MODEL PREDICTIVE CONTROL OF A CONTINUOUS KAMYR DIGESTER AT SCA-NORDLINER, MUNKSUND, SWEDEN

Offers basis for better control

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CONTINUOUS DIGESTERS and especially the Kamyr digesters present well-identified control problems. This paper describes Kappa number control, but the method presented can easily be extended to incorporate other control objectives. An introduction to the subject of Kappa number control is given in [1].

Progress in continuous digester control depends on the organization and exploitation of huge amounts of information, including:
- Scientific information (pulping chemistry, reaction kinetics);
- Information from process measurements (production rates, temperatures, alkali charge);
- Specific site information (existing control strategies and experience, digester size etc.).

The dream to be pursued is a control system that makes use of information from all of these sources and is capable of adaptation to improved knowledge in the future. The control system should represent an automated way of using available information for increased profits.

This paper presents the components of a system which realizes some parts of this dream, and documents performance of this system.

CONTROL CONCEPT

The digester control system employs three basic program modules. These are the real-time dynamic model, the state and parameter estimator and the algorithm for optimization.

Advanced real-time dynamic model: The real-time dynamic digester model represents scientific and site specific process information. The model used for real-time control is a simplification of the advanced model presented in [2].

This model represents the digester by dividing it into sections, Fig. 2. The sections may have different volumes, and the total volume of the sections corresponds to the digester volume. Typically, 15 to 60 sections are used. Each section has three regions. These are shown in Fig. 2 as wood substance, entrapped liquid and free liquid.

The model allows the flow of wood chips and entrapped liquid from one section to the section below. The flow rate depends on both the production rate and changes in chip packing in the digester. In addition, there is the flow of free liquid from one section to the section above and/or the section below. Liquid sideward or liquid input is possible for any section. This allows a site-specific configuration of the digester model.

Within each region, there is a set of state variables which define the wood and liquid compositions, and the temperature. The state variables change with time. The rate of change, which is expressed as a set of first order ordinary differential equations, is calculated using mass and energy balances. These calculations employ overall kinetic equations for lignin dissolution.

The model was originally developed at Purdue University, USA. It has been rewritten and extended without changing the basic concepts. Further descriptions of the model are given in [3,4,5].

Simplified real-time control model: The model used for real-time control is a simplification of the model described above, with seven sections. State variables are temperature, effective alkali and residual lignin. This reduces overall computation time for the control system and increases the on-line identifiability of the process.

Off-line simulation with real process data did not show any degradation in performance of the simplified models, compared with the original, large model.

Mathematically the real-time model may be written as a set of first order differential equations:
Optimization Algorithm

A model predictive algorithm was chosen for on-line control. It calculates the values of the manipulated variables given the desired future behavior of the process. These calculations involve a dynamic model of the process.

Model Predictive Control (MPC) has become very popular in the process industry over the last decade, especially in the oil refining industry which has had very good results using predictive algorithms. Well-known algorithms include Dynamic Matrix Control (DMC) [10] and Model Algorithmic Control (MAC) [11,12]. In most cases these algorithms are based on models developed from process experiments only.

The pulping process has many sources of disturbance. This makes it very tedious, yet possible, to identify the correct responses of the manipulated variables and of the most important measured disturbances. The inhomogeneous reaction material, wood chips, gives the process poor repeatability and “season-dependent” behavior. This suggests that the essence of process dynamics must be captured by other means.

In our case the process dynamics are represented through a real-time mechanistic model, continuously updated with information from process measurements by the state and parameter estimator.

The control algorithm is based on a linearization of the real-time model. The linearization takes place every time step, compensating for nonlinear effects and the effect of measured disturbances. The control algorithm develops as follows:

\[ y(k+1) = y(k+1 | u(k)) \]
\[ y(k+1) = y(k+1 | u(k)) + D(k) B(k) \Delta u(k+1) \]

In general:

\[ y_c(k+p) = y_c(k+p | u(k)) + \sum_{j=1}^{p-1} D(k) \Delta u(k+p-j) \]

where

\[ \Delta u(k+i) = u(k+i) - u(k) \]

The first term of the right hand side of equation (5) is the autonomous contribution to the prediction horizon, that is the contribution from past changes in manipulated variables. It is calculated using the linearized model and error corrections from the estimator assuming manipulated variables remaining constant after time k.

