Modeling of the wet end part of a paper mill with Dymola

Gianantonio Bortolin a,∗, Stefan Borg b, Per Olof Gutman c

a Optimization and Systems Theory, Department of Mathematics, Royal Institute of Technology, 100 44 Stockholm, Sweden
b Solvina Nyryda AB, 421 30 Västra Frölunda, Sweden
c Faculty of Agricultural Engineering, Technion-Israel Institute of Technology, Haifa 32000, Israel

Abstract

This paper describes the ongoing research on the physical modeling of AssiDomän paper mill in Frövi (Sweden). This project includes the developing of a Modelica base library for thermohydraulic, pulp and paper systems. Up to now, the model includes the wet end part of the paper process, that is the approaching system from the mixing chests to the cyclone systems, the headboxes and the wires.

© 2003 IMACS. Published by Elsevier B.V. All rights reserved.

Keywords: Paper mill; Modeling; Object-oriented

1. Background

There is a rapidly increasing use of computer simulations in industry to optimize products, to reduce product development costs and time by design optimization, and to train operator. Whereas in the past it was considered sufficient to simulate subsystems separately, the current trend is to simulate increasingly complex physical systems composed of subsystems from multiple domains. This paper describes the modeling of a part of AssiDomän paper mill in Frövi (Sweden). The model was carried out using Dymola an object-oriented simulation program.

AssiDomän Frövi produces 350,000 tons of board per year on one 7 m wide and 250 m long board machine. The board is composed of four plies formed in separated headboxes. Most of the used pulp is bleached and unbleached sulfate pulp produced within the plant.

The process equipment is controlled by local regulators within an integrated digital control system (DCS). There are some 600 local controllers involved in the board machine systems. The primary physical variables, basis weight and moisture, are measured on-line by traversing sensors and controlled by a dedicated computer. All available process information from on-line measurements and laboratory
tests are stored in a database within an advanced mill wide information system called Info. Unfortunately, most of the quality variables relevant for the customers of carton board, such as curl, bending stiffness, printability factors, etc., are not available on-line, but only from laboratory tests. The continuously moving web in the paper machine is rolled up on big rolls (tambours). Approximately every 55 min the operators start an automatic change of tambours. Samples for laboratory test are available from the last part of each roll, and some 20 quality variables are analyzed in the laboratory at different positions in the cross-machine direction. Then, the operator has to compare laboratory values to the nominal values and deviation limits in the product specifications and take the opportune decisions.

In such a complex industrial process, simulation tools are extremely useful since they can contribute to higher product quality and production efficiency in several ways. For example, modifications in the paper mill process could be tested (both statistically and dynamically) in advance in a simulator saving much of the trial and error procedure that is used nowadays. Besides, a dynamic simulator of the process and of its control would allow for a thorough study of different control strategies, and would be an efficient way to tune controllers for new equipments. Finally, a simulation tool can also be a way of training not only the operators but also the production engineers and technicians.

There have been different efforts to develop a simulation tool for the paper board in Frövi. In [1] a quasi ARMA model of the bending stiffness is presented. This model gives sufficient short term predictability but it is unsatisfactory since its parameters may vary considerably, even changing sign. In [2] a second attempt is carried out using grey box modeling. However, it turned out to be unsatisfactory since on some verification data set the standard deviation was good, while the prediction failed on other data sets. Finally, in [3] a more sophisticated grey box modeling was developed with very good results.

This project was financed by Nutek, and it is a joint project between different academical and industrial partners. For more information, the reader can refer to the home page of the project [6].

2. Dymola and Modelica

In the few years of research in modeling and simulation, the concept of object-oriented modeling has achieved a big relevance. Several works have demonstrated how objected oriented concepts can be successfully employed to support hierarchical structuring, reuse and evolution of large and complex models independent from the application domain and specialized graphical formalism.

To handle complex models, the reuse of standard model components is a key issue. But in order to exchange models between different packages an unified language is needed. Modelica is an object-oriented, general-purpose modeling language that is under development in an international effort to introduce an expressive standardized modeling language, see [4] and [5]. Modelica supports object-oriented modeling using inheritance concepts taken from computer languages such as Simula and C++. It also supports non-causal modeling, meaning that model’s terminals do not necessarily have to be assigned an input or output role. In fact, in the last few years it has been proved in several cases that non-causal simulation techniques perform much better than the ordinary object-oriented tools.

