurry flow* from the stock tank.

The quantities of the backwater flow and the recuperator return slurry flow are usually measured by magnetic flow meters. Their solids content or slurry density can either continuously be measured or estimated. With the slurry density of the fresh slurry being known from the upstream mixing process, the PLC can calculate its required target feeding flow rate into the homogenizer tank by evaluation of a mass balance equation.

The homogenizer density controller therefore consists of a density-to-feed-flow calculation and a fresh slurry feeding pump flow controller.

Pump types

Commonly used pump types for fresh slurry feeding in fibre cement production are

- peristaltic pumps (also known as roller pumps or hose pumps)
- progressing cavity pumps (also known as eccentric screw pumps)
- scoop wheels (also known as bucket wheel or noria)
- centrifugal pumps

Positive displacement pumps such as the first three pump types listed above offer the advantage of the flow rate being directly proportional to the pump speed. They, however, have also a number of disadvantages such as wear- and-tear issues, efficiency issues, pulsation or being sensitive to material sizing. Due to its simplicity and reliability the centrifugal pump is the most commonly used pump type for fibre cement slurry feeding.

Centrifugal pump properties

Centrifugal pumps show a non-linear relationship between pump speed, output pressure and flow rate. Their performance is often characterized in curve maps as **figure 2**, showing the pump head h_{pump} over the flow rate $\dot{V}$ for different pump speeds n. Pump manufacturers often provide these diagrams in graphic form with their product documentation.

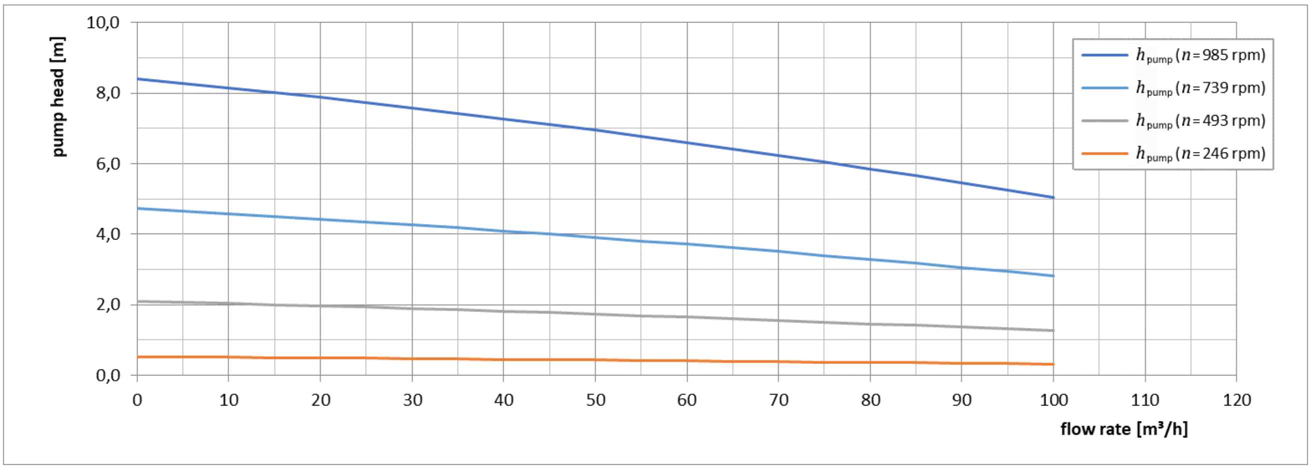

Figure 2 – characteristic curve map

At nominal pump speed n_{max} the pump head $h_{\text{pump,max}}(\dot{V}; n = n_{\text{max}})$ typically shows a theoretical maximum at zero-flow. With increasing throughput this delivery height decreases due to flow friction losses inside the pump. Usual curve shapes are characterized by a pump head decrease, proportional to the square of the flow rate, which indicates a similar effect to pressure losses in pipelines. Based on the typical curve shape, here a polynomial mathematical approach is used to approximate the pump head at nominal pump speed $h_{\text{pump,max}}$ as

$$h_{\text{pump,max}} = a \cdot \dot{V}^2 + b \cdot \dot{V} + c \qquad (1)$$

with the characteristic constants a, b, and c and the actual flow rate $\dot{V}$.

