Library ILM-River for simulation and optimal control of rivers and hydropower plants

T. Pfuetzenreuter & Th. Rauschenbach
Fraunhofer Center for Applied Systems Technology, Germany

Abstract

ILM-River is a universal MATLAB/Simulink-toolbox for the simulation and control of rivers and cascades of hydropower plants. The tool consists of two libraries, one for modelling rivers and reservoirs and the other one for the control of individual hydropower plants or cascades of such plants. The libraries contain modules, which can be associated with each other. The parameter estimation of the modules is left to the engineer.

Keywords: optimal control, real-time control, reservoir modelling, control of hydropower plants.

1 Introduction

The optimal design of an automatic control of rivers and reservoirs requires always an analytical model of the behaviour. If simulation techniques are used for determining the control parameters a simulation model is necessary, which has to be constructed from the analytical model. The MATLAB / Simulink toolbox ILM-River was created for this purpose. It resulted from studies of the design of new control strategies for the reservoirs of Danube Hydropower Austria in Vienna.

The toolbox consists of the modules River-MOD and River-CON. River-MOD implements simulation models that are needed for modelling a river section with its characteristics. New control oriented hydrodynamic models were developed for River-MOD, which are well suitable for the design and the verification of control strategies [4]. A precondition for its effective application is the possibility to build a model for a river section in a short time. Therefore, for each of the developed models a simulation block was constructed as part of MATLAB / Simulink. These simulation blocks are combined into the library
River-MOD. With the aid of a graphic editor, it is straightforward to build the entire model for one or more reservoirs or river sections.

Several control concepts are implemented in the module River-CON. Besides the traditional control according to operating rules further concepts are integrated:

- a fuzzy control strategy for smoothing of discharge,
- a concept for the coordinated control of multiple river sections (cascades) for the improvement of flood control called MEFURO.

The different methods allow us to test and compare different strategies for controlling the output of reservoirs and river sections.

The simulation model for a river reservoir and the concept MEFURO for coordinated control of cascades of reservoirs will be presented in this paper. This concept was applied to four Danube reservoirs (Abwinden, Wallsee, Ybbs and Melk). With this control concept an improvement in flood control and energy generation was reached.

2 Model library River-MOD for reservoir modelling

The simulation models for River-MOD rely on an analytical description of the hydrodynamic behaviour of reservoirs. For control, it is sufficient to know the behaviour at gauges for water level and flows.

Up to now the design of control concepts is done with models of control technology or black-box-models. Unfortunately, they cannot describe instationary behaviour with sufficient accuracy.

Models based on the Saint-Venant-equations can better meet these demands [1], [4]. However, such models are not suitable for an on-line optimization, because solving the differential equations system requires a lot of computational time. Furthermore, it is difficult to simulate overflow regions and backflow behaviour with these models. For this reason, a synthesis of both models was developed. The resulting, new control oriented hydrodynamic models are called HR-models. They meet all demands with respect to accuracy and simulation speed [7].

The aim of modelling a river section is to determine the flow and water level only at gauges, which are important for control. For this purpose, all characteristic features in a river course have to be considered. First of all, in case of stationary and instationary behaviour, e.g. by an increasing flood wave, models which compute flow and water level must be available. Otherwise, no satisfactory simulation is possible. Further models are necessary in addition to these models (fig. 1):

- Backflow: At narrow places in the river course, there are backflows into the bordering fields. As a result, the behaviour of flow and water level is modified.
- Overflow: While attaining a defined water level a part of the river runs into overflow regions. Therefore, the flow behaviour in these regions must be described. In this case usually the water does not run through the next power plant and so the balance of flow is not correct. This
complicates the modelling. Pumping stations in these regions and inflow from creeks must be considered too [2].

