A NOVEL MODEL FOR OPTIMIZED DEVELOPMENT AND APPLICATION OF SWITCHING VALVES IN CLOSED LOOP CONTROL

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Abstract

In this paper a novel and validated model to describe the dynamics of switching valves is presented and used to analyse the behaviour of switching valves. The paper starts with a brief discussion of the state of the art and the characteristics of switching valves, continuing with investigations of their dynamics, the development of the novel model and an analysis of the characteristics of switching valves based on the introduced model. The different operation modes which appear when fast switching control signals are applied are introduced and discussed. Additionally the application of the proposed model in closed loop simulations is pointed out and compared to state of the art models. It is demonstrated that the novel model offers a good trade-off between model accuracy and model complexity.

Keywords: digital hydraulics, switching valves, dynamic model, pulse width modulation (PWM), closed loop control, switching time, ballistic mode

1 Introduction

In recent years applications utilising digital hydraulics arose. The original idea and some reasons for the usage of digital hydraulics will be introduced in this section. At a first glimpse digital hydraulics has the potential to be more flexible, reliable and cost-efficient than conventional hydraulics. To be able to optimally employ and develop switching valves, which constitute one integral component of digital hydraulics, a deep understanding of the fundamentals of switching valves is necessary. In this paper insights about switching valves derived from a novel dynamic model are introduced.

1.1 Digital Hydraulics

Conventional hydraulic actuators like cylinders or hydraulic motors are controlled by hydraulic valves. Most of those valves are directional valves. For different requirements of several applications, there are valves with different performances and characteristics available. In most cases a correlation between cost and performance can be observed: the better the performance, the higher the cost.

One attempt to reduce costs is to use switching valves instead of directional valves. In Linjama et al. (2009) and Bosch Rexroth (2011) an approach is introduced to utilize switching valves in closed loop control. Whereas the first approach requires a huge number of switching valves to be able to achieve reasonable accuracy, the latter introduces an approach to reduce the number of required switching valves.

Among those mentioned in the previous paragraph there are also findings for digital hydraulics in research and development as well as applications by Plöckinger et al. (2009) and Sauer Danfoss (2007).

1.2 Characteristics of Switching Valves in Closed Loop Control

Even if not all advantages and disadvantages of switching valves are present simultaneously in one application it is worth having a closer look at them:

Variant-reduction: Most switching valves are composed by uniform components with low complexity which can be produced with moderate costs. When using the same switching valves to replace a greater variety of conventional valves, less variants of valves have to be developed and supported.

Absence of leakage: Switching valves that are implemented as poppet valves are without leakage and thus are outperforming many directional valves (e.g. in pressure control applications).

Flexibility: All metering edges from pump and tank to the hydraulic load can be controlled independently.

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This fact allows to mimic different kinds of directional valves with only one configuration of switching valves by just changing the control strategy for each valve.

Function: Digital hydraulic systems often exhibit the same small- and large-signal behaviour. Conventional directional valves have a slower dynamic for large control signals compared to small ones.

Installation Space: As numerous valves are necessary to control one consumer more installation space may be needed for the valves itself but also for their wiring and their electronics.

Control Methods: Controlling directional valves is more detailed investigated in comparison to digital hydraulic systems. The control algorithms for digital hydraulic systems are more complex and differ a lot to the control algorithms of directional valves especially as digital hydraulic systems are multible input systems.

Safety and Reliability: Digital hydraulic systems are often designed in a redundant manner. When using multiple switching valves per metering edge the malfunction of one switching valve can be compensated by the others with just a small reduction in performance (Siivonen et al., 2009). Never the less, the higher number of components in a digital hydraulic system may lead to a higher probability of faults. This probabilty depends to a great extend on the reliability of each digital switching valve, which is expected to be higher than the reliability of a directional valve.

1.3 Target of the Article

The target of the article is to develop and validate a novel model to describe the dynamics of switching valves during fast switching control signals to gain a better understanding of switching valves in general and their dynamic behaviour in particular. Additionally to this the target is to compare the novel model to state of the art models and to discuss the application of valve models in closed loop simulations.

2 Novel Switching Valve Model

Typically, switching valves are used in applications where the switching time is short compared to the duration in which the valve is open or close. Due to this relation it is not necessary to model the valve dynamics with a high accuracy. Looking at applications with digital hydraulics the valves are switching much more often making it necessary to model the valve dynamics more detailed. The accurate modelling of the dynamics gets even more important when the control signal changes as fast as or faster than the valve can switch between its states. In these cases the valve can be used in an intermediate state which also has to be covered by the model.

Beside this reason the accurate modelling and thorough understanding of the valve dynamics is important to design control strategies more time-efficiently and systematically instead of purely heuristically.

2.1 Model Requirements

The dynamics of the valve stroke from different kinds of switching valves have many similarities, which are shown and summarized in Fig. 1. This illustration shows the valve stroke s for a control signal u which is slightly shorter (curves A) and for one which is slightly longer (curves B) than the time the valve needs to be fully activated.

One main effect of the valve dynamics is the time lag between the rising and falling edge of the control signal and the beginning of the valve stroke. In general this lag is not symmetrical but different for activation and deactivation as shown in Fig. 1. To be more precise this lag is no time delay which means that short pulses or pauses of the control signal are completely suppressed by the valve.

On the one hand the time lags which occur whenever the valve was fully activated or deactivated are independent from the width of the pulses and pauses of the control signal and therewith independent from the time the valve was in the activated or deactivated state. On the other hand, if the control signal has its falling edge as soon as the valve is activated fully the time lag will be much smaller than in the case described above.