Dymola is a simulation tool for modeling of large systems, based on Modelica language. There are already several Modelica libraries intend for use with Dymola for various applications domains, such as multibody systems, hydraulics, thermodynamical systems and chemical processes. Models are hier-
architecturally decomposed into submodels. Reuse of modeling knowledge is supported by use of libraries containing model classes and by use of inheritance. Connections between submodels are conveniently described by defining cuts which model physical coupling. Special constructs are available for defining connection topology of composed models.

3. The pulp and paper library

As a first effort in the project, a Modelica component library with process objects used in paper mills was created. The initial focus was to model the wet-end part of the machine. This is basically a large hydraulic pipe network, consisting of open tanks, pipes, valves, pumps and specialized objects like pressure screens and pulp cyclones.

The wet end is of special interest from a system point of view because it contains dynamics of many different time scales, from orders of fractions of seconds (fast opening of valves) to hours, even days (slowly varying concentrations in the long circulation). This causes obvious problems when shifting the plant between different operating points.

Currently, the following component models have been implemented in the library:

- Pipes, valves, pumps and tanks. These are basic components that make up the hydraulic flow networks.
- Cyclones and screens (separators).
- Headbox and wire sections.
- Heat exchangers, heaters and coolers
- DCS objects like pressure and flow indicators, PID controllers, etc.
- Dry end objects like press section and steam dryers are under development.

Dymola supports encapsulations of models in graphical ‘units’, that can be stored in hierarchical graphical libraries. Drag and drop techniques are used to assemble the complete model from the library objects. Fig. 1 shows a Modelica object library in Dymola.

Modelica object-oriented language details was used in the development of the models. First, the different process objects required to model the wet-end were defined. Then, the physical connections between

![Fig. 1. Models are stored in class library.](image)
the objects were identified. Modelica allows these interfaces to be described in special classes, called connectors. Besides, the inheritance construct was used to create base classes that can be reused in several different objects.

In order to achieve a high degree of model reuse, all medium specific data (i.e. medium composition, densities, specific heat, etc.) was encapsulated in the properties of a medium submodel. The high flexibility of Modelica’s classes permits to change this subclass even after the overall model has been assembled. The result of this is that the decision of how many and what kind of physical components that should be included in the simulation does not have to be made until after the rest of model has been completed and parameterized.

Fig. 2 shows part of the declaration (in Modelica code) of a control valve model. This code has been generated automatically using the model editor in Dymola.

3.1. Development of components models

The wet end is a very large and complex system with hundreds of pipes, several tanks, valves and pumps. Although Dymola is highly efficient in simulating large DAE systems, this puts a limit on how detailed the objects can be modeled. The aim was that full system simulations would be possible to perform with reasonable execution speed.

The process object models generally consist of:

- Mass-energy-momentum balances over the component
- Constitutive equations such as pressure drop, separation efficiency, etc.
- Medium property calculations

The balances are made for an arbitrary number of components. The models distinguish between suspended solids and dissolved components and treat them differently in separators, for instance. The constitutive equations are usually empirical or semi-empirical relations. One example is the relation between...
pressure drop and flow rate in pipes and valves. Another is the relation between the pressure increase, volumetric flow rate and rotation speed in a pump, also known as a pump curve. This is usually provided from the manufacturer as graphical curves and can be expressed as an algebraic equation, for instance a polynomial fit.

The models were parametrized so that the necessary data was either found in, or could be calculated from the available mill documentation. The control system was modeled using the same controller algorithms as in the real mill DCS. This allows for the actual tuning parameters ($P$, $I$, $D$, ...) to be extracted from the control system and be used in the simulation. The implementation of the real parameters will take place in a later stage of the project.

4. Modeling of the mill

The model and its structure are shown in Fig. 3. All the basic components are taken and aggregated from the Pulp and Paper Library. At the moment the wet end section of all four layers, and most of the long circulation is completed. This includes the approaching system from the mixing chests to the cyclone cleaners, the screens, the short circulation loop including headboxes and wire sections, and part of the long circulation with the bleached water chest.

As we explained in the previous section, the Pulp and Paper Library can handle as many substances as one needs. In this particular case, three kinds of physical substances were included in the medium sub-class: two kinds of pulp and the fillers (chemical substances added to the pulp). We did not consider all the different kinds of pulp effectively used in the mill to avoid an excessive complexity at this early stage of the process. All the parameters of the different components were gathered during some months of data collecting at AssiDomän Frövi.

