Proceedings of Bath/ASME Symposium on Fluid Power & Motion Control
ASME/Bath 2015
October 12-14, 2015, Chicago, Illinois, USA

FPMC2015-9607

ANALYSIS OF WAVE PROPAGATION EFFECTS IN TRANSMISSION LINES DUE TO DIGITAL VALVE SWITCHING

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ABSTRACT

In digital hydraulic systems, switching valves have opening and closing times in the range of a few milliseconds. Due to this fast switching, high bandwidth pressure pulsation is excited, which is the stimulus for airborne noise up to some kilohertz. Since the human ear is very sensitive to audible noise in this frequency range, an analysis of the influence of the valve's opening curve on the pressure surge in the pipe system is intended. The study is based on simulations employing dynamic pipe models for linear wave propagation and laminar fluid flow. In particular, a simple pipe system with a valve at one end and a pressure boundary at the other end of the pipe is investigated. It is shown, how the valve opening characteristics of spool and seat type switching valves influences the pipe responses. Also the role of parasitic inductances due to the valve block bores is discussed and it is shown how the switching characteristics influences the dynamical effects on the pressure pulsations in the pipe system.

NOMENCLATURE

A	cross-section area of pipe line
c_0	wave speed
Δp	pressure drop
Δq	flow rate according to Δp
d_L	diameter of transmission line
d_P	diameter of parasitic pipe
K	bulk modulus of the fluid
$\varkappa$	polytropic exponent
l_L	length of transmission line
l_P	length of parasitic pipe
N	number of elements (MOC)
ν	kinematic viscosity
p_{0_G}	pre-pressure of accumulator
p_i	pressure at location i
p_L	load pressure
p_N	nominal pressure drop
p_S	supply pressure
q	flow rate
Q_N	nominal flow rate
ρ	fluid density
t_{MOC}	MOC time step
V_A	volume of accumulator
V_P	parasitic volume of the flow channels
ξ	valve orifice opening
Z_0	pipe impedance

INTRODUCTION

A major expected advantage of digital hydraulics is the possibility to replace expensive proportional valves by cheaper digital valves, which are also more robust with respect to oil contamination (see e.g. [1]). Furthermore, by a parallel arrangement of several valves like, for instance, in Digital Flow Control Units according to [2], the reliability of hydraulic systems can be improved significantly. Moreover, with fast switching digital hy-

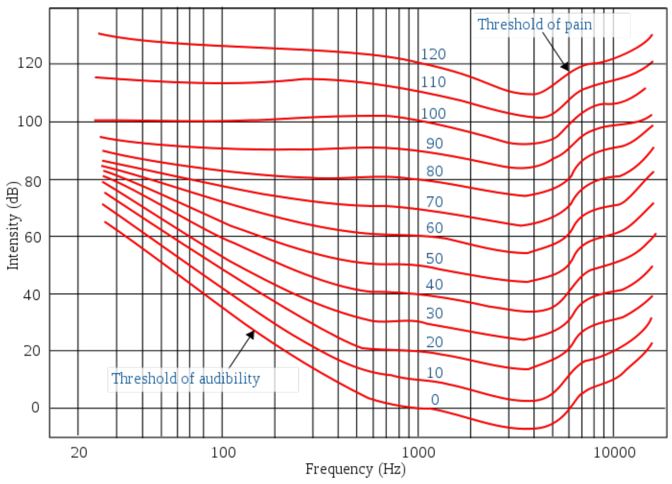

FIGURE 1. THRESHOLD OF HEARING

draulic valves a number of different hydraulic switching converters can be realized, which are able to operate at much higher efficiencies than conventional proportional hydraulics (see e.g. [3, 4, 5]). In contrast to the mentioned advantages digital hydraulics may suffer from additional noise due to the switching of the digital valves, which cause pressure surge effects in transmission lines or even in flow channels of valve blocks.

Noise in hydraulic systems is a well known problem for many years. According to [6] it is an interaction of structure-borne, fluid-borne and airborne noise effects. Especially the part which is radiated as airborne noise is a big topic in digital hydraulics, since health and safety issues for human operators become more important. So far, in hydraulics the source of noise was mainly determined by pumps and motors. The fast switching in digital hydraulics represents a further source of noise in hydraulic systems. The switching process causes sharp pressure edges, which may provoke mechanical vibrations of valve blocks, connected pipes and surrounding coverings, which at the worst could act as a sort of loudspeakers. Actually, the today feasible switching frequencies are in the range of $100 Hz$ and, thus, are hardly audible. But the high pressure gradients due to the switching correspond to a broadband excitation of the pipe system. Furthermore, hydraulic transmission lines are dynamical systems with certain natural frequencies, which may respond with large pressure pulsations even in case of low excitation. The shorter the pipe line, the higher the natural frequencies, which may reach up to frequencies of several kilohertz. According to [7] in this frequency range the human hearing is very sensitive as can be seen in Fig. 1, and noise is felt quite unpleasant. Since it is highly nontrivial to predict the complete system behavior resulting from the interaction between fluid-borne, structure-borne and airborne noise, the investigations are concentrated on countermeasures in hydraulic domain. This assumption is very common in practice because pressure pulsations are known as the major problem and their reduction in the undesired frequency range comforts the noise behavior in case of airborne noise problems. The intention of the investigations is to analyze the pressure responses due to valve switching and to find ideas, which are potentially qualified for airborne noise reduction in digital fluid power systems. For this purpose system responses of simulations in time domain are analyzed in frequency domain with regard to the critical frequency band of Fig. 1.

