Analysis of Control Methods for Switching Valve Configurations that Control Die Casting Machines as an Example

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Abstract

This article describes how switching valves can be used in the closed loop control. After studying the requirements of die casting machines, the requirements for a new valve with a switching valve configuration will be derived. In the valve configuration four switching valves are connected among each other, which mean one switching valve per metering edge. So the valve configuration differs to the typical digital valves with commonly four or five valves per metering edge. The switching valves in the valve configuration could not be controlled like normal directional valves. To control the switching valves, digital control methods are used. Commonly the pulse width modulation (PWM) is used. Another approach is the optimized pulse modulation (OPM), which is developed for hydraulic switching valves. In this article the switching valve configuration is used as a pilot for a two way directional valve size 63. The pilot will be controlled with the OPM and PWM, which will be compared in detail.

KEYWORDS: OPM, PWM, digital pilot, 2-way directional valve, die casting

1. Introduction

Switching valve configurations contains one or more switching valves per meter edge, which need to be controlled by digital control methods. Digital control methods have the discrete values one and zero as output like for example the well known pulse frequency modulation (PFM) or pulse width modulation (PWM). The optimized pulse modulation is another digital control method, which is developed especially for the hydraulics introduced by [1]. Another approach is the ballistic Mode (BaM) introduced by [2]. These digital control methods can be used for controlling one or more switching valves. Using more than one switching valve per meter edge the pulse code modulation (PCM) or also known as pulse number modulation (PNM), introduced by [2, 3] for example, are common to use. A novel approach is the meter in/ meter out (MIMO) method, introduced by [2]. The control methods PCM, PNM and MIMO are not part of the investigations in this paper. All these, the different control methods and different switching valve configurations are combined in the notion “Digital Fluid Power”. This notion is defined by [3] as:

“Digital Fluid Power means hydraulic and pneumatic systems having discrete valued component(s) actively controlling system output”.

In this article the investigations are focused on the PWM and OPM and a switching valve configuration with one switching valve per meter edge.

The most common tasks for valves are controlling the pressure or volume flow or positioning a connected actuator for example. In case of using switching valves it is necessary to use digital control methods. Using PWM, PFM, OPM or BaM the switching valves get pulsed input signals. The optimum to achieve the nominal value would be one pulse with the right duration, but this is impossible because of different unknown parameter in a system, like oil density, oil temperature, pressure, depending on the considered system. Normally fast switching valves are used in the digital hydraulics. These valves have switching times of a few milliseconds or less. Examples for fast switching valves are described in [4, 5]. Using the fast switching valves in valve configurations gives the opportunity to create on the one hand a valve with high dynamics, shown by [4]. On the other hand the pulsing gives the opportunity of good fine positioning or a pressure control with high accuracy, shown by [6, 2]. Combining both characteristics may not lead to a valve with high dynamics and a high accuracy. At the moment the fine positioning with a switching valve configuration takes more time compared with a directional valve. Due to the fact that switching valves only have the two static conditions open and close different averaged volume flows can be generated by pulsing. Depending on the systems the pulses can be very high. Connected systems can be affected by these pulses too.

1.1. Piloted valves

Common directional hydraulic valves, which are larger than size 10, are always piloted. These valves are piloted because the dynamics of these valves is much higher than direct controlled directional valves. For the pilot only 3-way valves or valves with the same functionality can be used. But the type of the 3-way valve can differ. The most common types are directional proportional solenoid valves or servo valves. Sometimes two parallelized directional proportional solenoid valves are use to increase the dynamics. Another variation is to use four switching valves.