The second term on the right hand side of equation (5) is the contribution from future changes in the manipulated variables. This term is calculated using the linearized model. The coefficients of the term form the impulse response of the model.

Substituting the left hand side of equation (5) with the desired setpoints gives:

\[ A \cdot \Delta u = e \]

The optimal manipulated variables are found through the solution of the following quadratic programming problem which is used in [13]:

\[ \text{Min } F = \frac{1}{2} \Delta u^T H \Delta u - G \cdot \Delta u \]

\[ \Delta u_{min} < \Delta u < \Delta u_{max} \]

\[ C \cdot \Delta u \geq b \]

\[ G = A \cdot W^T \cdot W \cdot e \]

\[ H = A \cdot W^T \cdot W \cdot A \]

FIG. 1. CONCEPT FOR DIGESTER CONTROL.

FIG. 2. THE KAMYR DIGESTER IS DIVIDED INTO SECTIONS.
Finding the least square solution, \( Q \), through quadratic programming, is not always adequate because it enables the consideration of hard process constraints while finding the optimal manipulated variables. When the controller is used on line, the first step in the control horizon is implemented. All the calculations are redone for the next step.

Controller characteristics: The controller is a multivariable, model-based predictive controller. The feedback to the controller algorithm comes from the estimator-compensated real-time model. The controller also includes feed-forward compensation from all measured disturbances provided they are accounted for in the real-time model.

**Implementation**

The system is implemented as a server on a VAX 3400, answering requests coming from the local process computer. Fig. 3. The system services are transparent to the operator.

Any input signal to the model may be selected as a manipulated variable, and any function of the states of the model, including Kappa number and wash-extraction effective-alkali may be selected as controlled variables. System features include online configuration and tuning, and rigorous treatment of manual samples, repeating all calculations from when the sample was taken up to the present.

Problems originating from computer power limitations are not experienced, mainly due to the comparatively slow dynamics of the digester process.

The system in Fig. 3 is installed and running at SCA-Nordliner's paper mill at Munksund, Sweden. The measurements employed by the state estimator are temperature and a manual sample of the Kappa number taken approximately every other hour.

**Results**

An example of typical on-line performance of the combined real-time model and estimator is given in Fig. 4 showing actual on-line behavior of the system compared with manual samples of Kappa number. Typical standard deviations between model predictions and manual samples are between 3 and 4.

Before the on-line test was done, the new MP strategy was compared with the existing PI controller in Fig. 4 through-off-line simulations. The manipulated variable for the PI loop was lower heater outlet temperature, the manipulated variables for the MP controller were lower heater outlet temperature and the flow of alkali to the top of the digester. Real process data were used in the off-line simulations. Results are illustrated in Fig. 5.

As would be expected, the MP controller is superior to the existing controller in the case of a perfect model.

The controller is currently tested online in closed loop configuration. The preliminary reports from the testing are very promising.

**Conclusion**

We consider that the ideas behind the presented system form the basis for future solutions for digester control because more information can be used in a consistent manner.

**Notation**

A - \( A \), \( A \) x \( A \) dimensional matrix containing a special arrangement of impulse response coefficients. It is similar, but not identical to the "dynamic matrix" of reference [10].

b - Right hand side of \( Q \) inequalities.

C - LHS vector of \( Q \) inequalities.

Résumé: Cette communication porte sur l'intégration de différentes sources d'informations et de connaissances du procédé pour obtenir un meilleur contrôle sur machine des lessiveurs continus.

Un modèle mécanique en temps réel compensé par un évaluateur d'état optimal est la base d'une algorithme de contrôle prédictif pour un modèle. Le système complet est implanté et installé, et fait preuve d'un comportement très prometteur. On croit que les idées se trouvant à la base de ce système forment la base des solutions futures dans le domaine de contrôle des lessiveurs continus.

Abstract: This paper addresses the subject of integrating different sources of process information and knowledge to achieve better on-line control of continuous digesters. A mechanistic real-time model compensated by an optimal state estimator, is used as the basis for a model predictive control algorithm. The total system is implemented and installed, showing very promising behavior. The ideas behind the system are believed to form the basis for future solutions within the field of continuous digester control.


Keywords: CONTINUOUS DIGESTERS, KAPPA NUMBER, MODELS, PARAMETERS, VERTICAL DESIGN, ESTIMATION, CONTROL SYSTEMS, ALGORITHMS.

REFERENCES


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