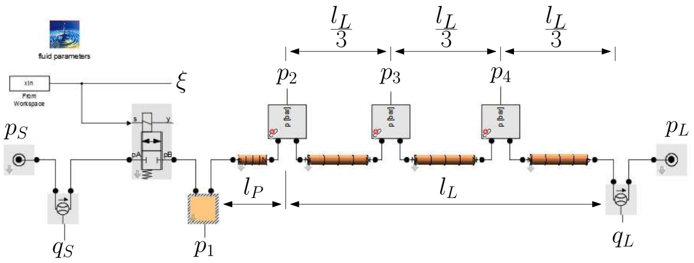

FIGURE 2. SIMULATION MODEL OF A SIMPLE TRANSMISSION LINE IN *MATLAB/SIMULINK*

MODELING

In the following subsections the different simulation models used for the investigations are presented. The individual simulation models are set up in Matlab/Simulink based on a linear method of characteristics (linear MOC) with regard to [8], which is implemented in the hydrolib3 toolbox according to [9].

Transmission Line Model with a single Valve

The basic structure of the models consists of a straight transmission line controlled by a 2/2-way directional valve, as shown in Fig. 2. The valve's opening curve (ξ) is directly provided from the workspace in Matlab, i.e., no further switching dynamics are considered in the valve model. The valve connects the transmission line at an initial load pressure p_L with supply pressure p_S. The open end of the pipe line has a pressure boundary condition, which is representative for a number of applications like, for instance, a cylinder drive. However, to keep the considerations as simple as possible, the pressure boundary is sufficient for the investigations, which means that coupling of the load is neglected. In Fig. 2 the additional cavity (p_1) between the transmission line and the valve represents the flow channel, which is inevitable in a real valve block design. The pressure in the transmission line is calculated at three more locations (p_2, p_3, p_4) along the pipe in order to observe wave propagation effects.

Transmission Line Model with Valve Block Channels

The second simulation model considers a further dead end pipe branch according to Fig. 3. The corresponding pipe and the

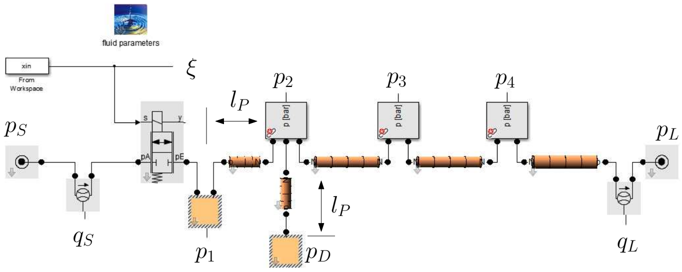

FIGURE 3. SIMULATION MODEL OF A TRANSMISSION LINE WITH A DEAD END BORE IN *MATLAB/SIMULINK*

cavity (p_D) at its end represent the flow channel to another closed directional valve, which would be necessary for a flow in the reverse direction through the transmission line like, for instance, a linear cylinder drive operating in both moving directions. Thus, this model represents the minimum dynamic model of a drive line comprising a digital valve block.

Simulation Parameters

The simulation parameters used in this investigation are listed in Tab. 1. The pipe dimensions are chosen in the range of common hydraulic applications. The nominal size of the valve is dimensioned for laminar pipe flow in all simulated operating points. The switching times of the valve are varied between $1\,ms$ and $3\,ms$, which is common for hydraulic switching converters.

SIMULATION

In the following the different pipe responses due to digital valve switching are presented. The main effects are studied along transient responses due to opening and closing of the valve, respectively.