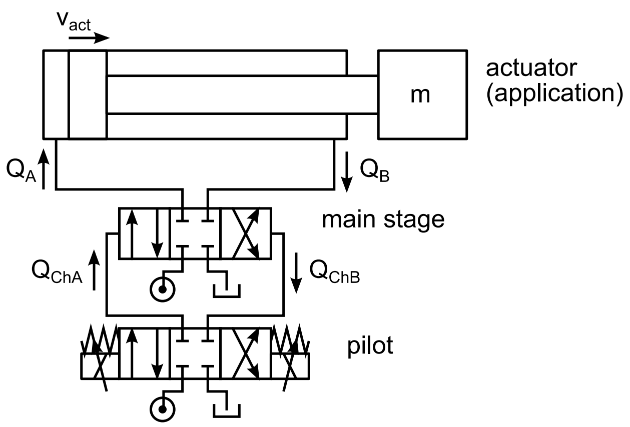

Figure 1: Schematic illustration of a piloted valve connected with an actuator

The requirements for the pilot and for the main stage are different. The requirements for the main stage will be generated by the application. Out of these requirements the requirements for the pilot will be derived. The relations between the pilot and the main stage are fixed. If the requirement of the application is an accurate volume flow, the main stage needs to be positioned precise. So the target of the pilot is to position the main stage precise and not generate an accurate volume flow. If the pilot can generate accurate volume flows, the main stage generates accurate derivations of the volume flow. So the requirements for main stage differ to the one of the pilot.

2. Applications

Switching valves can be used for different tasks. Traditionally poppet switching valves are used for security tasks; they have no leakage by definition. In the car industry switching valves are commonly used in anti-lock breaking systems (ABS) [3] or in electronic fuel injection systems [3]. 2008 a project for electro-hydraulic brakes switching valves were used for braking a car [7]. In 1995 a PhD thesis investigated switching valves for steering a car [8]. In combustion engines switching valves are used for controlling the intake and exhaust valves [9]. In mobile applications switching valves are successfully used as pilot [3, 10]. For mobile applications the requirements differs to industrial applications. At the moment it is common to use directional valves in industrial applications and just a few projects with digital hydraulics can be found.

2.1. Die casting

Die casting machines as shown in **figure 2** can produce casting products in high quality. The cast process is also very fast, so it is used in mass production. For example the engine blocks or the gear casings are typical die casting products.

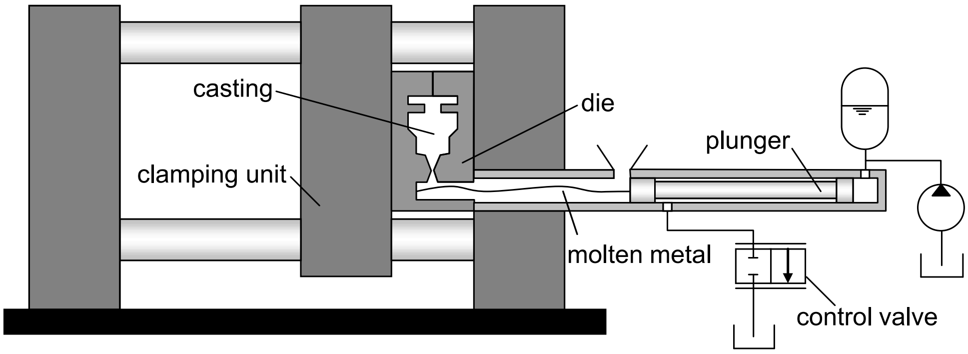

Figure 2: Schematic illustration of a cold chamber die casting machine

The die casting process has three phases. Before the first phase starts the molten metal is filled in the casting cylinder. The quantity depends on the size of the casting. Then the plunger telescopes the molten metal, which is identified as phase 1, and is illustrated in **figure 3**. Therefore the plunger accelerates to about 300 mm/s. This velocity depends on the molten metal, the size of the die casting machine and other parameters. Important is to reach the nominal velocity exactly, because it must be ensured that no air will be trapped from the molten metal. When the molten metal is telescoped completely it will be squeezed into the die. Therefore the plunger must accelerate rapidly to the nominal maximum speed of phase 2. When the molten metal is completely squeezed in the die, the metal will be pressurized. This decreases the shrinkage of the casting during quenching process.