For a given constant flow rate $\dot{V}$, the pump head $h_{\text{pump}}(\dot{V} = constant; n)$ raises with increasing pump speed. Considering the centrifugal force as the pump-driving effect being proportional to the square of the circumferential speed, here the following equation is utilized to approximate the pump head within the pump speed range from zero to nominal speed $0 \leq n \leq n_{\text{max}}$

$$h_{\text{pump}} = h_{\text{pump,max}} \cdot \left(\frac{n}{n_{\text{max}}}\right)^2 = \left(a \cdot \dot{V}^2 + b \cdot \dot{V} + c\right) \cdot \left(\frac{n}{n_{\text{max}}}\right)^2 \qquad (2)$$

This *pump model (2)* is the basis for the curve map in **Figure 2**. It shows the pressure behaviour of the pump as a function of pump speed and flow rate, but without consideration of the surrounding system in which it is installed.

Centrifugal pump control system setup

The typical setup of a slurry feeding system with centrifugal pump is shown in **figure 3**. A pipeline with the length l, the inner diameter d and the resulting pipe cross section $A = \frac{\pi}{4} \cdot d^2$ is connected with the outlet of the *stock tank* as the source tank and has an open end above the *homogenizer tank* as the target tank.

In state ① close to the pipe inlet the slurry with the density ρ is approximately at rest. Within the pipeline and at its outlet in state ② the slurry moves with the cross-sectional average speed u. Depending on the current slurry level inside the stock tank, the static height h is to be overcome.

The *actual flow rate* $\dot{V}$ inside the pipeline is continuously measured by a flow meter and compared with the *target flow rate*, resulting from the above described slurry density calculation for all inflows into the homogenizer tank. The deviation between both values is evaluated by the PI-controller (Proportional-Integral controller) which adjusts the rotational speed n of the slurry feeding pump appropriately in order to achieve the flow rate target.

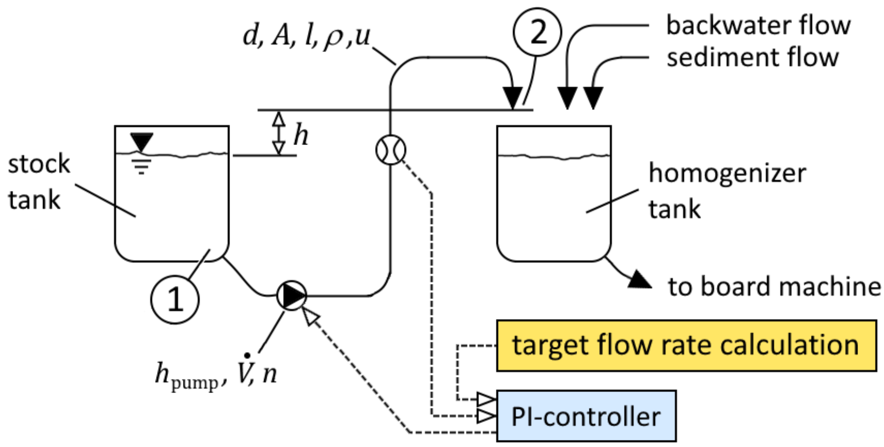

Figure 3 – slurry feeding pump setup

SLURRY FEEDING PUMP SYSTEM MODELLING

A mathematical model representing the involved process components is a useful tool to determine suitable controller parameters. Setting up the model as a time-discrete numerical computer simulation allows to evaluate different controller settings in a much easier and faster way than by optimizing them on the real machine.

For the slurry feeding pump setup shown in **figure 3**, the application of Bernoulli's equation for unsteady flows (Grote, 2007, page B47) under consideration of pipe friction delivers the differential equation

$$\dot{u} = \frac{1}{l} \cdot \left\{ -\left(\lambda \cdot \frac{l}{d} + \zeta \cdot n_{\mathrm{b}} + 1 \right) \frac{u^2}{2} + g \cdot (h_{\mathrm{pump}} - h) \right\} \qquad (3)$$

with

the slurry speed u ,

the slurry acceleration $\dot{u}$,

the driving influence of the pump head $g \cdot h_{\mathrm{pump}}$, the influence of the static height between source tank slurry level and slurry pipe outlet $-g \cdot h$,

the dynamic pressure influence due to the slurry outlet speed $-\frac{u^2}{2}$ and

the pipe resistance influence $-\left(\lambda \cdot \frac{l}{d} + \zeta \cdot n_{\mathrm{b}}\right) \frac{u^2}{2}$

with the pipe friction coefficient λ, the pipe bend coefficient ζ and the number of bends n_{b}.