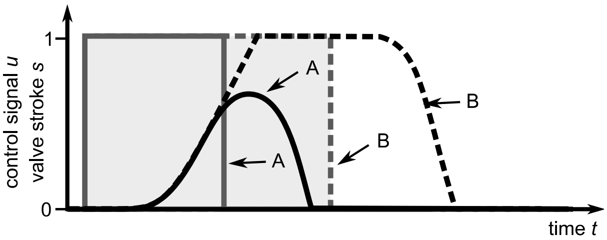

Fig. 1: *Schematic representation of valve stroke for different control signals*

Another characteristic is the velocity the valve reaches during activation and deactivation. Because of physical reasons this velocity is limited and generally not the same for activation and deactivation. Describing the valve dynamics with limited velocities it is also necessary to cover the effect of partial valve stroke as shown in curves A.

The effects described above are mainly influenced by design parameters like spool or poppet mass, spring constant and spring preload or the orifice which controls the damping of the valve stroke but also by parameters which result in different solenoid forces like electric resistance, inductivity or voltage.

To be suitable for the use in simulations of fast switching valves and the analysis of the behaviour of those, a dynamic model should at least cover the effects presented here.

2.2 Model Development

In some cases the model for a switching valve is separated into one part describing the dynamics of the valve stroke and another part describing the hydraulics. In these kinds of models the feedback from the hydraulic to the dynamic part, i.e. the flow force acting on the piston, is neglected. This feedback can only be implemented in more complex models based on force equilibrium. The hydraulic part can be described by a static characteristic curve (effective flow area versus valve stroke) and the pressure drop across the valve and is not the focus of this article.

As described in the last section the appropriate accuracy of the valve model strongly depends on the specific application. In many systems modelling the dynamics with a simple binary switch is sufficient. Such a model can only represent the states "fully activated" or "fully deactivated" none of the effects described in section 2.1 are covered by this model. Due to this one possibility is to model the dynamics with a constant time delay in combination with different slew rates for activation and deactivation, as used by Long et al. (2010) for example. This model is simple to realize but it does neither reproduce the effect of the suppression of small pulses nor pauses and the effect of independent time lags for activation and deactivation which only occur when the valve reaches the end stops. These restrictions limit the use of this model to applications where the change of the control signal is slower than the switching time of the valve so that the valve will reach its end stops before the control signal changes and restricts the usage to valves with time lags for activation and deactivation which are similar. To extend this model different dead time elements for activation and deactivation could be used in principal but this causes discontinuities whenever the pulses are smaller than the dead time during deactivation or the pauses are smaller than the dead time during activation. Other than these models with constant spool or poppet velocity, second order lag models are sometimes used to describe the dynamics between the control signal u and the valve stroke s (Plöckinger et al., 2009). In these models it is hard to account for different velocities for activation and deactivation and for different time lags too.

On the other hand more complex, physically motivated models, as described by Becker (2004) or Taghizadeh et al. (2009), will reproduce the described effects as they are focused on one particular valve and thus can hardly be generalized. Furthermore the effort to create and compute these kinds of models is higher compared to the models described in the last paragraph.

This leads to the conclusion that there is a need for a valve model which is capable of describing all the relevant effects which occur when the change in the control signal is faster than the switching time but which is also as simple and universal as possible.

To cover all required effects described in 2.1 a novel model was developed. The novel valve model proposed in this paper consists of two parts. The first part is the valve dynamics and the second is the hydraulic part. The valve dynamic calculates the valve stroke s with respect to the control signal u and the valve parameters. Due to the separation of the valve into two parts the flow force acting on the piston is not represented.

In the hydraulic part a spool or a poppet valve can be represented. This part of the model contains the piston geometry like the piston diameter, the overlap of the piston and the detailed geometry of the piston, for example rounded edges. With the valve stroke and the piston geometry the flow area of the modelled valve can be calculated.

The model of the dynamics presented in this paragraph is created to fulfil the observations of switching valves as shown in section 2.1. As shown in Fig. 2 after the start of the pulse, the piston does not move for a constant time lag. This time lag is called $t_{i,min}$. After the duration $t_{i,min}$ the piston motion starts sharply. The observations of switching valves show that the period of acceleration is in many cases very short, so that this period is neglected in the model. The velocity of the piston during the period of activating the valve is modelled to be constant. The time between the start of the pulse and time when the piston reaches the upper end stop is called t_{on}. On the other hand, the duration between the end of the pulse and the piston starts to move to the lower end stop is called $t_{p,min}$ and the duration between the end of the pulse and the valve reaches to lower end stop is called t_{off}.

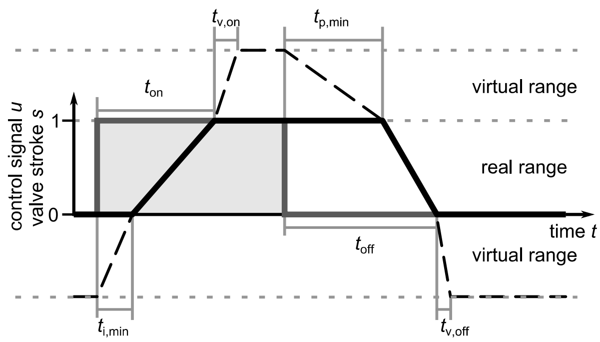

Fig. 2: *Novel model for the valve dynamics*

To account for the fact that the piston stroke of small pulses are suppressed a virtual range was implemented. Two virtual ranges exist, one at the lower end stop and one at the upper end stop as shown in Fig. 2. In these virtual ranges no physical piston movement occurs. At the initial state the piston is at the lower virtual end stop. During the period of $t_{i,min}$ the pistons virtually moves with a constant velocity to the real lower end stop and reaches the real range after the time $t_{i,min}$. The chosen velocity for the virtual range and the duration $t_{i,min}$ define the height of the virtual range. The same procedure is done for the upper virtual range.