Commonly 2-way fast directional proportional valves or 2-way servo valves are used for controlling the die casting process. One requirement for the control valve is to control small volume flows accurate, to realize the small velocities in phase 1. The second requirement is to open the valve very fast to achieve high volume flows, which induce to high velocities of the plunger in phase 2. The third requirement is to control the pressurization of the casting in phase 3, which should be also very accurate. From these requirements the requirements of the pilot can be derived. For phase 1 it is necessary to position the main stage accurate with no overshoots. The dynamics in this case is not that important. In phase 2 the dynamics are the most important requirements. The main stage should open as fast as possible. Short overshoots may lead to no reduction of the casting. The pressurization in phase 3 should be without any overshoots, but the dynamics may not need to be as high as in phase 2.

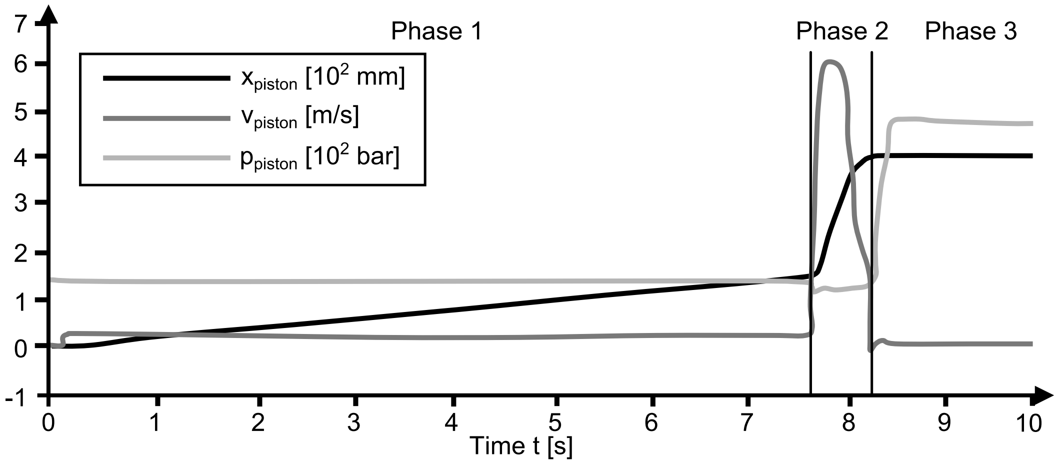

Figure 3: The three phases of the die casting process

2.2. Pilot with switching valve configuration

As also mentioned in chapter 1.1 the most common used valves as a pilot are directional proportional solenoid valves and servo valves. Servo valves have high dynamics and a high quality of control. But the servo valves also have a leakage volume flow and a control volume flow. These volume flows are negative for the energy efficiency of the valve, because these volume flows are always present, also when the valve is close. The used oil for the control volume flow needs to be very clean too.

Using the switching poppet valves for a pilot no control and no leakage volume flows exist. Other switching valves normally have a very low leakage compared with servo valves. The switching valves are not loosing the functionality as fast as servo valves when using particle contaminated oil. Using switching valves in many different applications the possibility of low production cost exists for the future. So there is a potential for lower costs for a switching valve pilot than a servo valve pilot. As mentioned in chapter 1, the switching valves cannot have high dynamics and high quality of control at the same time. But the requirements for a pilot of a control valve that can be used in die casting machines, as mentioned in chapter 2.1, seems to be achievable with switching valve configuration.