The above differential equation can as well be derived by applying Newton's law of motion on the slurry mass inside the pipeline, which leads to the same result.

Given

$$\dot{u} = \frac{du}{dt} \approx \frac{\Delta u}{\Delta t} \tag{4}$$

an iterative calculation for small time steps Δt can be used to approximate the flow speed $u(t + \Delta t)$ as

$$u(t + \Delta t) = u(t) + \Delta u \approx u(t) + \dot{u} \cdot \Delta t \tag{5}$$

With the differential equation (3) and the slurry feeding pump model (2), the dynamic properties of the slurry feeding pump setup are completely described. After combining these with a further differential equation for a PI-controller and a set of starting conditions, the system can be numerically simulated to determine the temporal behaviour of the cross-sectional average slurry speed u, or respectively the flow rate $\dot{V}$ as

$$\dot{V} = A \cdot u \tag{6}$$

To assess the controller performance, the system reaction to a *target flow rate step function* as the result of such simulation is shown in **Figure 4**. Yellow marks the target flow rate, jumping up from 0% to 90% of the maximum flow rate at 0 seconds. After 120 seconds the target flow is rapidly reduced from 90% to 80%. Grey displays the control deviation as the PI-controller input. Red is the PI-controller output. Blue shows the actual pump speed including ramp delay, drawn as a percentage of the maximum pump speed. Light green reflects the real flow rate as delivered by the pump as a percentage of a reference flow. Dark green visualises the flow rate signal, as sent from the flow meter to the controller, here modelled as a PT1-link with a damping time of 3s.

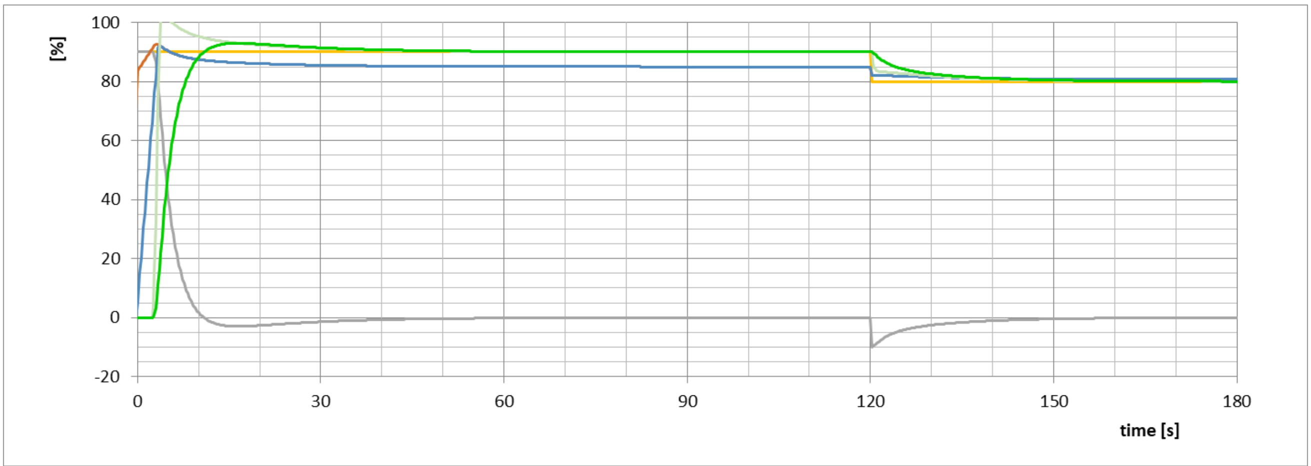

Figure 4 – slurry flow response to a rapid start and target drop with best possible PI-controller parameters

Figure 5 displays the dynamic behaviour of the same pump setup with non-ideal controller parameters. At start-up, the target flow rate is reached slower than in **Figure 4**. During the target drop, a significant undershooting of the desired flow rate is observed (light green), even if the detected flow rate (dark green) shows the deceiving picture of an ideal control dynamic.