- **Retention area**: Retention areas are located beside river courses to cut off part of the flow discharge in case of a huge flood event. Typically, the inflow from the river into the retention area is controlled with gates or pumping stations, which behaviour is modelled together with the non-linear storage characteristic of the area.
- **Barrages**: Reservoirs are typically formed by barrages. The barrage model combines the storage of water and the computation of water levels before and after the barrage.

![River-Mod Simulation Library](image)

**Figure 1**: The River-Mod simulation library.

### 3 Model library River-CON for reservoir control

#### 3.1 Introduction

Reservoirs are constructed with the aim to use the environment-friendly hydropower for generation of electric energy. In most cases, this fact leads to the construction of reservoir cascades in rivers. The reservoirs in a cascade influence one another by hydraulic link-up. As a result, the natural flow behaviour is strongly affected by the control strategies of the reservoirs.

Reservoir cascades have further tasks in addition to energy generation, e.g. to avoid overflows and to guarantee ship navigation. The energy production must be subordinate to these tasks in order to avoid danger for people and real values. To solve these tasks, rules were determined for the operation of the river reservoirs. Two modules were developed for the model library River-CON to realize a control according to operating rules, fig. 2. These comprise of a conventional PID-concept and the Fuzzy-concept FUGERA. However, these concepts cannot optimally solve the mentioned multi-criterial tasks necessary for a coordinated operation of reservoir cascades. The new concept MEFURO
instead is well suitable for such problems. Furthermore, a module for smoothing of discharge was integrated as fourth module [8].

![Diagram of River-Con SIMULINK - Library](image)

Figure 2: The River-Con simulation library.

### 3.2 Modules of the library River-CON

The above mentioned modules are combined in the library River-CON. Subsequently, the individual modules are presented in brief.

a) **PID-concept**
This module realizes a control of water levels with prescribed set-points. These water levels must be controlled situation-related at spatially separated gauges. A recognition of the current situation is done using the water levels. After that the corresponding PID-controller is activated.

b) **Fuzzy-concept FUGERA**
This concept is used to solve the same task as the PID-concept. Instead of using different controller for the different situations only one controller is used for all control situations which is implemented as a Fuzzy-adapted PID-controller [1]. The Fuzzy system determines the parameters for the PID controller depending on the current situation. The situation is characterized by the water levels in the reservoir.

As additional input a total control error is used, that is determined by a second Fuzzy system. This error consists of the weighted sum of the partial control error of each situation. With help of this value, a smooth transition between the control situations can be achieved. Furthermore, an improvement in robustness against disturbances is reached.

c) **MEFURO-concept for optimal coordinated control of reservoir cascades**
The activation of this module occurs after a flood situation was predicted. The task of the coordinator is to compute the optimal set points for the sub-controllers at each hydropower plant. The objectives of this control concept are:
- to realize the best quality flood control by minimizing the maximum discharge of each reservoir in the cascade,
• to avoid the exceeding of limit values for water level and
• to maximize the energy generation during the transition from normal
  operation to flood control.

The input of the coordinator is the predicted inflow to the cascade and the current
state of each reservoir (water levels and flows). The computation of the control
trajectory is done for all power stations using a situational optimization criterion
[9].

Each of the objectives mentioned above is considered by one partial criterion
in the optimization criterion. Every partial criterion is weighted by a factor,
which is computed by a Fuzzy system according to the current situation. The
optimization is carried out iteratively – after an updated forecast or a significant
state change of the reservoirs a new optimization run is initiated. As result, new
control trajectories for the reservoir controllers are generated. As optimization
techniques the Simplex method and evolutionary algorithms are used [5].

d) Control-concept for discharge smoothing
The aim of this module is to minimize the discharge ups and downs. In this case,
the tolerance limits of the water levels must not be exceeded. A Fuzzy system is
used for this control task. In addition to the water level, the gradient of the
incoming flow is also taken as an input to the Fuzzy-system to smooth the
discharge of the reservoirs.