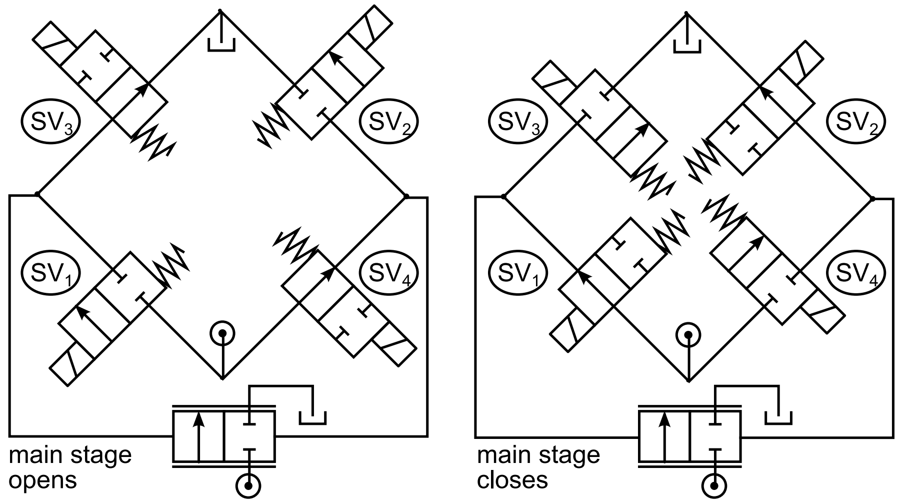

Figure 4: Schematic illustration of a piloted valve witch a piloted valve

Typically piloted 2-way directional valves of the size 63 are used in die casting applications. For this main stage the following switching valve configuration is designed. Four 2-way switching valves are used with a nominal volume flow of 40 l/min at a pressure drop of 5 bar over a switching valve. Which switching valves need to be switched to open and close the main stage is shown in **figure 4**. The independent metering edges are chosen, to have more options for optimization in future work. In this paper switching valve one (SV_1) and two (SV_2) or switching valve three (SV_3) and four (SV_4) will be always switched at the same time.

3. Modelling

For the analysis of the PWM and OPM a model for fast simulations is required on the one hand. On the other hand a certain deepness of detail is also required, to ensure the possibility of simulating the ballistic mode. In this mode the pulse of a control signal for one switching valve is as short as the piston cannot reach the upper end stop. A model with these two requirements and which is also used in the simulations of this paper, was developed and is discussed in detail in [11].

The focus of this paper is on comparing the OPM and PWM for controlling a piloted 2-way directional valve of the size 63. Therefore the OPM will be introduced briefly and the behaviour of the switching valve using the OPM and PWM will be discussed. For this the operation modes of a switching valve will be introduced in chapter 3.1

The main stage is modelled as a double-rod cylinder with mass, friction, leakage and averaged volume forces. Basis for the model is the Newton's equation of motion and the data from the data sheet of the piloted 2-way directional size 63 (Bosch Rexroth AG) [12].

3.1. Digital control methods

In [11] the operation modes of a switching valve are discussed in detailed. Every switching valve can operate in the following five modes: the valve is always deactivated (1), ballistic mode (2), normal mode (3), inverse-ballistic mode (4) and the valve is always activated (5). These five modes are shown in **figure 5**. In which operation modes the valve operates depends on the control method. Using the PWM for example, the frequency is fixed. The chosen frequency in figure 5 allows the switching valve to operate in all operation modes. Choosing higher frequencies it is possible that the valve cannot operates in every operation mode. Using the PWM it is only possible to move on a vertical line in the operation modes diagram.

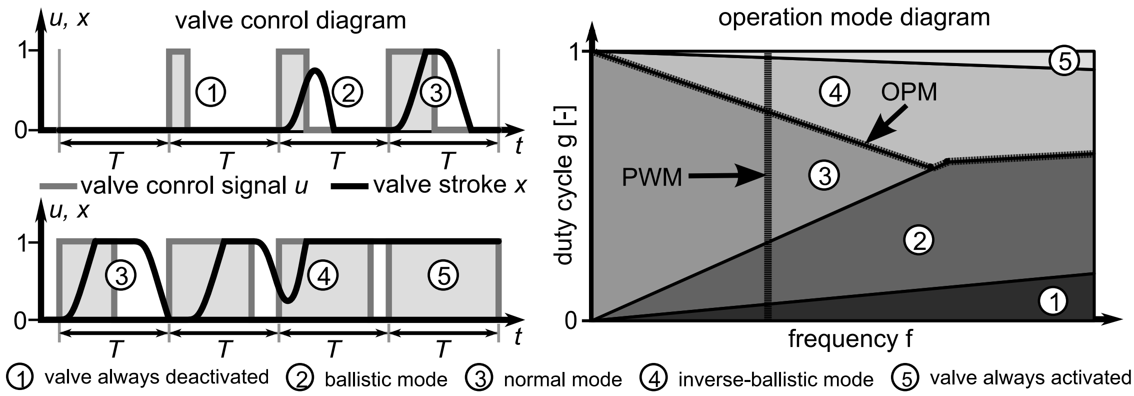

Figure 5: Operation modes of a switching valve as introduced in [11]