To complete the model the parameters $t_{v,on}$ and $t_{v,off}$ are necessary to specify how fast the virtual end stops are reached.

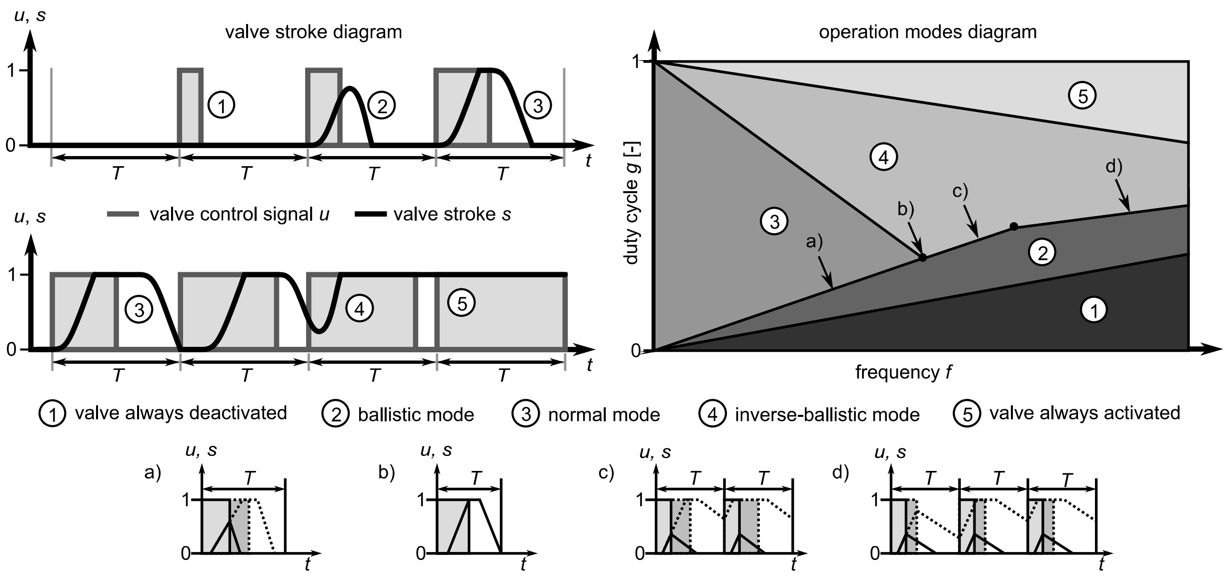

Fig. 3: *The five operation modes of a switching valve in case of using digital control methods*

2.3 Model Analysis

The control signal u can be described by the two states "logical one" and "logical zero" named pulse t_i and pause t_p, respectively. The periodic time is the sum of the pulse t_i and the pause t_p:

$$T = t_i + t_p \tag{1}$$

The switching valve has mainly five different operation modes which depend on the relation between the pulse t_i and the pause t_p. For the following analysis the periodic time is considered to be constant. In Fig. 3 on the left side different durations of the pulse t_i and the pause t_p are shown. Starting with $t_i = 0$ of course the piston is not moving but also after increasing the pulse t_i to the value $t_{i,min}$ the piston is still not moving. In this mode ① the valve is always deactivated. Continuing to increase the pulse t_i the piston starts to move, but does not reach the upper end stop and is pushed back to the lower end stop. This mode is called "ballistic mode" ②. If the pulse t_i is longer than the valve needs to open completely and the pause is longer than the valve needs to close completely the valve operates in the "normal mode" ③. Continuing to increase the pulse t_i the pause t_p gets smaller and smaller because the periodic time is constant. If the pause t_p is too short the piston cannot reach the lower end stop any more; this mode is called the "inverse-ballistic mode" ④. When the pauses t_p decrease further to $t_p < t_{p,min}$ the valve is always activated ⑤. These are the five static modes which exist for a switching valve. Of course more modes exist but these are transient and are influenced by the previous movements of the piston or influence the following movements of the piston. Also the state of suspense where the piston is moving between the end stops without touching them is neglected.

These five static modes can be mapped in a 2D-diagram depending on the periodic time and pulse t_i. The maximum of the pulse t_i correspond to the periodic time T. The duty cycle g is defined as the standardized pulse t_i:

$$g = \frac{t_i}{T} \tag{2}$$

For the following analysis of the behaviour the parameters $t_{v,on}$ and $t_{v,off}$ are set to zero. In Fig. 3 the five static modes are shown depending on the duty cycle g and the frequency f, which is the reciprocal of the periodic time T. Static means the movement of the piston repeats every cycle. This 2D-diagram is constructed using the dynamic model presented in section 2.2. The switching valve always starts in a deactivated mode so the piston is at the lower virtual end stop.

When the chosen periodic time T is high compared to the switching times of the valve all static modes can be mapped. If the frequency f is high the pulse is too short to open the valve completely. For those frequencies no normal mode is possible so only the ballistic mode and the inverse-ballistic mode are usable to control an actuator. The critical point is defined as the point in the intersection between the two borders of the normal mode. This point is marked in Fig. 3 and the movement of the piston for this point is shown in Fig. 3 b. The periodic time corresponds to the sum of t_{on} and t_{off}.