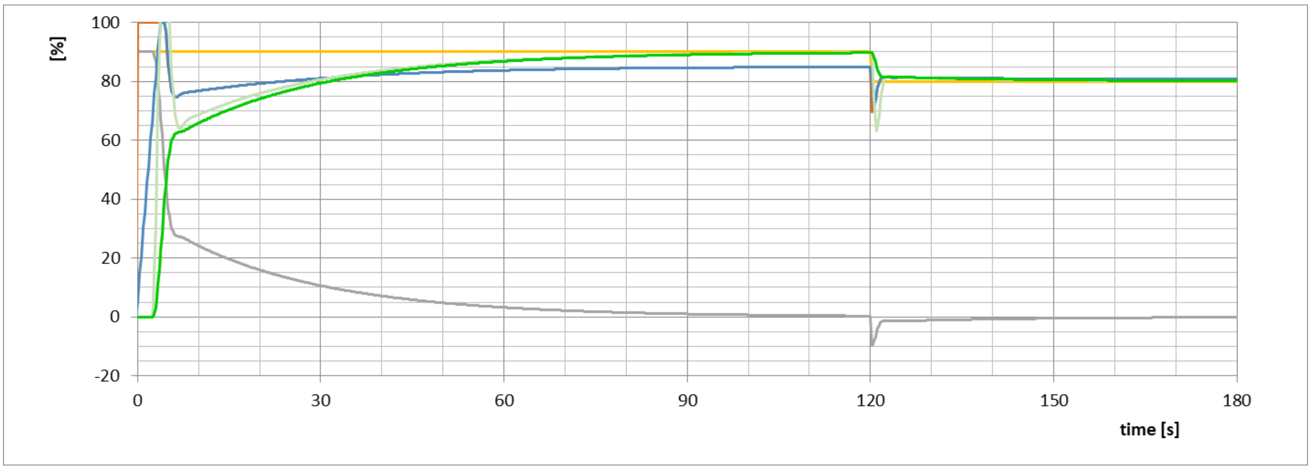

Figure 5 – slurry flow response to a rapid start and target drop with non-ideal PI-controller parameters

SLURRY FEEDING PUMP SYSTEM IN STEADY-STATE OPERATION

Prediction of the required pump speed and pump pilot control

The above diagrams show the dynamic behaviour of the slurry feeding pump system during speed-up or speed-down of the pump with the resulting temporal flow response. During continuous fibre cement sheet production however, the control system keeps the fresh slurry flow rate almost constant and adapts the slurry feeding pump speed only slowly to the changing filling level of the source tank. During this steady-state operation the flow speed u inside the pipeline is about constant and therefore

$$\dot{u} = \frac{1}{l} \cdot \left\{ -\left(\lambda \cdot \frac{l}{d} + \zeta \cdot n_{\mathrm{b}} + 1 \right) \frac{u^2}{2} + g \cdot (h_{\mathrm{pump}} - h) \right\} \approx 0 \qquad (7)$$

Combining this equation with the pump model (2), the required pump speed n for a certain flow rate $\dot{V}$ can be calculated as

$$n = n_{\max} \cdot \sqrt{\frac{\left(\lambda \cdot \frac{l}{d} + \zeta \cdot n_{\mathrm{b}} + 1 \right) \cdot \frac{\dot{V}^2}{2 \cdot g \cdot A^2} + h}{a \cdot \dot{V}^2 + b \cdot \dot{V} + c}} \qquad (8)$$

Assumed that the map-determining constants a, b and c are correctly chosen to describe the pump behaviour, the *pump system model* equation (8) allows to predict the necessary pump speed to achieve a certain flow rate $\dot{V}$ in steady-state. The equation is valid for any static height h and therefore for any filling level of the source tank. It can be used to set up a feed-forward pilot control to keep the slurry feeding pump on optimal speed for all required flow rates and source tank levels. An additional PI-controller is then only required to compensate deviations between the pump system model and reality.

Flow-rate-over-pump-speed map in steady-state

If the performance of the complete pump setup including pipeline and source tank shall be visualized or if the flow rate for a certain pump speed shall be calculated, then the reverse function $\dot{V}(n; h)$ of equation (8) is of interest. It can be derived with the method of *completing the square* (Merzinger, 1993).