In contrast to the PWM the OPM behaves in a complete different way. The target of the OPM is to minimize the pauses and ensure that the piston is at the end of the pause always at the lower end stop as shown in **figure 6**. The pause will be calculated by a model of the switching valve. The real valve will not behave like the valve model, because the temperature of the oil changes or the manufacturing tolerances is commonly neglected in the valve model. Therefore the robustness parameter k_{robust} is added. As shown in figure 6 the pause is always optimized independently of the duration of the pulse.

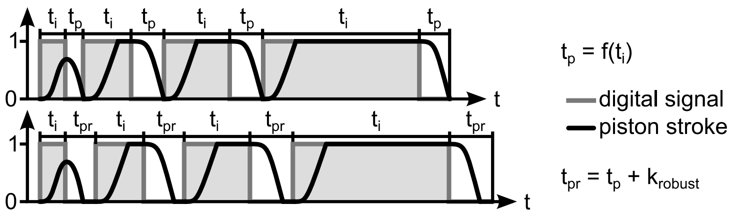

Figure 6: OPM modulated signal and piston stroke of a switching valve [1]

For the following investigations the robustness parameter k_{robust} is set to zero. In this case the valve behaves as shown in figure 5. The valve always operates at the border to the inverse-ballistic operation mode. Using valves with different switching times the behaviour of the valve is still the same; the valve always operates at the border to the inverse-ballistic mode. This is the result of including the valve model in the OPM. In other digital control methods like the PWM no valve model is included.

Using the robustness parameter k_{robust} the valve will not directly operate at the border to the inverse-ballistic mode but in the normal mode and in the ballistic mode close to the border of the inverse ballistic mode. The distance to the border depends on the value of the robustness parameter.

4. Simulation results

The two control methods OPM and PWM will be compared. In chapter 3.1 the two control methods are compared generally. Now simulations were done with the same hardware. The pilot and the main stage had the same conditions. The system pressure of the pilot $p_{0,pilot} = 79\ bar$ and a Tank pressure of $p_{T,pilot} = 5\ bar$. The four used switching valves for the pilot have a volume nominal flow $Q_{nenn,SV} = 40\ l/min$ at a pressure drop $dp = 5\ bar$. When the main stage is open, there is a pressure drop of 5 bar over the main stage.

The controller for the OPM and the PWM are different, but can be compared with a proportional controller. The OPM needs the pulse duration $t_{i,OPM}$ as input in contrast to the PWM, which needs the duty cycle g_{PWM}, the normalized pulse duration $t_{i,PWM}$ as input. The OPM controller uses the displacement error x_{error} of the main stage for calculating with the chambers' geometrical data of the main stage the oil volume V_{error} that is needed. With the averaged volume flow $Q_{averaged}$ over the pilot and the needed oil volume the pulse duration t_i can be calculated by:

$$t_i = \frac{V_{error}}{Q_{averaged}} = \frac{x_{error} \bullet \left(d^2_{outer,chamber} - d^2_{inner,chamber}\right) \bullet \pi}{4 \quad Q_{averaged}} . \quad (1)$$

The outer diameter of the control chamber of the main stage is represented by $d_{outer,chamber}$ and the inner diameter of the control chamber of the main stage by $d_{inner,chamber}$. With the duration of the pulse t_i the pause t_p can be calculated with the model of the switching valve that is left in the OPM like proposed in [1]. Such a calculation cannot be done for the PWM. There just a proportional controller is needed.