4 Simulation model for Danube reservoir Ybbs

Using the ILM-River toolbox different simulation models for river reservoirs
were developed. As an example this paper presents the model for the Danube
reservoir Ybbs, fig. 3. Main aim is to model the dynamic behaviour of the flow
section between the two hydropower plants Wallsee and Ybbs. The model must
describe the real inflow and discharge behaviour as well as the water level
trajectories.

![River Basin Management III 125](image)

Figure 3: River section between hydropower stations Abwinden and Ybbs.
The river length in the reservoir Ybbs is approx. 34 km, the width ranges from 150 m to 1,000 m. The bottom slope in the reservoir is $3.4 \times 10^{-4}$. The most important distances are Sarmingstein - Ybbs: 13 km, Ardagger - Sarmingstein: 12 km, Wallsee - Ardagger: 9 km.

Behind the gauge Au (in the middle of backwater area) a part of the water bypasses the hydropower station Wallsee at flows larger than 6000 m$^3$/s. Therefore, the downstream gauge does not register the total incoming flow to the reservoir Ybbs. For this reason, it is necessary to consider the effect of bypassing in the model.

The activation of the retention rooms occurs with the aid of floodgates and pumping stations at a flow of 4700 m$^3$/s. With a flow of 5400 m$^3$/s, the water pours directly into the retention rooms. Fig. 4 shows the rough simulation model of the reservoir Ybbs.

![Figure 4: Simulation model for reservoir Ybbs.](image)

With this model, good simulation results can be achieved in all flow ranges. As an example, fig. 5 shows the simulated discharge of the hydropower station Ybbs during the flood of July 1993 compared to the original time series. The water level models produce also a correspondingly small error. Analogous simulation models for three further reservoirs Abwinden, Wallsee and Melk were also developed. The modelling error is similar for all of them. The existence of these models is a precondition for developing a coordinated control for a cascade of reservoirs [9].
5 Optimal coordinated control of four Danube reservoirs

In section 3, the concept "MEFURO" for coordinated control of cascades of reservoirs was presented. This concept was applied to the four Danube reservoirs Abwinden, Wallsee, Ybbs and Melk [9]. The principle of the coordinated control is shown in fig. 6.

Figure 6: Principle of coordinated control of reservoir cascades.

This strategy bases on the theory of hierarchical control. As before, every reservoir has its own underlying automatic controller. These are effective in standard situations and they work according to the “up to now” valid operating
rules. The coordinator is activated in the case of a predicted flood situation. In this case, the coordinator computes the optimal discharge trajectories for every hydropower station in the cascade. This new set point data is delivered to the underlying automatic controllers. The coordinator is constantly informed about the current situation in the reservoirs. By exceeding boundary values, the control strategy is changed.

The results from a simulation run with the coordinated control are shown in fig. 7. The achievement of the primary objective of this control strategy—minimizing the maximum discharge of each reservoir in the cascade—can be evaluated directly. The maximum discharge of the last coordinated reservoir Melk is noticeably reduced compared to the inflow into the cascade.

To use this control strategy in practice it is necessary to suspend the up to now valid operational rules for flood situations. The latest reservoir in the cascade, in the example the reservoir Melk, has to reduce its water storage at first. This has to be done before the flood reaches the reservoir.

![Figure 7: Results of coordinated control.](image)

6 Conclusion

The MATLAB / Simulink toolbox ILM-River consisting of two libraries for simulation and control of rivers and cascades of hydropower plants was presented in this contribution. The practical usability of the simulation blocks was shown on a practical example for a set of reservoirs at the Austrian Danube. With this strategy, a good conformity with the reality could be obtained. The coordinated control scheme achieves an improvement in flood control and energy generation for the considered reservoir cascade.

The main focus of the ongoing work is the further development of the library. Especially models for the water supply network elements (pumping stations, waterworks), for groundwater storage and reuse of treated wastewater are under
active investigation. Such models are necessary for one current project of the Fraunhofer Application Center for System Technology developing a water resources allocation decision support system for the city of Beijing [10].

References