Simple Pipe Line

Figure 4 shows a common pressure response along a transmission line due to a ramp-like valve opening at a switching time of $2\,ms$ simulated with the model according to Fig. 2. The ramp-like opening curve $\xi(t)$ in the lower graph corresponds to the hydraulic valve edge opening of a digital spool valve with an *ideal* valve overlap, which means that no leakage is considered in the closed position of the valve. Fast switching digital spool valves have an overlap in the range of 50% of the full spool stroke in order to keep the leakage sufficiently low in the closed position of the valve (see, for instance, [10]). As a consequence the spool passes the valve overlap at high speed, which leads to sharp edges in the pressure response in the upper graph. Thus, spectral components of higher frequencies are present in the pressure signal. Additionally, in practice, the flow channels in a valve block

TABLE 1. SIMULATION PARAMETERS

Parameter	Value
supply pressure	$p_S = 200\,\text{bar}$
line pressure	$p_L = 100\,\text{bar}$
bulk modulus of the fluid	$K = 14000\,\text{bar}$
density of the fluid	$\rho = 860\,\frac{\text{kg}}{\text{m}^3}$
kinematic viscosity of the fluid	$\nu = 46\,\text{cSt}$
nom. flow rate of the switching valve	$Q_{N_{Sx}} = 10\,\frac{\text{l}}{\text{min}}$ @5bar
length of the transmission line	$l_L = 3\,\text{m}$
hydr. diameter of the transmission line	$d_L = 15\,\text{mm}$
length of the parasitic pipe	$l_P = 0.125\,\text{m}$
hydr. diameter of the parasitic pipe	$d_P = 8\,\text{mm}$
parasitic volume of flow channels	$V_{P_{1,D}} = 4\,\text{ml}$
volume of the accumulator	$V_A = 0.321$
pre-pressure of the accumulator	$p_{0_G} = 80\,\text{bar}$
polytropic exponent	$\varkappa = 1.3$
number of MOC elements for l_L	$N_{l_L} = 3 \cdot 38 = 114$
number of MOC elements for l_P	$N_{l_P} = 6$
MOC time step	$t_{MOC} = 2 \cdot 10^{-5}\text{s}$