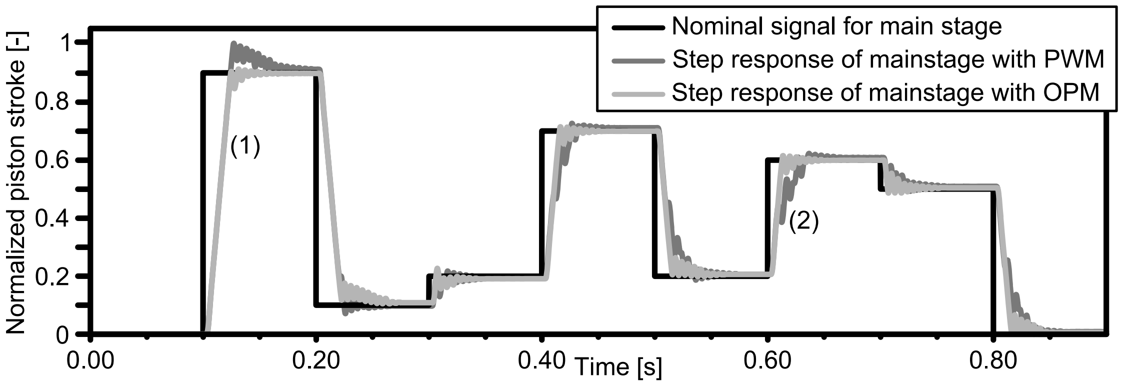

Figure 7: Comparison of the OPM and the PWM ($f_{PWM,1}$ = *100 Hz*) with step responses of the main stage with switching valve pilot

For the PWM the two frequencies $f_{PWM,1}$ = *100 Hz* and $f_{PWM,2}$ = *40 Hz* are chosen. The first frequency $f_{PWM,1}$ = *100 Hz* was chosen as a compromise between the reaction of the switching valve using the PWM and switching not too often. Both reaction and the number of switching operations are important requirements. The comparison of the PWM with $f_{PWM,1}$ = *100 Hz* and the OPM is shown in **figure 7**.

The step response of the PWM is not optimal. At the first step from 0% to 90% (1) of the maximum piston stroke the main stage opens rapidly, but there is a big overshoot. In contrast to the first step the one from 20% to 60% (2) is much slower as the first one. In this case the durations of the pulses are for the step (2) not optimal. Of course some steps also have the optimal durations to compensate the control deviation. In contrast to that the OPM can optimize the durations of the pulses as illustrated in figure 7. Both OPM and PWM are oscillating around the nominal value. This oscillating is due to the modelled main stage. These oscillations can be also observed in the second comparison.

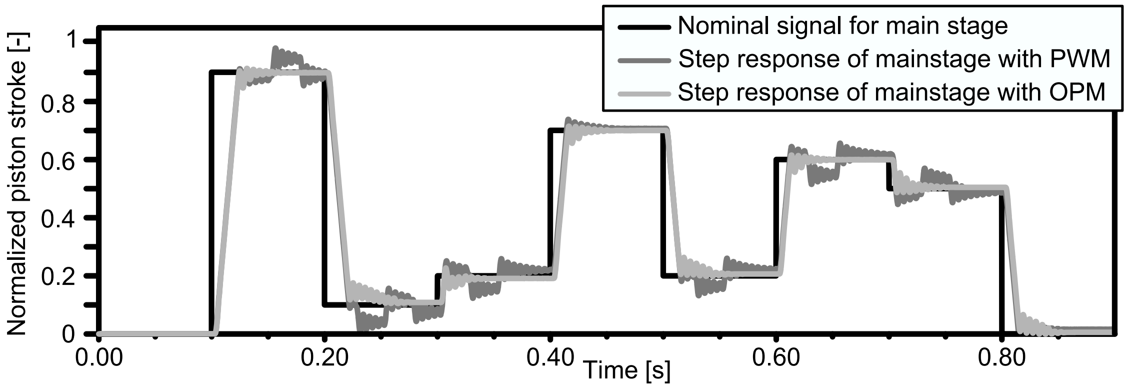

Figure 8: Comparison of the OPM and the PWM ($f_{PWM,2}$ = *40 Hz*) with step responses of the main stage with switching valve pilot

The second PWM frequency $f_{PWM,2}$ = *40 Hz* was chosen to show that the fast compensation of the control deviation can be also achieved as shown in **figure 8**. The PWM frequency corresponds to the PWM period T_{PWM} = *25 ms*. This duration is longer than the opening time of the main stage. But now the reaction of the pilot is very slow. The profile of the steps is optimal for the PWM frequency $f_{PWM,2}$ = *40 Hz*, because four periods fit exactly into the duration of 0.1 s. The problem of the reaction depends on the duration of the PWM period. The lower the PWM duration the faster is the reaction. Compared to the OPM the usage of a PWM with a frequency of 40 Hz is also no opportunity. One possibility to tune up the PWM is to use different frequencies. For large control deviations small frequencies and for small control deviations high frequencies can be used. The OPM does exactly this, the larger the control deviation the smaller is the frequency. This is also shown in eq. 1 and figure 5.

