From driver feedback to valve spool

Dipl.-Ing. Daniel Dix, Dr.-Ing. Oliver-Carlos Göhler
Xuzhou Construction Machinery Group (XCMG) European Research Center (ERC) GmbH, Europark Fichtenhain B4, D-47807 Krefeld, Germany
E-Mail: dix@xcmg-erc.com

In the last decades, simulation tools and virtual prototypes were vastly promoted to speed up development processes. But for complex systems, the modelling and model validation effort is very high, and always some modelling inaccuracies have to remain due to account for effective cost and computational effort for the simulations and validation tests. To contribute to the discussion from another point of view, this paper will present a new approach to speed up development by extreme reduction of hardware iteration time to test changes of main valve spool geometry according to operator feedback.

Keywords: control edges, valves, design process, design tool, CAM
Target audience: Valves, Design Process, Mobile Hydraulics

1 Introduction

The XCMG European Research Center GmbH was founded in Krefeld/Germany in 2013. XCMG ERC is responsible for all research and development activities in Europe and owns test rigs and test grounds for detailed investigations with XCMG’s mobile machines. The goal is to optimize and develop innovative technologies for our construction machinery in the fields of hydraulic, drive and control systems that finally result in especially efficient, environmentally friendly, multifunctional and ergonomic construction equipment products for the global market [1].

Through the last five years in excavator-related development projects, our team investigated and optimized various systems, components and test conditions. All investigations covered different hydraulic system approaches like negative flow control and load-sensing systems. These systems get optimized with regard to costs, higher dynamics and controllability as well as fuel consumption and digging performance. The optimizations realized were implemented in consideration of own hydraulic components like valve spoons and main control valve manifolds, new control principles in the sub-circuits for pilot oil supply and joystick actuation as well as the selection of new pumps and drives of new suppliers.

This approach combines a structured operator feedback evaluation and calculation methods to get an optimized valve spool design. Especially a developed macro named MUV (Muko unterstützte Ventilscheibenauslegung / macro supported valve spool design) will be presented which converts an optimized valve characteristic into the design of a new hardware component. Other program modules will be explained which allow a further reduction of the development process time as well as the error prevention in the manufacturing of valve spoons. Furthermore recent results will be outlined. Questions concerning costs and process times will also be discussed.

2 Valve development for a 21t crawler excavator at XCMG ERC

For a successful development of main control valves for a crawler excavator the requirement for consumers such as boom, bucket, swing, arm and travel must be defined. These requirements can be divided into two categories: requirements which can be defined and proved by the designer (simple criteria) and requirements which are unknown in the first step and have to be defined by the operator of the machine throughout the development process (criteria difficult to quantify). In the following, these requirements are described as well as an iteration loop of the development process at XCMG ERC.

2.1 Evaluation criteria for development process of Hardware Components

As described, evaluation criteria can be divided into simple and difficult to quantify criteria. In Table 1 examples for those criteria are shown.

<table>
<thead>
<tr>
<th>Hard to quantify criteria/subjective criteria</th>
<th>Simple to quantify criteria/objective criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>User-friendly speed allocation</td>
<td>Maximum velocity</td>
</tr>
<tr>
<td>Impacts</td>
<td>Cavitation</td>
</tr>
<tr>
<td>Accuracy of positioning</td>
<td>Oscillation</td>
</tr>
<tr>
<td>Intuitive operation</td>
<td>Travelling straight</td>
</tr>
<tr>
<td>Annoying sounds</td>
<td>Hysteresis</td>
</tr>
</tbody>
</table>

Table 1: Examples for hard and simple to quantify criteria of the development process for an excavator hydraulic system.

An important aspect in the development of a hydraulic system for a crawler excavator is the controllability of each consumer. Many evaluation criteria for the operability of each function, e.g. maximum velocities, valve hysteresis, resolution related to the joystick stroke, overrunning of consumers and fuel consumption by pressurising a consumer can be detected by installed measuring devices and evaluated with thorough analysis. In addition to these numerous evaluation criteria other criteria exist which are difficult to quantify such as e.g. intuitive operability, controllability and user-friendly speed allocation of each function, which have to be evaluated by the driver of the machine.