By transforming the pump system model (8), the following equation can be obtained

$$\left\{a-\left(\frac{n_{\max}}{n}\right)^{2}\cdot\frac{\left(\lambda\cdot\frac{l}{d}+\zeta\cdot n_{\mathrm{b}}+1\right)}{2\cdot g\cdot A^{2}}\right\}\cdot\dot{V}^{2}+b\cdot\dot{V}+\left\{c-\left(\frac{n_{\max}}{n}\right)^{2}\cdot h\right\}=0 \tag{9}$$

Here the terms

$$P=a-\left(\frac{n_{\max}}{n}\right)^{2}\cdot\frac{\left(\lambda\cdot\frac{l}{d}+\zeta\cdot n_{\mathrm{b}}+1\right)}{2\cdot g\cdot A^{2}} \tag{10}$$

$$Q=b \tag{11}$$

$$R=\ c-\left(\frac{n_{\max}}{n}\right)^{2}\cdot h \tag{12}$$

can be summarized to solve

$$P\ \cdot\ \dot{V}^{2}+Q\ \cdot\ \dot{V}+R=0 \tag{13}$$

as

$$\dot{V}=-\frac{Q}{2\cdot P}+\sqrt{\frac{Q^{2}}{4\cdot P^{2}}-\frac{R}{P}} \tag{14}$$

This conversion of the pump system model (8) delivers the pump flow rate as a function of the pump speed and the actual static height $\dot{V}(n;h)$ in steady-state, shown in **figure 6** for an empty, a half-filled and a full source tank. The curves for every filling level start at a minimum pump speed at which the slurry can just reach the level of the outlet pipe at zero-flow. With increasing speed, the gradient of the flow decreases due to rising flow losses in pipeline and pump. This is the reason why different controller parameters for lower and higher flow rates prove to be optimal in a standard PI controller setup. For a quick controller response without undershooting, the controller-gain needs to be increased for higher flow rates.

In case of a feed-forward pilot control as described above however, a gain-adaption is not necessary as the system properties are already mapped with the application of equation (8).

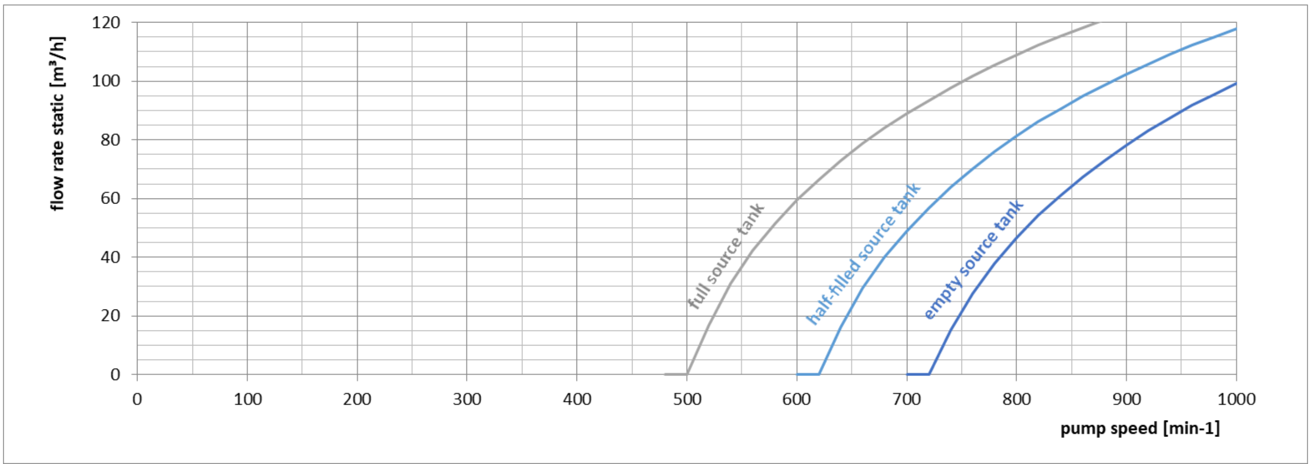

Figure 6 – flow-rate-over-pump-speed map for the slurry feeding pump setup

SELF-LEARNING ADAPTATION OF CHARACTERISTIC PUMP CURVE MAPS

Physical meaning of the characteristic constants *a*, *b*, and *c*

In the pump model equation (2), the three characteristic constants a, b, and c define the behaviour of the pump head with changing flow rate and pump speed. These constants can be determined by a polynomial regression if a graphic characteristic pump map is available with the pump manufacturers documentation. The constants a and b determine the pump head reduction with increasing flow rate $\dot{V}$. They are therefore negative.