The borders between the five modes depend on the frequency f and the valve parameters which are shown in Fig. 2. The time lag $t_{i,min}$ is constant for all frequencies so that the border between mode ① and mode ② is a straight line with an intersection in the origin:

$$t_i = t_{i,min} \Rightarrow g(f) = t_{i,min} \cdot f \tag{3}$$

The second border between the ballistic mode ② and the normal mode ③ shown in Fig. 3 a or between the ballistic mode ② and the inverse-ballistic mode ④ shown in Fig. 3 c is also a straight line with the intersection in the origin, because the switching time t_{on} is constant:

$$t_i = t_{on} \Rightarrow g(f) = t_{on} \cdot f \tag{4}$$

The other two borders are analogue to the mentioned borders. The switching time t_{off} is also constant. Because of that the border between the normal mode ③ and the inverse-ballistic mode ④ is a straight line too:

$$t_{\mathrm{p}} = t_{\mathrm{off}} \Rightarrow g(f) = 1 - t_{\mathrm{off}} \cdot f \tag{5}$$

Analogue to the time lag $t_{\mathrm{i,min}}$ the time lag $t_{\mathrm{p,min}}$ is also constant. So the border between the mode ④ and mode ⑤ is again a straight line with the following formula:

$$t_{\mathrm{p}} = t_{\mathrm{p,min}} \Rightarrow g(f) = 1 - t_{\mathrm{p,min}} \cdot f \tag{6}$$

The critical point is the intersection of the straight line in Eq. 4 and Eq. 5 so that the critical frequency f_{crit} is characterized by

$$f_{\mathrm{crit}} = \frac{1}{t_{\mathrm{on}} + t_{\mathrm{off}}} = \frac{1}{T_{\mathrm{crit}}} \tag{7}$$

and the duty cycle g_{crit} is characterized by

$$g_{crit} = \frac{t_{\mathrm{on}}}{t_{\mathrm{on}} + t_{\mathrm{off}}} = \frac{t_{\mathrm{on}}}{T_{\mathrm{crit}}} \tag{8}$$

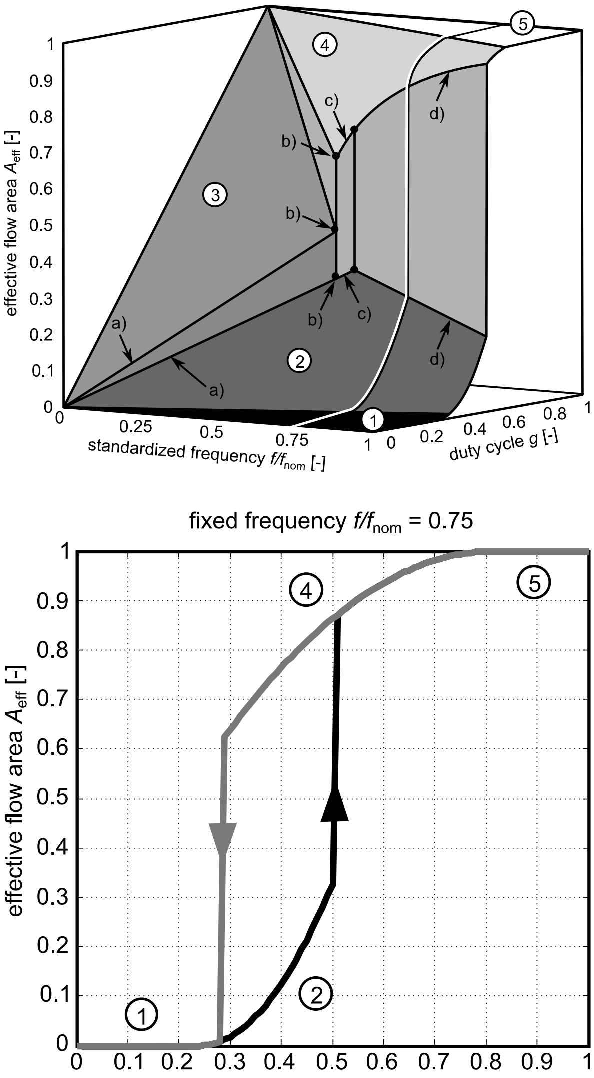

Fig. 4: *Effective flow area A_{eff} of a switching valve depending on frequency f and duty cycle g and the five operation modes*

For frequencies higher than the critical frequency f_{crit} a direct transition from the ballistic to the inverse-ballistic mode exists. Two different kinds of transitions are possible. For lower frequencies the ballistic mode ends when the valve reaches the upper end stop while the pause is too short to reach the lower end stop again, Fig. 3 c. The equation describing this transition is similar to Eq. 4. If frequencies get even higher the pulse may be too short to reach the upper end stop while the pause is still too short to reach the lower end stop as described before, Fig. 3 d. The valve stroke will increase more and more until it reaches the inverse-ballistic mode as a steady state. With respect to the proposed model this transition can be described by the linear equation

$$g(f) = f \cdot m + c \tag{9}$$

$$g(f) = f \cdot \frac{t_{\mathrm{i,min}} \cdot (t_{\mathrm{off}} - t_{\mathrm{p,min}})}{(t_{\mathrm{off}} - t_{\mathrm{p,min}} + t_{\mathrm{on}} - t_{\mathrm{i,min}})} + \frac{t_{\mathrm{on}} - t_{\mathrm{i,min}}}{(t_{\mathrm{off}} - t_{\mathrm{p,min}} + t_{\mathrm{on}} - t_{\mathrm{i,min}})} \tag{10}$$

In the following investigations a normally closed valve with a linear relation between valve stroke and flow area is used for illustration, so if the valve is deactivated the valve is closed. In mode ① and ⑤ the valve is completely closed or open. In the ballistic mode ②, the normal mode ③ and the inverse-ballistic mode ④ the valve is not completely open during one periodic time. In Fig. 4 the effective and standardized flow area A_{eff} of the switching valve (standardized mean value during one periodic time) is shown in 3D-diagram. The effective flow area depends on the frequency f and the duty cycle g. These are the results of the simulation of a exemplary valve with typical parameters. The ranges of the operation modes shown there have similar size than the ones in Fig. 3. The parameters $t_{\mathrm{v,on}}$ and $t_{\mathrm{v,off}}$ are set again to zero so that the borders between the modes are clearly observable. Increased values of $t_{\mathrm{v,on}}$ and $t_{\mathrm{v,off}}$ makes the transition between the named modes smooth. The high step between the ballistic mode ② and the inverse-ballistic mode ④ cannot be prevented.