2.2 Iteration loop of the development process

The following explains the iteration course of the development process at XCMG ERC, see Figure 1. At the beginning of each iteration loop, the previous experiment gets evaluated. A decentralized modular measuring system based on Beckhoff components is installed in the machine and detects all system pressures as well as cylinder strokes, the speed of the diesel engine and the oil temperature, in total about 120 measuring channels. The transmission of the measurement data is done via WLAN to the measurement computer. For the “Experimental Evaluation”, the operator feedback is used in addition to the measured metrics. The recorded data of the machine as well as the change requests of the operator, such as speed adjustments as a function of his joystick movement (valve characteristic curve), are evaluated in the second step "Analysis and Derivation".

Functional deficiencies such as cavitation of an actuator get solved or operator requests get implemented. Implementation takes place through the optimization of hardware components or a new adoption of the hydraulic circuit. The last can be implemented quickly by simple structural alterations works on the machine. In this case a jump to the iteration step "Assembly" takes place. In case of hardware optimization the third iteration step "Implementation to CAD" follows. This time-intensive task involves the creation of a 3D part, an assembly including its derivation and a production drawing.

The subsequent manufacturing of new prototypes is characterized by time-consuming programming work for the CNC machine operator. In a further iteration step the quality assurance of the manufactured components take place. At this point it must be checked, if the component is cleaned and free of burrs and thus suitable for use in
the excavator. A second and also very time intensive work is to check if all requested features of the component are available according to the manufacturing drawing.

After the prototype has been assembled, a first validation will be done on the test rig (Iteration Step „Validation Test Rig”). If no defects are detected the component will be installed and tested in the experimental excavator (Iteration Step „Validation Excavator”). In the last iteration step the evaluation of the machine takes place by the operator. This “Operator Feedback” serves as input for another iteration loop.

These scripts allow:
- Automated data preparation,
- Determination of various characteristics such as delay of functions,
- Calculation of volume flows from the time sequence of the cylinder position,
- Power and energy balances of the excavator,
- Creation of standardized visualizations and diagrams.

3.2 Questionnaire for Operator

As mentioned before, it is very difficult to solve problems or defects detected by the driver. The difficulty is to get two problems under control. The first point is a communicative problem between the operator and engineer. It has to be secured that both parties are using the same terms to describe effects. The second challenge is to solve the problem without creating new problems in other areas of the excavator hydraulics, e.g. the impact while stopping a cylinder function must be reduced without an overrunning of this function. To handle these problems a technical questionnaire table was developed. A small abstract is shown in Figure 2. The whole table includes round about 150 evaluation criteria.

The subjective driver feedback gets collected and monitored by traffic light principle after each change in excavator hydraulics. Priorities on next tasks in development process are easier to define and a direct overview about the current state of the machine is given. Furthermore the connection between driver feedback and changes of main valve characteristics can be derived.

3.3 Virtual Excavator

Models for the excavator kinematics as well as the developed excavator hydraulics are implemented in the simulation software DSHPlus/2/. The advantages of using such simulations as a virtual prototype come from the pre-development of special circuits or simplifications of the existing hydraulic system before they get implemented in the experimental machine. The tuning of valve characteristic curves in relation to parallel-operated functions is very demanding. The challenge is to match the valve characteristic curves of each

![Figure 1: Iteration loop of the development process at XCMG ERC for a 21t crawler excavator.](image)

![Figure 2: Abstract from the operator evaluation sheet.](image)
consumer so that machine-specific movements can be realised, e.g. horizontal movement of bucket by using arm and boom section (plum).(3)

3.4 Macro for Valve Development

An important step in the development of a hydraulic system is to find suitable valve characteristics for the respective consumers with the help of subjective driver evaluations and simulation results. In a second step the developed valve characteristic curves must be transferred into new valve spool design (control edges). This implementation is often characterized by computationally intensive and time-consuming calculation tasks, such as CFD analyses. To speed up this process a macro named MUV was developed which generates valve characteristic curves out of special geometric features by fast analytical calculation methods.