But the characteristic constants also have further physical meanings. From equation (1) can be seen that $h_{\text{pump,max}}(\dot{V} = 0) = c$. The reverse function of the pump system model (9) with the flow rate $\dot{V} = 0$ delivers

$$c = \left(\frac{n_{\max}}{n}\right)^2 \cdot h \qquad (15)$$

With the highest possible *zero-flow pump speed* at a given static height h known, c can directly be calculated.

Deriving equation (1) after the flow rate leads to

$$h'_{\text{pump,max}} = 2 \cdot a \cdot \dot{V} + b \qquad (16)$$

Therefore $h'_{\text{pump,max}}(\dot{V} = 0) = b$ characterizes the gradient of the pump pressure at zero-flow and it approximates the pump pressure decrease for low flow rates.

Due to the influence of the square of the flow rate $\dot{V}$ in the pump model equation (2), characteristic constant a mainly drives the pump pressure decrease for high flow rates.

Adaption of characteristic constants *a*, *b*, and *c*

Whenever the slurry feeding pump system is in steady-state, operation points $(\dot{V}; n)$ can automatically be logged by the PLC. Each operation point can be compared with the calculated pump speed according to equation (8) for that respective flow rate. Depending on the position within the flow rate range $0 \leq \dot{V} \leq \dot{V}_{\max}$, the characteristic constants a, b, and c can be trimmed by an iterative calculation to achieve a closer approximation of a dynamic pump model with the real system properties:

For $0 \leq \dot{V} \ll \dot{V}_{\max}$, mainly <u>constant c</u> shall be trimmed to a new value c^*, constant b is kept unchanged and constant a can be recalculated to a^* with

$$a^* = a + \frac{c - c^*}{\dot{V}_{\max}{}^2} \qquad (17)$$

to keep $h_{\text{pump,max}}\left(\dot{V} = \dot{V}_{\max}\right) = constant$ and $h'_{\text{pump,max}}\left(\dot{V} = 0\right) = constant$ for this trimming step.

For $0 \ll \dot{V} \ll \dot{V}_{\max}$, mainly <u>constant b</u> shall be trimmed to a new value b^*, constant c is then kept unchanged and constant a need to be recalculated to a^* with

$$a^* = a + \frac{b - b^*}{\dot{V}_{\max}} \qquad (18)$$

to keep $h_{\text{pump,max}}\left(\dot{V} = 0\right) = constant$ and $h_{\text{pump,max}}\left(\dot{V} = \dot{V}_{\max}\right) = constant$ for this trimming step.

For $0 \ll \dot{V} \leq \dot{V}_{\max}$, mainly <u>constant a</u> shall be trimmed to a new value a^* and constants b and c are kept unchanged to hold $h_{\text{pump,max}}\left(\dot{V} = 0\right) = constant$ and $h'_{\text{pump,max}}\left(\dot{V} = 0\right) = constant$ for this trimming step.

During pump model adaptation two secondary conditions need to be considered to keep the characteristic constants a^* and b^* within a suitable range. These are $a^*_{\min} < a^* < a^*_{\max}$ and $b^* < b^*_{\max}$.

Figure 7 shows the flow-rate-over-pump-speed map for the slurry feeding pump setup with adapted characteristic constants after being trimmed with a new steady-state operation point, gained with a half-filled source tank.