The simulation results show that only at frequencies lower than f_{crit} the complete spectrum of flow area can be used. For low frequencies the normal mode ③ is dominant. If a frequency f closer to the frequency f_{crit} is chosen the size of the normal mode will be reduced. In this mode the gradient of the effective flow area A_{eff} is constant with respect to the duty cycle g and frequency f. In contrast to the normal mode the gradient of the ballistic and inverse-ballistic mode have a nonlinear shape. The step between the normal mode ③ and the ballistic mode ② or the inverse-ballistic mode ④ is the result of the chosen parameter $t_{\mathrm{v,on}}$ and $t_{\mathrm{v,off}}$. Increased values of $t_{\mathrm{v,on}}$ and $t_{\mathrm{v,off}}$ makes the transition between the named modes smooth. If the chosen frequency f is higher than f_{crit} no normal mode exists. Only the transition from the ballistic mode to the inverse-ballistic mode exists. The effective flow area increases abruptly at the transition between the ballistic mode and the inverse-ballistic mode. The higher the frequency f the bigger is the step of the effective flow area at the transition between the ballistic and inverse-ballistic mode.

The 2D-diagram in Fig. 4 shows the effective flow area at a fixed frequency f. In this graph two curves are shown. The black one describes the behaviour when the piston starts at the lower end stop, the grey one when piston starts at the upper end stop. If the valve operates in the ballistic mode the duty cycle g can be increased or decreased and the valve always behave in the same way. But when the valve operates in the inverse-ballistic mode or is fully opened the hysteresis must be taken into account. For a closed loop control the hysteresis is disadvantageous because it reduces the control performance of linear controllers. For this exemplary valve only the range from g = 0.25 to 0.5 is useable for closed loop control by using the fixed frequency f. Higher duty cycles g lead to a discontinuity and hysteresis in the effective flow area A_{eff} curve. If the complete effective flow area is required in an application, this discontinuity and the hysteresis must be considered.

2.4 Model Validation

In section 2.3 the dynamics of the model were analysed in detail. In this section for one exemplary switching valve it is shown that the model behaves like a real valve with respect to the effects, defined in section 2.1. To generate the 2D-diagram of the operations modes' ranges the depending on the duty cycle g and the frequency f the following experiments were done. The circuit diagram of the test rig (Fig. 5) shows a hydraulic constant pressure source that is connected by hoses to an accumulator and the test valve.

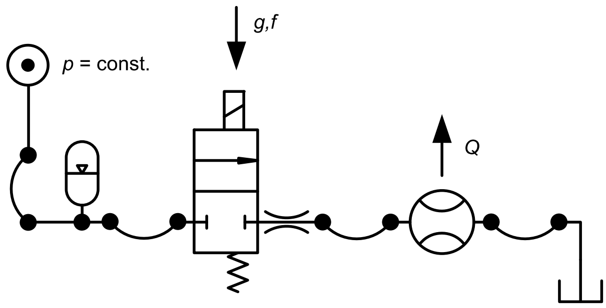

Fig. 5: *Circuit diagram of test rig*

The test valve is a modified pressure compensated poppet valve with a nominal volume flow of $Q_{\text{nom}} = 10$ l/min at a corresponding pressure drop of $\Delta p = 5$ bar. An orifice that limits the volume flow is connected to the test valve. Between the orifice and the volume flow sensor a hose is installed ensure that the effective volume flow is measured. The effective flow area A_{eff} is calculated using the relation

$$Q = \alpha_{\text{D}} \cdot A_{\text{eff}} \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho}} \tag{11}$$

Assuming that α_{D}, ρ and Δp is constant the effective and normalized flow area A_{eff} is directly proportional to Q.

In Fig. 6 the effective flow area depending on frequency f and duty cycle g is shown from the simulation (upper diagram) and the measurements (lower diagram). The reference frequency f_{nom} was chosen to be f_{nom} = 80 Hz. The five modes can be mapped between simulation and measurement very well. Therefore the operation modes of the simulation model are highlighted in both diagrams to show the transitions between each mode calculated out of the simulation model. In these two graphs the effective flow area is difficult to compare. Therefore the effective flow area is shown for a fixed frequency f depending on the duty cycle g in Fig. 7. Additionally, the hysteresis is shown to illustrate the difference whether the valve was activated or deactivated before the measurement started. In this figure two different simulation results are shown. The parameters of simulation 1 are optimized to get a good correlation of the simulation and the measurement with respect to all frequencies. These parameters were also used for the simulation in Fig. 6. In contrast to this the parameters of simulation 2 were optimized to get a good correlation for the rising and falling part of the curve for the fixed frequency shown in Fig. 7.

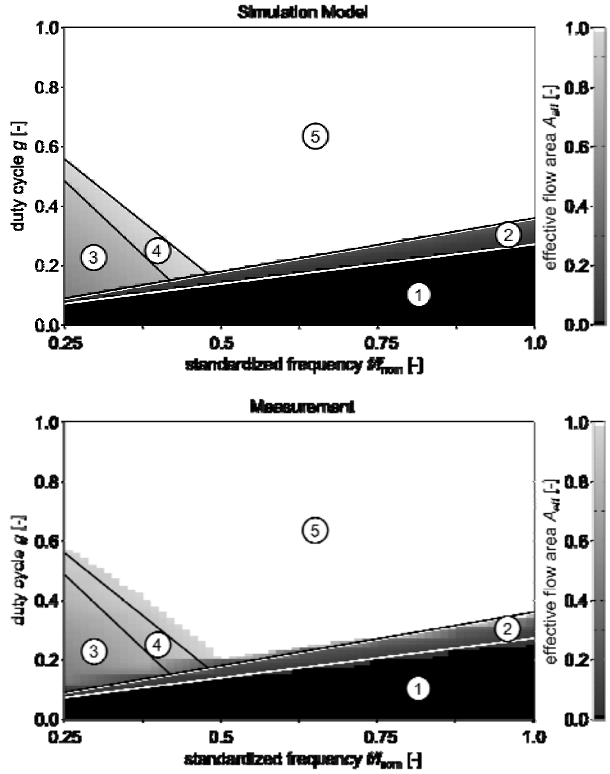

Fig. 6: *Validation of valve model for a normally closed poppet valve with respect to the operation modes (operation modes of simulation model highlighted in both diagrams)*