4 Makro-Unterstützte Ventilscheibenauslegung (MUV)

The high-frequency changes to the inflow and outflow control edges of the main control valves as part of the prototype development of an excavator hydraulics made it necessary to create a computing-time-optimized tool to convert valve characteristic curves into new hardware. Therefore a macro named MUV was programmed by using VBA, which uses MS Excel as a platform. With the help of MUV valve characteristic curves can be adapted easily by modifying the geometrical dimensions of control edges. Figure 3 shows the structure of the developed macro. In addition to the main program, additional features (sub-programs) have been developed and implemented that significantly shorten the process time of the iteration steps “Implementation to CAD” and “Transfer to CNC”.

4.1 Main Program

The oil density \( \rho \) as well as the pressure drop over the inflowing control edge \( \Delta p_{1}(x) \) are input parameters. The macro contains different geometries for the control edge such as triangular contours, grooves and circles. All these geometric features can be parameterized regarding dimensioning and positioning. It is possible to use 32 features on each control edge. It will be automatically detected if there is not enough space to place these features on the coat surface of the spool.

In the following the calculation of valve characteristic curves \( Q_{o}(x) \) for flow over the meter-in control edge and the determination of the meter out control edge as a function of the pressure loss \( \Delta p_{o}(x) \) will be described. The smallest cross section \( A_{i}(x) \) will be detected according to /3/. The radial cross section \( A_{r} \) (see Figure 4) calculation is simplified by assuming a planar spool outer surface, neglecting the roundness. As the relation between spool diameter and notch size is big in our valves, the error is negligible. The axial cross section \( A_{a} \) does not include any simplifications.

![Figure 4](image)

**Figure 4: Definition of radial Cross Section \( A_{r} \) and axial Cross Sections \( A_{a} \) /3/.

\( A_{i} \) and \( A_{a} \) will be compared for each spool displacement \( x \). According to equation (1) the smallest cross section \( A_{i}(x) \) for one geometric feature is given.

\[
A_{i}(x) = \min\{A_{i}(x), A_{a}(x)\}
\] (1)

The discharge coefficient \( q_{o,\text{in}} \) for the meter-in control edge is calculated from a map depending on the chosen geometry features and its dimensions as well as the displacement \( x \) of the spool. These specific maps were developed by numerous test rig trials. The influence of temperature according to /4/ was not taken into account in these characteristic maps.

The inlet volume flow \( Q_{\text{in}} \) via a respective geometric feature \( i \) is calculated according to the orifice formula, see equation (2) /5/.

\[
Q_{\text{in}}(x) = q_{o,\text{in}}(x) \cdot A_{i}(x) \cdot \frac{\sqrt{x}}{\sqrt{\rho}} \cdot \sqrt{\Delta p_{i}(x)}
\] (2)

The total volume flow \( Q_{o} \) to an actuator via meter-in control edge corresponds to the sum of the individual volume flows \( Q_{\text{in}} \), see equation (3). \( x \) describes the number of chosen geometric features.

\[
Q_{o}(x) = \sum_{i=1}^{x} Q_{\text{in}}(i)
\] (3)

These calculations will be repeated by adjusting the geometry features or their dimensions until the desired characteristic curve gets reached. The calculation time of the macro for such an iteration step takes around 5 seconds.
Depending on the inflow volume and the respective actuator the outflow volume is calculated by equation (4). Factor \( c \) describes the hydraulically acting area ratio of an actuator depending on movement direction.

\[
Q_{\text{out}}(x) = c \cdot Q_{\text{in}}(x) 
\]  
(4)

The discharge coefficient \( a_{\text{out}} \) is assumed to be constant to calculate the meter-out control edge. By transforming the orifice equation according to equation (5) the smallest cross section can be determined for the whole control edge.

\[
A_{\text{out}}(x) = \frac{Q_{\text{out}}(x)}{a_{\text{out}} \cdot \frac{1}{2} \cdot \sqrt{2 \cdot \rho \cdot p_{\text{out}}(x)}} 
\]  
(5)

From available geometric features the required area \( A_{\text{out}} \) is approximated by an iterative calculation. The solutions are sorted on the one hand according to the achieved accuracy and on the other according to production-optimized solutions. The calculation of the meter-out control edge can take up to 5 minutes.