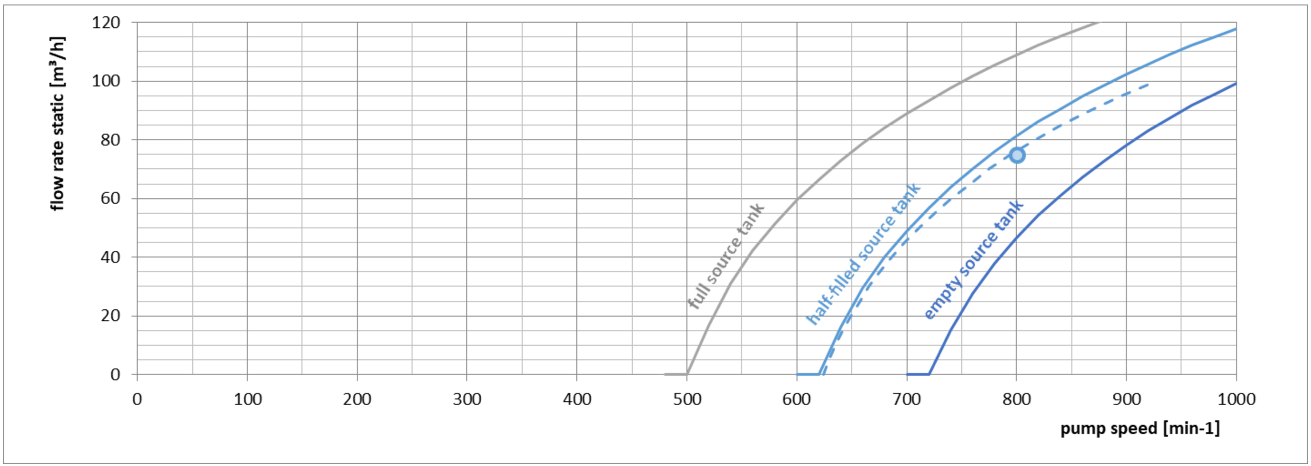

Figure 7 – flow-rate-over-pump-speed map for the slurry feeding pump setup with adapted characteristic constants