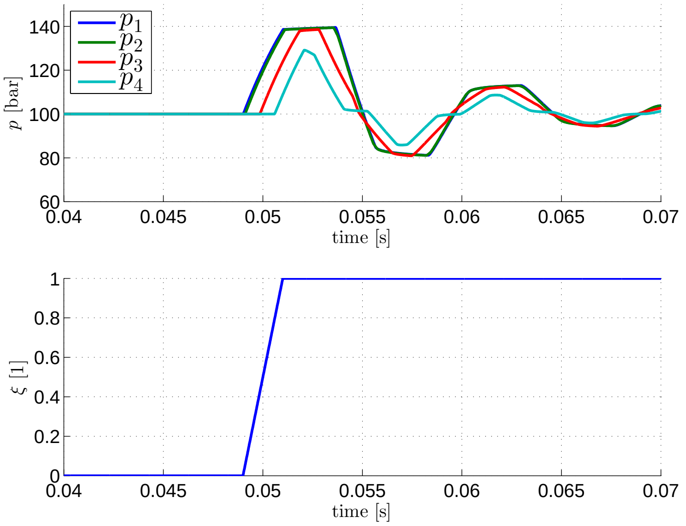

FIGURE 4. RAMP-LIKE VALVE OPENING FOR A SIMPLE TRANSMISSION LINE

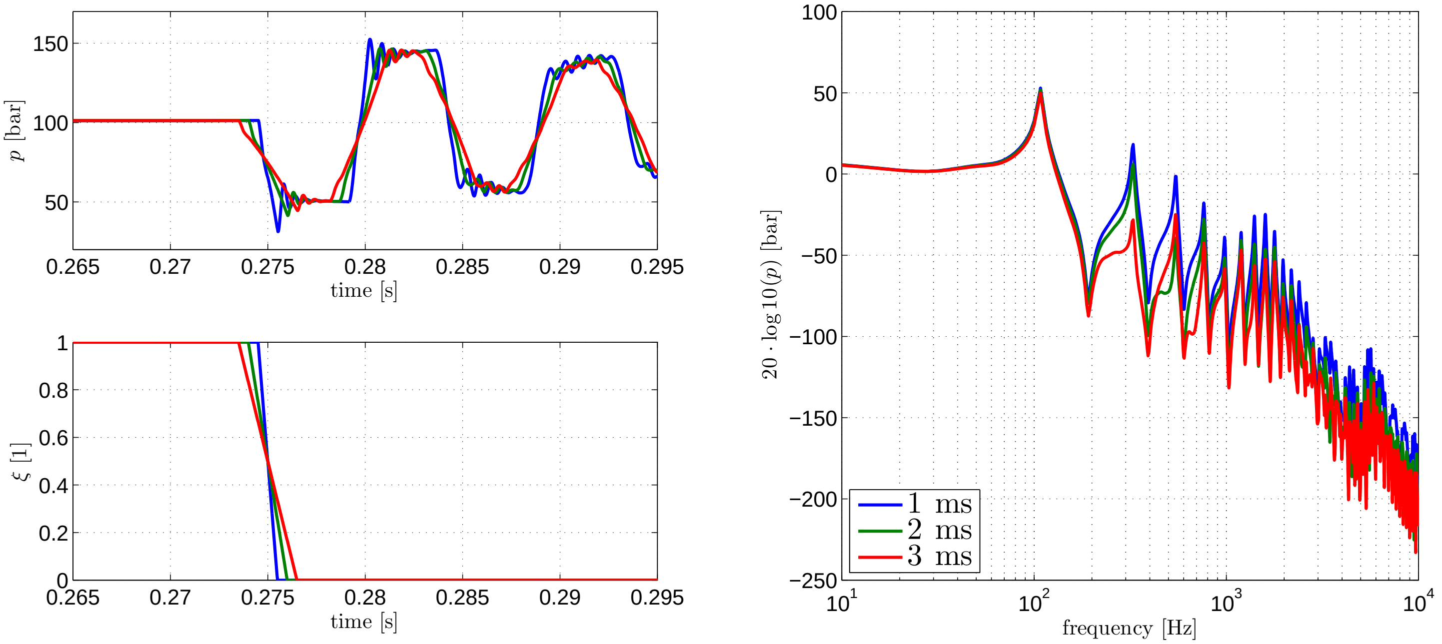

FIGURE 6. RAMP-LIKE VALVE CLOSING WITH PARASITIC INDUCTANCE AT DIFFERENT CLOSING TIMES

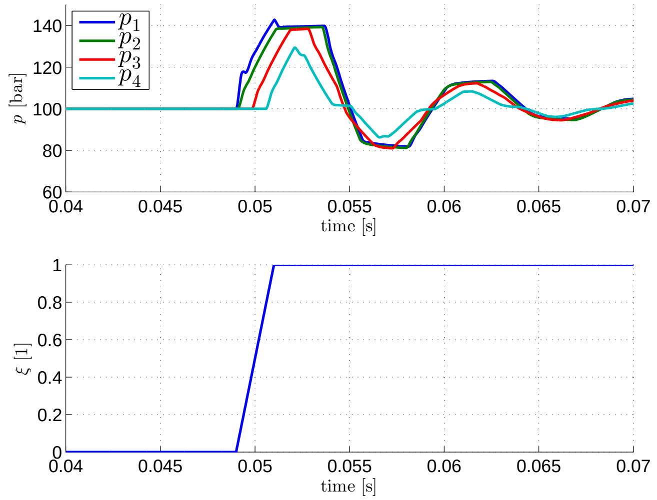

FIGURE 5. RAMP-LIKE VALVE OPENING WITH A PARASITIC INDUCTANCE

consist of bores with different cross-sections. Figure 5 shows a pressure response of the model according Fig. 2, in which the diameter of the pipe l_P was reduced from $15\,mm$ to $8\,mm$ in order to demonstrate the dynamic effect of such a short thinner *parasitic* bore between the valve edge and the main transmission line. The harmonics of the ramp-like valve opening result in additional small oscillations in the pressure response along the pipe line due to the parasitic inductance. In contrast to the valve opening, where the noise effect due to the parasitic inductance seems to play a secondary role, the closing of the valve shows to be much more critical. In Fig. 6 responses for ramp-like valve closure at the location p_1 in the valve cavity are depicted. On the right hand side the frequency responses of the transient pressure signals are illustrated for three different switching times. It can be seen, that the harmonics of the closing ramp of the valve excites many natural frequencies of the main transmission line and, furthermore, of the parasitic inductance. Moreover, the magnitudes of the frequencies above $1\,kHz$ are even raised. The main reason for this broadband excitation is the instantaneous transition from "valve open" to "valve closed" at maximum speed of the spool due to the valve overlap. This effect is getting even more relevant, if another parasitic pipe inductance is present according to Fig. 3, as shown in the following.

Valve Block Model

In Fig. 7 the pressure signals and the corresponding frequency responses of the model considering a side branch pipe to a second closed valve and the valve cavity according to the model of Fig. 3 are depicted. The parasitic pipe system, which consists of the two branches and the corresponding valve cavities, represents a resonator, which is excited by the ramp-like closing action. In the frequency response on the right hand side of Fig. 7 a resonance peak at approximately $2\,kHz$ appears, which is obviously in the most sensitive area of the threshold of hearing according to Fig. 1. Thus, the response of the parasitic pipe system potentially leads to an undesired airborne noise behavior.