4.2 Sub Programs

The transfer of the calculated control edges into a CAD model and the programming of the CNC machine are error-prone steps that go hand in hand with elaborate checks. To minimize the errors and the cycle time of these two process steps sub-programs have been developed for the described macro MUV.

4.2.1 Interface to CAD

An interface to the CAD Software ProE was engineered which allows to overpass the calculated control edge designs into a 3D part at the push of a button. Thereafter a parametric CAD model was built up. In addition to the 3D part an automatic creation of a manufacturing drawing takes place. This drawing is grouped into two parts. On the one hand the green body which does not change is dimensioned and on the other hand the changeable control edges are defined at a further development of a at XCMG ERC existing bore table. This new table includes the type of geometric feature and the associated dimensions as well as the position and direction of each feature. Such an interface ensures an error-free changeover from the iteration step “Analysis and Derivation” to “Implementation to CAD”.

4.2.2 Interface to CNC-Machine

A second sub-program forms the interface to the manufacturing process. The working principle is similar to CAM (Computer-Aided-Manufacturing) systems. The Macro adds the geometric features, its dimensions and positions to an existing NC Program which contains the manufacturing process of the downstream valve part. The NC-Code is based on DIN-Programming. In addition to the transfer of the geometry features the DIN-Program is optimized with regard to tool changes in the manufacturing step. With the help of such an interface a drawing-free manufacturing is possible. However, the two major benefits are the savings in programming time for the CNC machine operator and the error-free step from "Implementation to CAD" to "Manufacturing".

5 Results

5.1 Quality of implemented valve characteristics

In addition to a quick and error-free transfer of a desired valve characteristic curve in a new valve spool it is of great importance to reach a small deviation between desired and real valve characteristic curves. Figure 5 shows an example of three different meter-in control edge calculations in comparison to measured volume flow curves depending on the displacement \( x \) of the spool.

![Figure 5: Comparison between calculated and measured characteristic valve curves.](image)

Through a continuous improvement of specific maps for MUV due to numerous test rig trials a maximum deviation of 3% could be achieved between desired and calculated meter-in control edge over the full spool stroke.

![Figure 6: Comparison between Calculated and measured characteristic valve curves including pressure drop at meter-out control edge.](image)

Figure 6 shows exemplary in addition to Figure 5 the calculated and on the test rig measured pressure drop at the meter-out for an associated flow curve over the meter-in control edge. The values for the pressure drop have been recorded at specific positions. The measured and calculated result shows a similar curve progression but differ in their values. The maximum deviation is about 25 %. Such a deviation can be justified on the one hand by the discharge coefficient to calculate the meter-in control edge which is assumed to be constant. Another reason is that the input quantity \( Q_{\text{in}}(x) \) for calculation the pressure drop at the control edge also contains a small
derivation. These derivations are initially tolerated due to fast prototyping. Furthermore such detected
derivations can be used to determine a characteristic map for the outflow discharge coefficient to improve the
quality of MUV.

5.2 Costs and processing time

The use of the Macro MUV saves development time as well as money. In the past the development of new valve
spools at XCMG ERC has taken several working days. Today a new prototype valve can be manufactured from
the characteristic curve to a machined product within about 1.5 hours. Such a reduction of developmental time
leads to a faster build-up of knowledge and faster completion of projects. In addition to the reduction of
processing time costs are saved, as the development costs for such macroes did not exceed the saving potential. At
XCMG ERC the following costs are reduced significantly:

- Engineering costs for the development of a new valve design due to a needed valve characteristic curve
- Costs of creation 3D parts as well as manufacturing drawings
- Costs for machining due to programming (eliminated)
- Costs due to defective parts
- Costs for quality assurance
- License-fees for expensive simulation software as well as costs for a qualified operator for such tools

6 Summary and Conclusion

This paper presents the hardware iteration loop at XCMG ERC to develop a new main valve spool design for a
hydraulic system of an excavator. In the last decades, simulation tools and virtual prototypes were vastly
promoted to speed up development processes. But for complex systems, the modelling and model validation
effort is very high, and always some modelling inaccuracies have to remain due to account for effective cost
and computational effort for the simulations and validation tests. To contribute to the discussion from another point
of view, this paper presents the new approach to speed up development by extreme reduction of hardware
iteration time to test changes of main valve spool geometry according to operator feedback.