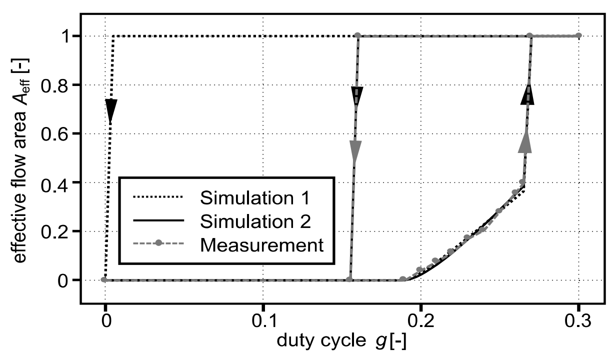

Fig. 7: *Validation of valve model for a normally closed poppet valve with respect to the effective flow rate*

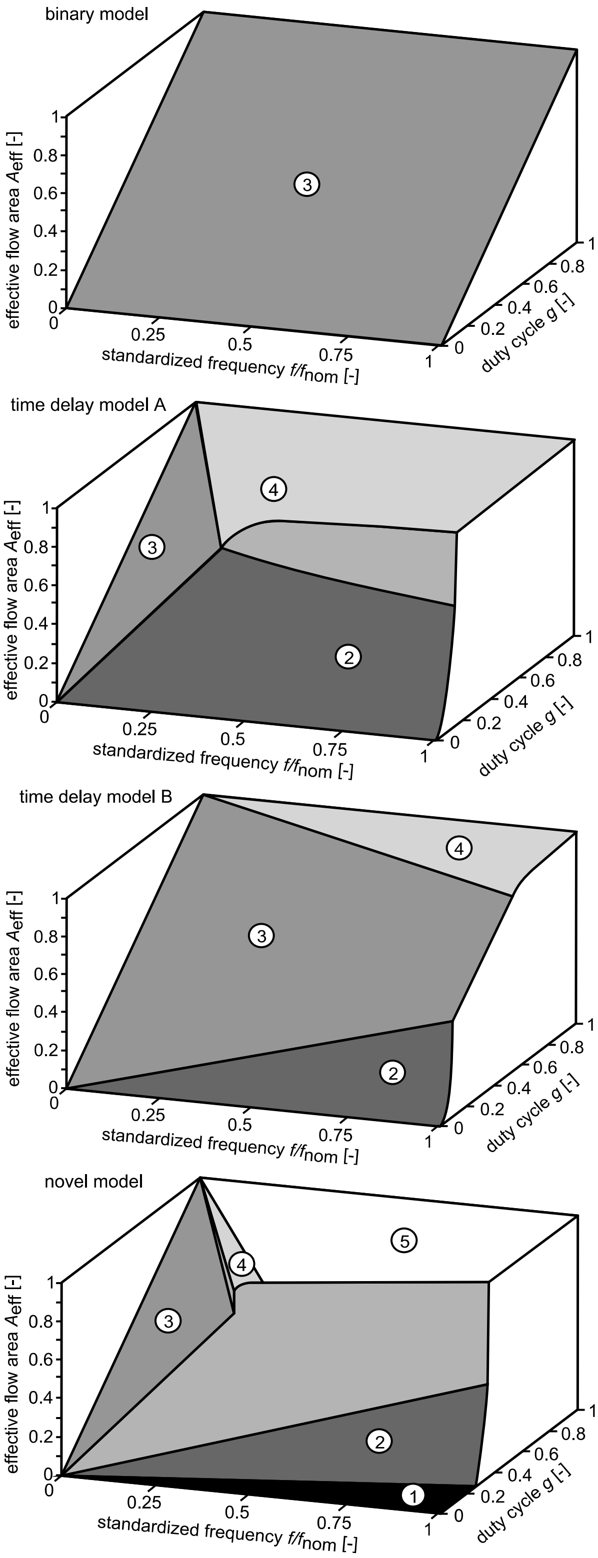

Fig. 8: *Effective flow area A_{eff} depending on duty cycle g for different valve models at a fixed frequency of f/f_{nom} = 0.75*

For the rising edge both simulated curves fit very well to the measurements. Regarding the falling part of the curve simulation 1 shows the hysteresis in principle but not with the correct value of the duty cycle g at which the piston moves from the upper end stop to the lower one. The curve of simulation 2 shows that the behaviour of the novel model can be adjusted very well to given measurements for the fixed frequency even with respect to hysteresis.

The model parameters $t_{i,min}$, t_{on}, $t_{v,on}$, $t_{p,min}$, t_{off} and $t_{v,off}$ which are needed for the model can be identified in different ways, for example by measurements. With the identification of the parameters by measurements a model validation is done in the same iteration.

One possibility is to measure the piston stroke. With these measurements the parameters can be identified easily. Also the sound emission of the valve can be measured. By analysing the recorded sound emissions the borders between the five modes can be identified. Every operation mode has a characteristic sound emission that depends on how many end stops were reached. Eq. 3 to 6 can be fitted to these borders and the parameters can be identified. A third possibility is to measure the volume flow Q and calculate the effective flow area A_{eff}. In this case, to fit the parameters to the measurement an automated fitting tool was used. The parameters can be identified not only by measurements but also by simulations of a more complex and validated existing CFD/FEM-model, for example.