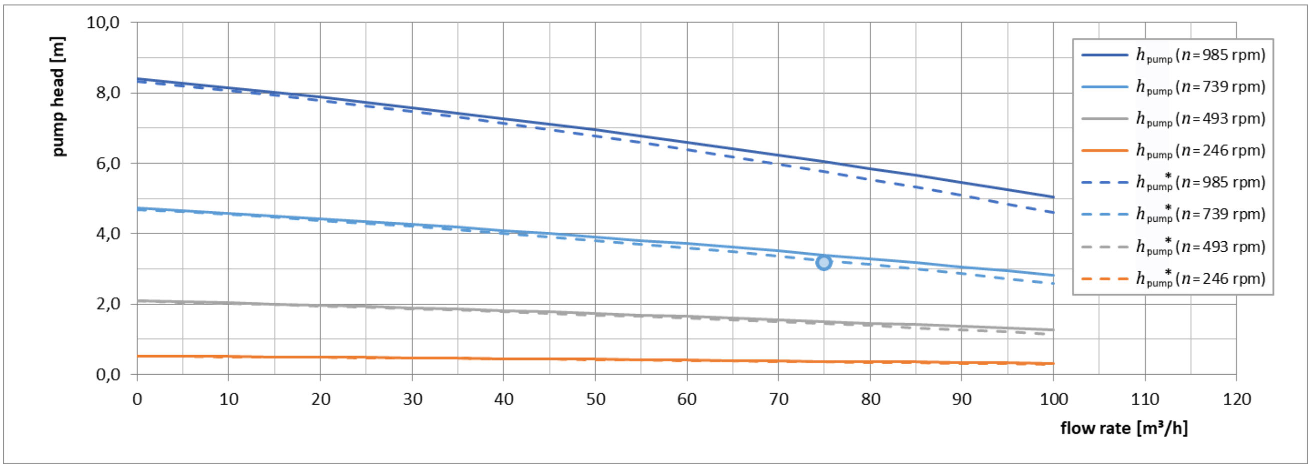

Figure 8 – characteristic curve map with adapted characteristic constants

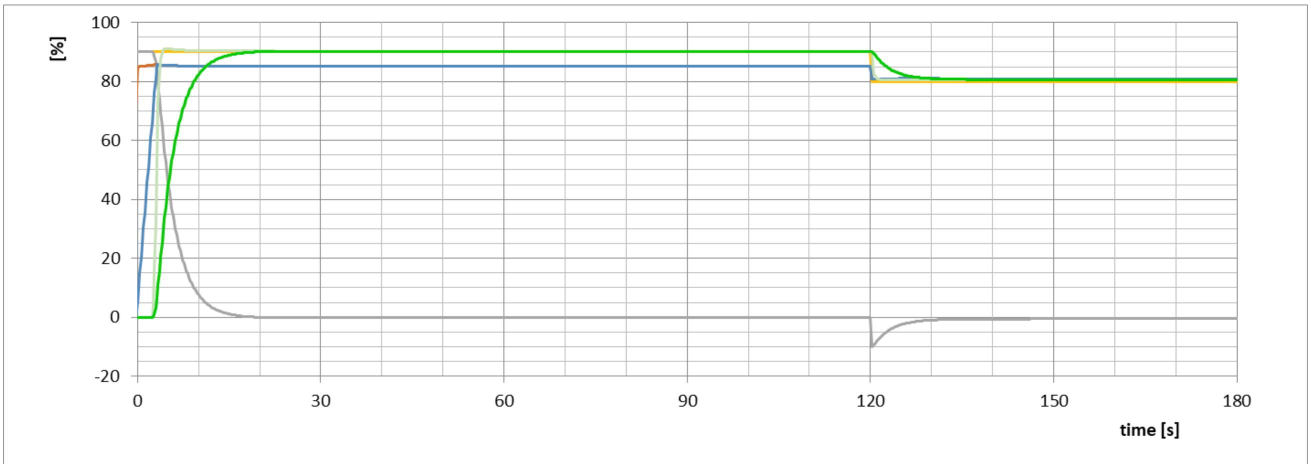

Figure 9 – slurry flow response to a rapid start and target drop with feed-forward pilot pump speed control

Continuous adaption with steady-state-operating points at different flow speeds shapes the pump model to the best fit with the properties of the real system. **Figure 8** is the corresponding adapted characteristic pump curve map with the trimmed pump head curves ${h_{\mathrm{pump}}}^*$ over the flow rate $\dot{V}$ displayed as dotted lines.

If the adapted dynamic pump model is applied as a feed-forward pilot pump speed control according to equation (8), then the dynamic behaviour of the slurry feeding pump setup is even faster and closer to the target flow than with ideal controller parameters. The pilot-control based temporal system behaviour is shown in **figure 9**. The improvement gets obvious when comparing it with **figure 4**.

Monitoring of pump condition and pipeline clogging

The dynamic pump model adaptation as described above trims the characteristic constants a, b, and c. Especially the constant a and constant c can be used to create a warning if the adjustment exceeds certain limits.

Another monitoring option exists during refilling of the source tank of the slurry feeding pump. Whenever the flow rate $\dot{V}$ is kept constant by the pump controller, steady-state operation can be assumed and equation (8) is valid. Rearranging it provides:

$$\frac{a \cdot \dot{V}^2 + b \cdot \dot{V} + c}{{n_{\mathrm{max}}}^2} = \frac{1}{n^2} \cdot \left\{ \left(\lambda \cdot \frac{l}{d} + \zeta \cdot n_{\mathrm{b}} + 1 \right) \cdot \frac{\dot{V}^2}{2 \cdot g \cdot A^2} + h \right\} = constant \tag{19}$$

For pump speed n_1 and static height h_1 before tank filling and pump speed n_2 and static height h_2 after tank filling and with

$$A = \frac{\pi}{4} \cdot d^2 \tag{20}$$

can be found

$$d^* = \sqrt[4]{\frac{16}{\pi^2} \cdot \frac{\frac{1}{{n_2}^2} - \frac{1}{{n_1}^2}}{\frac{h_1}{{n_1}^2} - \frac{h_2}{{n_2}^2}} \cdot \frac{\lambda \cdot \frac{l}{d^*} + \zeta \cdot n_{\mathrm{b}} + 1}{2 \cdot g} \cdot \dot{V}^2} \tag{21}$$

Equation (21) allows an iterative numerical calculation within the PLC to continuously determine the apparent pipeline diameter d^* with the clean pipeline inner diameter d as a starting value.

This apparent diameter d^* can then be used to adapt the system model equation (8) in a similar way as described for the dynamic pump model characteristic constants a, b, and c. Moreover the drifting variable d^* can continuously be monitored by the PLC to predict a possible cleaning requirement for the pipeline.

CONCLUSION

Mathematical modelling of the mechanical systems within the water circulation system of a sheet production machine and their control logic helps to gain in-depth understanding of the dynamic system behaviour. Simulation on basis of the derived differential equations is a useful tool to find optimal parameter settings for the individual controllers involved in a sheet thickness control system and to improve its dynamic behaviour.

The gained equations can furthermore be used to program additional logic into the PLC-system:

- *Pre-calculation of target values* allows for appropriate controller action under changing operation conditions and extremely quick control path reactions. This saves raw materials and energy and helps making better products.
- The introduction of *self-adjusting characteristic parameters* makes it possible to keep the control system operate in an optimal way, even with changing equipment state. The drift of characteristic parameters can be used to predict preventive maintenance requirements and increase plant availability.

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