The tools that were developed at XCMG ERC to improve the cycle time of such a hardware iteration loop are
explained. The focus is placed on the macro MUV. The structure as well as the mode of operation to generate out
of control edge features and several boundary conditions a specific valve characteristic is explained. The saving
potential with respect to cycle time and the associated cost savings are finally presented.

In order to constantly improvement of MUV and the related potential concerning time and costs further efforts
should be made in the development of a more detailed description of the meter-out control edge. Another
approach to increase the effectiveness in the iteration loop of the development process is to think of more
subprograms such as a subprogram for a full documentation of the valve.

The precise matching of experimental measured and MUV calculated flow curves shorten the period of
development and engineering significantly. Steps of calculation, engineering and simulation are done
automatically inside the MUV tool. In the end there is a complete set of drawings and a fully CNC machine
code for manufacturing. A short development time of roughly about four weeks for MUV led to a significant
reduction of each iteration loop of the development process. MUV also creates the possibility to renouncing
expensive simulations such as CFD analysis. MUV should also serve as an inspiration to build up more effective
tools to accelerate projects such as new interfaces to CNC machines for an error minimized manufacturing of
more complex parts than valve spools without an investment for expensive CAM systems.

### Nomenclature

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_x$</td>
<td>Axial cross section</td>
<td>[mm$^2$]</td>
</tr>
<tr>
<td>$A_t$</td>
<td>Smallest cross section</td>
<td>[mm$^2$]</td>
</tr>
<tr>
<td>$A_{in}$</td>
<td>Smallest cross section for meter-in control edge</td>
<td>[mm$^2$]</td>
</tr>
<tr>
<td>$A_{out}$</td>
<td>Smallest cross section for meter-out control edge</td>
<td>[mm$^2$]</td>
</tr>
<tr>
<td>$A_r$</td>
<td>Radial cross section</td>
<td>[mm$^2$]</td>
</tr>
<tr>
<td>$\Delta p_{in}$</td>
<td>Pressure drop at meter-in control edge</td>
<td>[bar]</td>
</tr>
<tr>
<td>$\Delta p_{out}$</td>
<td>Pressure drop at meter-out control edge</td>
<td>[bar]</td>
</tr>
<tr>
<td>$Q_{in}$</td>
<td>Volume flow at meter-in control edge</td>
<td>[l/min]</td>
</tr>
<tr>
<td>$Q_{out}$</td>
<td>Volume flow at meter-out control edge</td>
<td>[l/min]</td>
</tr>
<tr>
<td>$c$</td>
<td>Acting area ratio of an actuator</td>
<td>[-]</td>
</tr>
<tr>
<td>$x$</td>
<td>Displacement of valve spool</td>
<td>[mm]</td>
</tr>
<tr>
<td>$x_{max}$</td>
<td>Stroke of valve spool</td>
<td>[mm]</td>
</tr>
<tr>
<td>$z$</td>
<td>Number of geometric features at a control edge</td>
<td>[-]</td>
</tr>
<tr>
<td>$\sigma_{in}$</td>
<td>Discharge coefficient for meter-in control edge</td>
<td>[-]</td>
</tr>
<tr>
<td>$\sigma_{out}$</td>
<td>Discharge coefficient for meter-out control edge</td>
<td>[-]</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Oil density</td>
<td>[g/cm$^3$]</td>
</tr>
</tbody>
</table>

### References

1. N.N., [http://xcmg-europe.de/unternehmen/xcmg-erc](http://xcmg-europe.de/unternehmen/xcmg-erc), visited on January 5, 2018