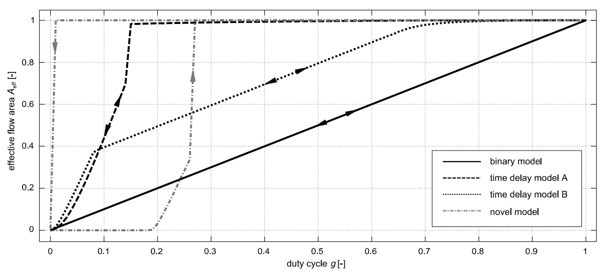

Fig. 9: *Effective flow area A_{eff} depending on duty cycle g for different valve models at a fixed frequency of f/f_{nom} = 0.75*

3 Application of Switching Valve Models

After the discussion about the behaviour and the characteristics of switching valves the novel model will be compared with less complex and more complex models and the area of application of these models will be pointed out.

The less complex models were explained briefly in section 2.2. The simplest model is the binary model, which has just two states. The velocity during activation and deactivation of the valve is infinitely high. So the valve always reaches the upper end stop independently of the duration of the pulse. Therefore only the normal mode ③ can be represented. The behaviour of the binary model is independent of the frequency f as shown in Fig. 8. The effective flow area is linearly dependent on the duty cycle g as shown in Fig. 9. Compared to the novel model the binary model behaves totally different.

A more detailed model with a constant time delay and different slew rates for activation and deactivation behaves more closely to the real valve. If the time delays for activation and deactivation are the same it is not possible to optimally fit this model to the real behaviour. Two possibilities using two different parameter sets for the time delay model are shown in Fig. 10. These two parameter sets were chosen because therein some similarities to the novel model are visible. Of course other parameter sets in between the two chosen parameter sets can be used.

Comparing the time delay model A with the novel model in Fig. 8 the normal mode is very similar in size and effective flow area. As the mode ① and ⑤ cannot be described by every time delay model the ballistic and inverse-ballistic modes are bigger in size and effective flow area. Thus, the step of the effective flow area between both modes is smaller. The time delay model B has more similarities to the binary model than to the novel model. The normal mode is very large and the critical point is shifted to higher frequencies. In the time delay model B the range of the ballistic mode ① has similarities to the one in the novel model, as shown in Fig. 9. In this figure it is illustrated that only the novel model can map the effective flow area to the validated duty cycles which were shown in Fig. 7. Furthermore the time delay model B cannot represent the step at this frequency.

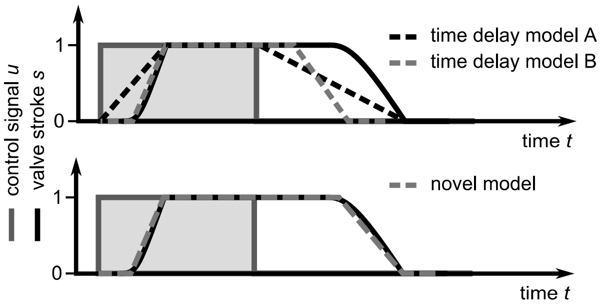

Fig. 10: *Valve stroke for a dynamic model with constant time delay and for the novel model*

The hysteresis of the switching valve is just represented by the novel model. The binary model and time delay models are not able to represent an hysteresis. The accuracy of the novel model is compared to the other models in many operation modes higher.

One reasonable possibility for application of a time delay model in system simulations is a hydraulic system where the valve always opens and closes completely all the time. If the relation between switching speed and switching rate is higher, the valve operates in a intermediate state so the operation modes ① and ② have to be represented exactly and the novel model should be used.

Regarding the effort to identify the model parameters it can be stated that the binary model can be implemented in a simulation easily because no parameters are needed. Using a time delay model the parameters of the time delay and the slew rates are necessary. The effort to gather these parameters is similar to the effort of the novel model, because both parameter sets must be generated out of measurements for example.

After discussing the behaviour of the three different models on valve level the behaviour in an open loop system simulation is analyzed. The structure of the hydraulic system is shown in Fig. 11. It mainly consists of a constant pressure supply, four normally closed switching valves and the hydraulic cylinder connected with a spring-mass-damper system. For each metering edge one switching valve is used to control the cylinder flow. Valve V_1 and valve V_2 or valve V_3 and valve V_4 get the same control signal. The control signal is a pulse-width-modulated signal with a fixed frequency and a varying duty cycle. The chosen dependency of the duty cycle regarding time is shown in Fig. 12. The duty cycle first increases linearly to $g = 0.25$. Then the duty cycle is set to zero and is decreased to $g = -0.25$. This means the actuator first extends - for positive duty cycles - and then retracts - for negative duty cycles. This is done with three different PWM frequencies.