In the real plant, the setpoints for the thick flow valve, the headbox pressure and the lips opening are calculated from the overall control system. In our simulations, these setpoint values were extracted from the Info database and fed to the model.
Fig. 4. Middle layer 1 and bottom layer jet speed and headbox concentration for two different grade changes.

Despite the fact that only the main flows are taken into consideration, this model, all together, handles about 800 state variables, more than 10,000 general variables, and more than 1000 time delays.

The model was validated for different grade changes. In Fig. 4 one of the validation case is presented for the bottom layer and for one of the two middle layers. The setpoint changes consist of an increase of the thick flow from the mixing chests, a decrease of the headbox pressure and of the slice opening. All this causes a decrease of the concentration in the headbox flow, and so a final product with a smaller basis weight.

From a process control point of view, the most interesting variable to consider for the validation is the headbox pulp concentration. The lower graphs in Fig. 4 present the measured headbox concentrations of the two layers, and their predicted values. The simulations show that the dynamic behavior during the grade change is quite well described by the model. However, the simulated concentrations have a static error, which is very large in the case of the top layer and middle layer 1. In particular, in the case of the middle layer 1, shown in Fig. 4, the mismatch due to the static error is about 25% of the nominal value. One of the main reason for this model/plant mismatch is believed to be the fact that the sub-model of the headbox is not accurate enough to handle more than one input flow. For this reason, we had to neglect a large flow coming from a secondary control screen. However, this secondary input is not added to the headboxes of the bottom layer and middle layer 2, and, in fact, the static errors in their concentrations are much smaller, around 5% of their nominal values. Other causes of errors are parameter and input uncertainties, neglected elements (that is, minor flows or not modeled yet), and un-modeled nonlinearities.

Regarding the other variables of interest, the validation showed quite good results. For example, the simulated pressures and jet velocities are very close to the measurement and the maximum error is less than 2% of their nominal values for all the layers, see the upper graphs in Fig. 4.
5. Results and discussion

A Modelica library for pulp and paper applications has been developed by Solvina. The concepts of object-oriented and non causal modeling have been used in order to make the library flexible and easy to use.

This library is being used for the modeling of AssiDomän Frövi paper mill. At present, the wet end process of the four layers has been completed and different grades changes have been considered for the validation of the model. The simulations have shown a good agreement between the predicted and measured dynamics. However, one of the most important variables, the headbox concentration, displays a static error which in the case of the top layer and middle layer 1 is considerably large. Such an error is believed to be caused by a secondary flow which is not included in the model. Since this secondary flow is controlled by the operators, and it is changed very seldom, it can be considered as a constant bias in the simulated values. Besides, the present headbox model can include only one input flow, and the introduction of a secondary dilution flow is not trivial at all. For these reasons the agreement with the validation data is considered satisfactory, at least at this stage of the project.

One of the main problem we encountered during the modeling, was the search of a consistent set of initial conditions for the simulation. In fact, it has to be “close” to a set of stable solutions of the system of differential equations, otherwise the nonlinear solver may encounter numerical problems. This problem has been studied by Dynasim, and the next versions of Dymola will have a tool for optimizing the search of the initial conditions.

Another problem, we are facing, is the simulation execution time. In fact, the present model is handling a huge number of state variables, delays, and a lot of different time constants. The resulting set of differential equations is very large and stiff. Even though Dymola has efficient algorithms to handle stiff problems, the simulation of the process takes quite a lot of time. A possible solution would be to provide the model with a more flexible structure, so that the user is allowed to choose whether or not to neglect the dynamical effects of the time constants he is not interested in. For instance, he could neglect small time constant (i.e. valves, short pipes, pumps, etc.) if he is interested in the long ones (i.e. tanks, headbox concentration, etc.) or viceversa. At the moment, the model can already be used for different aims: for example it can be employed to evaluate the effect of friction on the valves, to estimate time delays for an input change, qualitative testing of different control strategies or, in general, to get a better understanding of the wet end process. Besides, an operator interface which uses the model as a background has been developed at Solvina and can already be used by the operators and process engineers to evaluate some specific situations.

Next, we are planning to complete the model, including the press and drying section, and improving some of the present submodels to take into consideration some of the neglected nonlinearities and also chemical reactions.

Acknowledgements

The three authors thanks the Fund for the Promotion of Research at the Technion for its support.

References