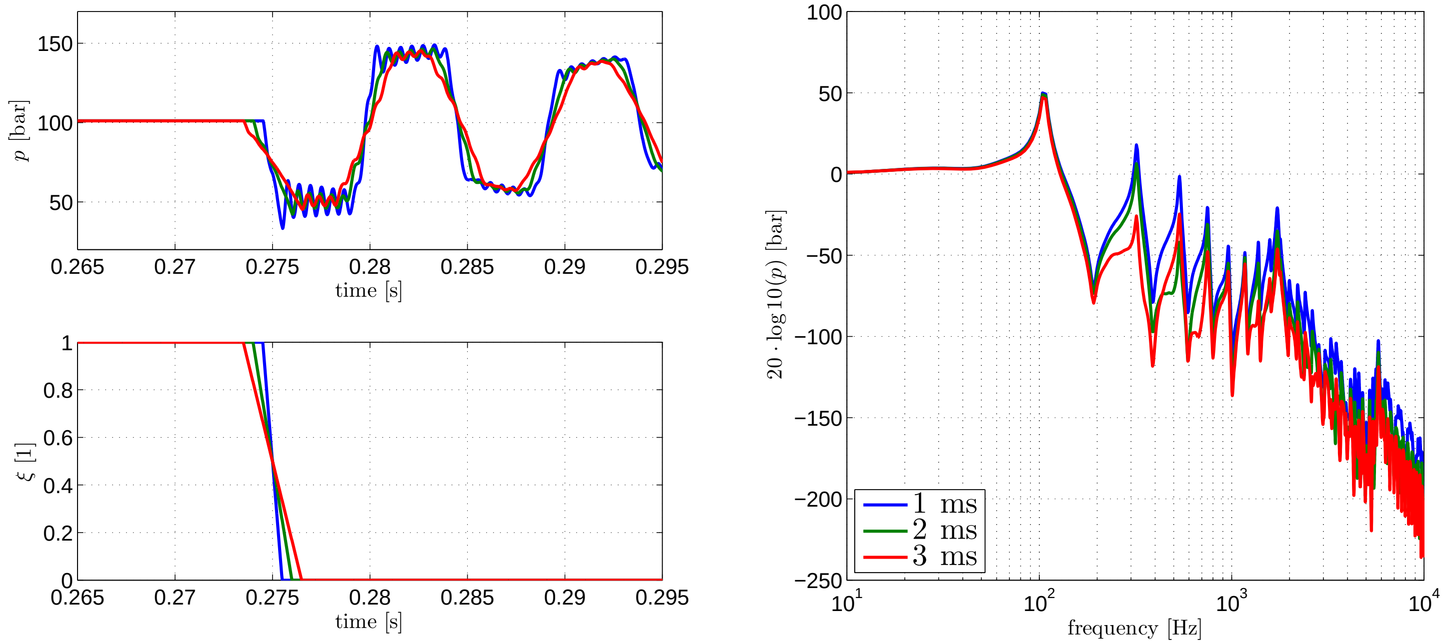

FIGURE 7. RAMP-LIKE VALVE CLOSING AT DIFFERENT CLOSING TIMES WITH AN ADDITIONAL PIPE BRANCH

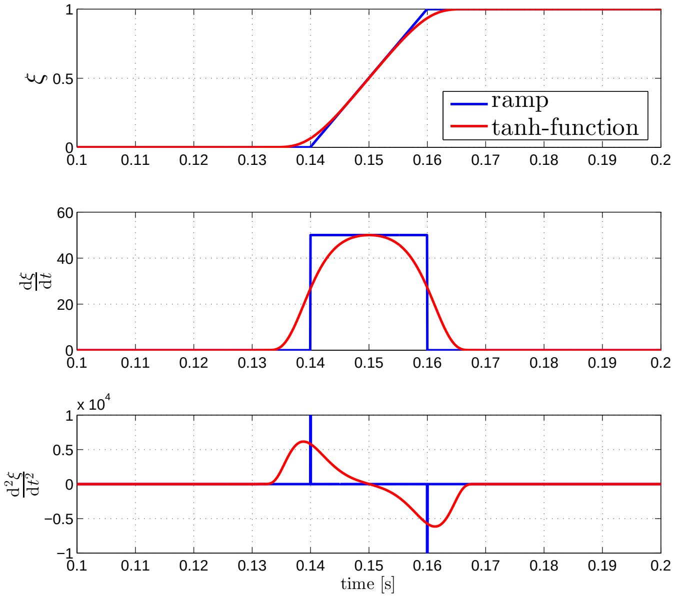

FIGURE 8. DIFFERENT VALVE OPENING CURVES

The ramp-like spool movement means a step function in the velocity $\frac{d\xi}{dt}$, if an ideal valve overlap is assumed. Moreover, the second derivative with respect to time represents even a type of Dirac-δ-function, which is known as a broadband excitation signal. Since this effect is caused by the sharp edges of the ramp, the idea is to reduce the broadband excitation by smoothing of the edges of the ramp. In Fig. 8 two different valve opening curves ξ and their derivatives with respect to time are illustrated, where the ramp-like movement is compared with a hyperbolic tangent movement. It is expected that the hyperbolic tangent spool movement shows a reduced pressure amplitude response level for the higher harmonics of the pipe system due to its increased smoothness. The predicted behavior is substantiated by the results shown in Fig. 9, where the individual responses for the ramp-like and hyperbolic tangent closing for a switching time of $2\,ms$ are compared. It can be concluded that a smooth valve actuation dramatically reduces the frequency response of the pipe system in the sensitive audible region. For the sake of completeness, the corresponding responses for a valve opening are presented in Fig. 10, and it can be seen that the magnitudes can be reduced significantly in the critical frequency band. In most cases transient pressure responses are less critical in the sense of noise than periodic switching. However, employing a smooth valve actuation, a reduction of magnitudes in the frequency responses of the pipe system due to periodic switching can be expected. Figure 11 shows the responses of the model according to Fig. 3 at a switching frequency of $50\,Hz$. The magnitudes of the critical frequencies above $1\,kHz$ can be reduced significantly. It must be remarked, that a realization of the smooth valve opening curve is not easily achievable with conventional overlapped spool valves. The stroke of fast switching spool valves is sup-