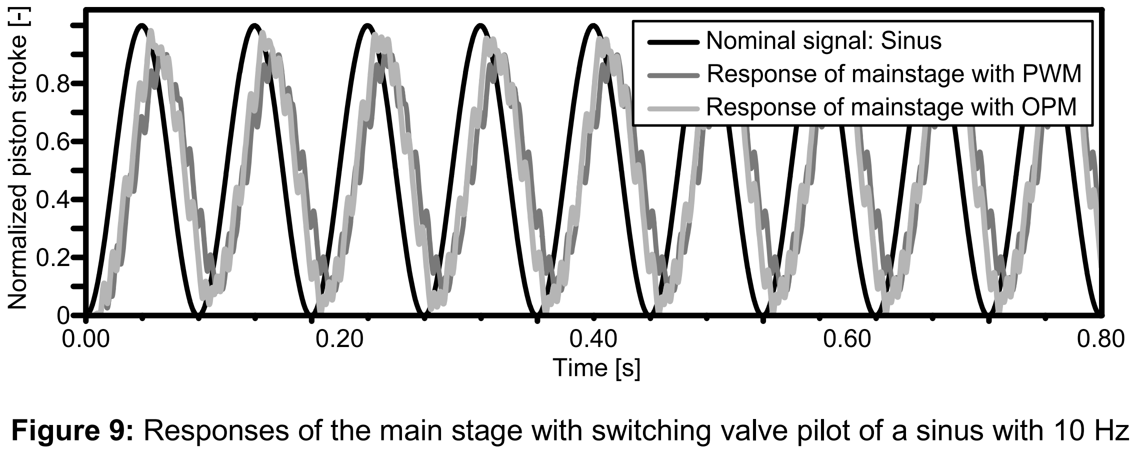

Figure 9: Responses of the main stage with switching valve pilot of a sinus with 10 Hz as input signal

The last comparison is done with a sine wave signal. The amplitude is 50% of the maximum piston stroke of the main stage and the mean level is 50% of the piston stroke. The frequency is $f_{sin,nom}$ = *10 Hz*. This nominal signal is hard to follow for a main stage with a switching valve pilot, because the velocity of main stage always changes. The changing velocity of the main stage corresponds to different volume flows, which the switching valve pilot has to generate. But exactly this is one the disadvantages using switching valves and digital control methods, what was also mentioned in chapter 1.

5. Conclusion and outlook

The first approach of the OPM was presented in [1]. Further simulative investigations of the OPM, presented in this paper, showed the advantages of the OPM in contrast to the PWM. The advantage of the OPM is, having the opportunity, to generate all pulse durations. The PWM does not have this opportunity; the maximum duration of a pulse corresponds to the PWM period. The key to achieve better results for the step responses is the optimization of the pause. In [1] the qualitative differences of the OPM and PWM were shown for a main stage size 32. In this paper further investigations with a main stage size 63 confirmed the qualitative investigations of [1] and the disadvantages of using switching valves with digital control methods. But the requirements of the die casting machine, which is a possible application for the switching valve pilot still seems to be achievable in the future with a prototype.

The next steps are to develop a test bench for the switching valve pilot in combination with the use of digital control methods. The pilot will be tested on a main stage size 63. After this validation the simulation can be enlarged to a system simulation of a die casting application.

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7. Symbols

f	Frequency	Hz
g	Duty cycle	-
p	Pressure	bar
Q	Volume flow	l/min
t_i, t_p	Duration of pulse and pause	s
v_{piston}	Velocity of plunger	m/s
V	Volume	m^3
x	Position	mm