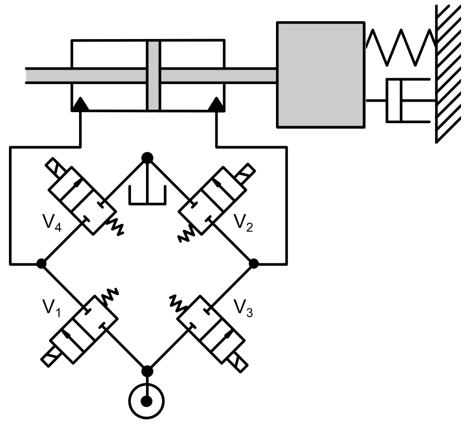

Fig. 11: *Schematic representation of the hydraulic plant*

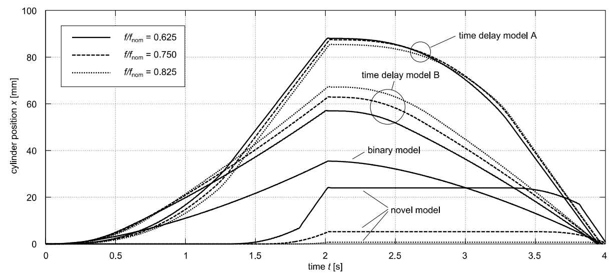

Fig. 13: *Comparison of different valve models on system level for different frequencies*

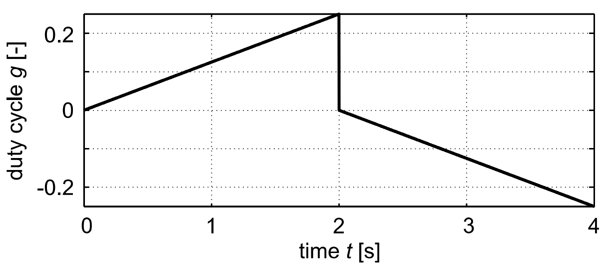

Fig. 12: *Duty cycle of pulse-width-modulated control signal*

The effective orifice area of the binary model is linearly dependent on the duty cycle so the piston stroke of the actuator is a parabolic curve as shown in Fig. 13. For all frequencies the movement of the piston is the same so only one curve is shown. Using the time delay model A or B differences between the three simulated frequencies can be observed. For parameter set A the extension and retraction of the cylinder using different PWM-frequencies is very similar. For this model lower PWM-frequencies result in higher actuator speed. Using the parameter set B higher frequencies result in lower actuator speed. The differences between these two parameter sets are that the actuator extends faster using time delay model A as in this model the inverse-ballistic mode is reached at lower duty cycles, Fig. 9.

The simulation with the novel model shows that for short pulses the actuator does not move, because the valve is still closed. When the duty cycle increases for all frequencies the valve operates in the ballistic mode first. The duty cycle at which the piston of the actuator starts to move is for all three frequencies different because of the constant value of $t_{i,min}$ as shown in Eq. 3. In this particular case only for the lowest frequency the duty cycle is high enough that the valve operates in mode ⑤. That means the valve is completely open and the actuator extends with the maximum velocity.

Obviously the different dynamic models have a huge impact on system level whenever the relation between switching speed and switching rate is high. This is especially the case when the valve is controlled with a pulse-width-modulated control signal with frequencies higher than the critical frequency. The behaviour of the real system was not measured, but it can be expected that the real actuator movement is close to movement which was simulated with the novel model as this valve model is validated regarding the measurements of the effective flow area and the other parts of the model like the cylinder or the spring-mass-damper-system were well proven in other systems.

Comparing the novel model to more complex ones in general is difficult because more complex models are typically tailored to specific valves. Most of these models are nonlinear one-dimensional multi-domain models where many parts like the hydraulic, electric, mechanical or magnetic part are modelled individually (Becker, 2004). Depending on the purpose it is also possible to substitute some of the one-dimensional parts with two- or three-dimensional models with finite elements for example. Characterizing for this kind of more complex models is the fact, that most of the parameters have a physical representation. As these models have many degrees of freedom – the physical parameters itself – and as many physical characteristics of the valve are accounted for the accuracy of these models is obviously higher than the accuracy of the novel model proposed in this paper. Hence, more complex models are necessary whenever specific aspects of the valve itself have to be analyzed or parts of the valve have to be optimized like the metering edge geometry for example. On the other hand the higher accuracy and the higher degrees of freedom generally go along with a higher computational time. The novel valve model is thereby suitable for model-based system simulations during system development like in optimization runs for example in which a trade-off between model accuracy and model complexity has to be made. Regarding the effort to identify the model parameters the novel model and the more complex models also differ. As described in section 2.4 information about the switching behaviour of the valve is needed to identify the parameters of the novel model. This information can be generated out of measurements, for example. In more complex and physically motivated models many parameters can be determined without experiments but can be derived from design documents. But after all for complex models intensive validation tests are inevitable too.

4 Conclusions

It was pointed out that the novel model is capable of describing some of the important effects of the dynamics of switching valves and the resulting operation modes like the ballistic mode which occurs when fast switching control signals are applied. Using the model the characteristics of different operation modes were analyzed to get a more detailed understanding about the behaviour of switching valves.

By comparing the novel model to state of the art models with similar or lower complexity it was pointed out that the results of the novel model in ballistic mode is closer to the behaviour of the real valve than the results of the existing models with lower complexity. The ballistic mode becomes important as soon as the pulse or pause time of the control signal are of the same order of magnitude than the switching times of the valve.

Hence, the novel model is suitable for the use in system simulations with closed loop control of switching valves as it describes the behaviour of the real valve in an adequate manner. Furthermore the novel model offers a good trade-off between model accuracy and model complexity.

Nomenclature

A_{eff}	effective and standardized flow area	[-]
c	y-intercept	[-]
f	frequency	[Hz]
g	duty cycle	[-]
m	slope	[s]
Q	volume flow	[l/min]
s	standardized valve stroke	[-]
T	periodic time of control signal	[s]
t	time	[s]
t_i	pulse time	[s]
t_p	pause time	[s]
u	valve control signal	[-]
x	cylinder position	[m]

Parameters of the valve model

t_{on}	time to complete valve activation	[s]
t_{off}	time to complete valve deactivation	[s]
$t_{i,min}$	minimal t_i for beginning of valve stroke	[s]
$t_{p,min}$	minimal t_p for beginning of valve stroke	[s]
$t_{v,on}$	virtual time constant on activation	[s]
$t_{v,off}$	virtual time constant on deactivation	[s]

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