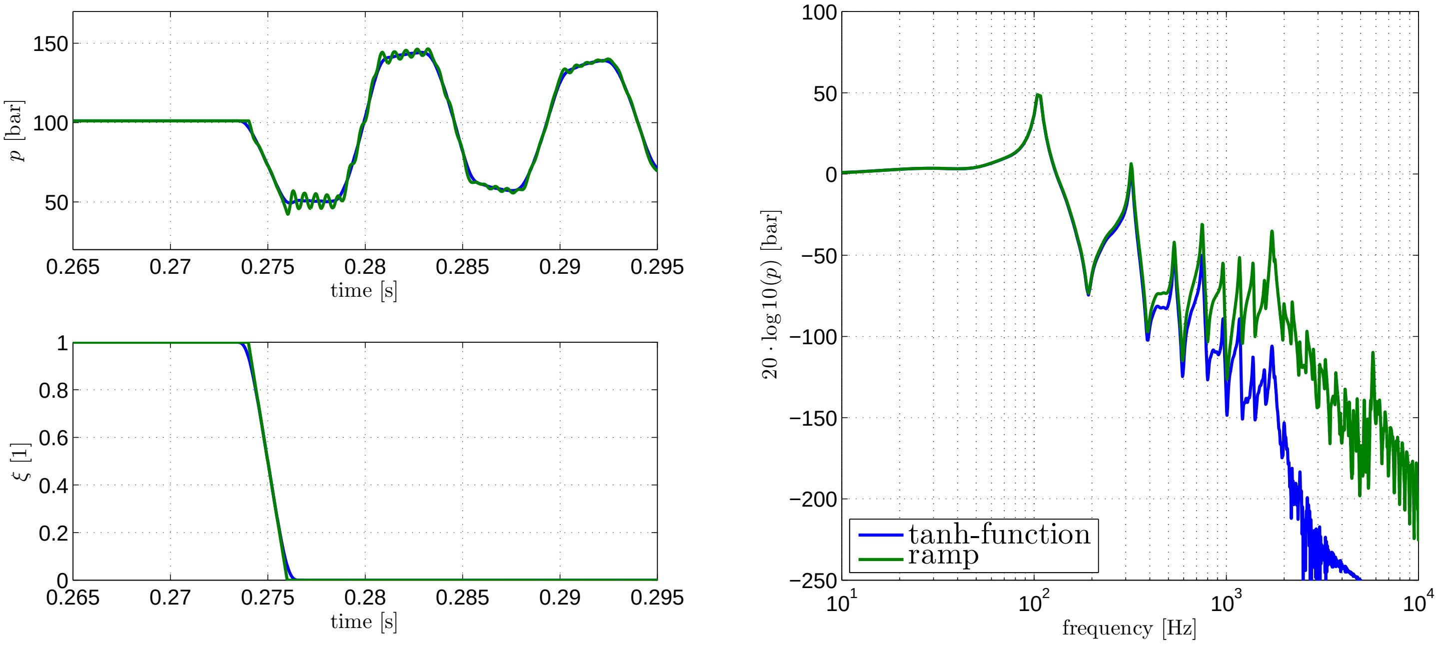

FIGURE 9. COMPARISON OF RAMP-LIKE AND HYPERBOLIC TANGENT FOR A VALVE CLOSING TIME OF $2\,ms$

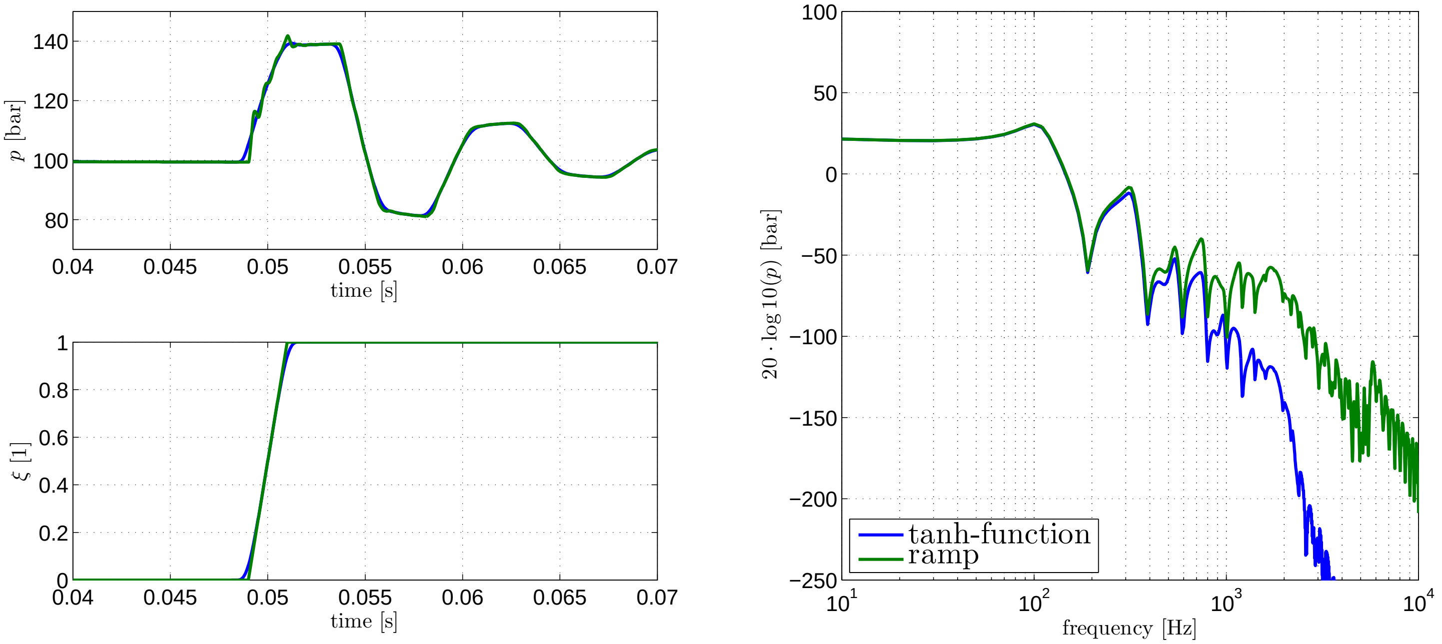

FIGURE 10. COMPARISON OF A RAMP-LIKE AND HYPERBOLIC TANGENT FOR A VALVE OPENING TIME OF $2\,ms$

posed to be short in order to achieve short switching times. As mentioned before, the overlap is mostly designed in the range of 50% of the maximum stroke to keep the leakage sufficiently low in closed position of the valve. Thus, a real valve overlap results in a reduced excitation due to the leakage through the small gap between spool and sleeve, but on the other hand the spool passes the overlap at maximum speed. In contrast to spool valves an improved valve opening can be realized, for instance, with seat valves, which do not have any valve overlap and where the inertia of the poppet causes the necessary smoothness.

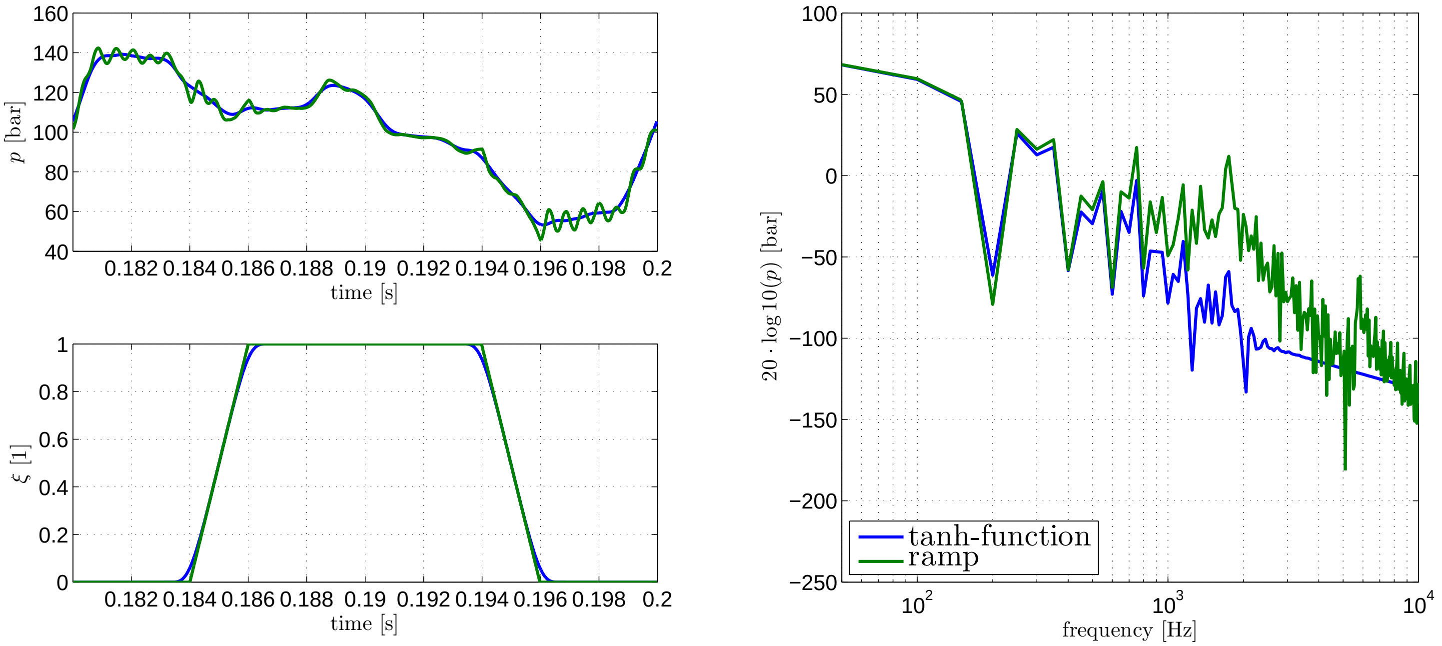

FIGURE 11. PERIODIC RAMP-LIKE AND HYPERBOLIC TANGENT SWITCHING AT A SWITCHING FREQUENCY OF 50 HZ

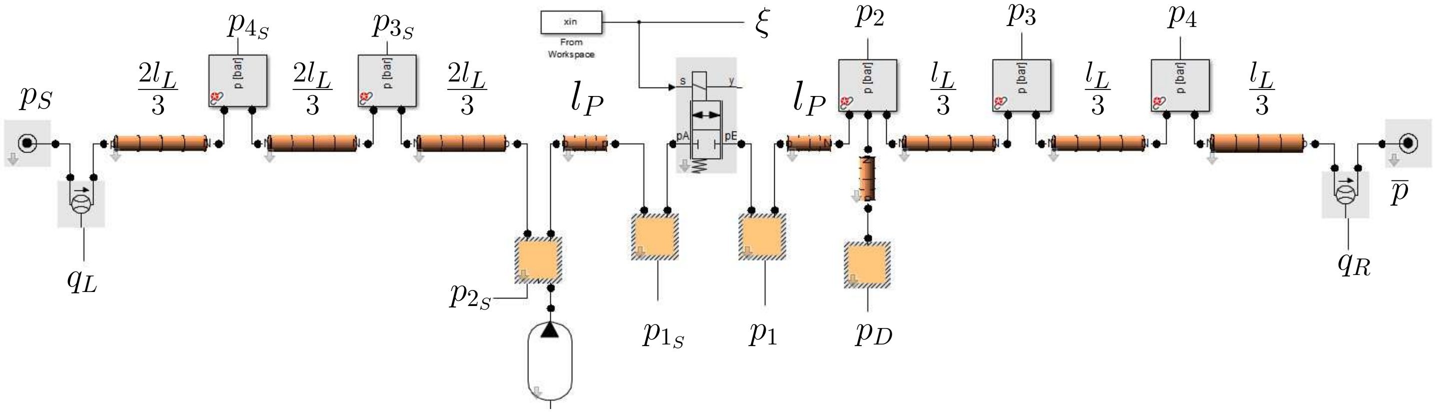

FIGURE 12. SIMULATION MODEL OF A TRANSMISSION LINE WITH SUPPLY SYSTEM IN *MATLAB/SIMULINK*

Model including a Supply Line

In the previous investigations described above the transmission line with the valve were supplied by a constant pressure p_S. In a more realistic case, the valve is not directly located at the pressure supply unit. Thus, a supply line connects the valve with constant pressure. Such a configuration is modeled and depicted in Fig. 12. In the simulation model the supply line has twice the length ($6m$) of the drive transmission line with the same inner diameter according to Tab. 1. Directly at the valve edge the additional valve cavity (p_{1_S}) is considered like in the drive line (p_1). Furthermore, between the supply line and the valve cavity an accumulator (p_{2_S}) is situated, which is connected via a parasitic pipe to the valve cavity (p_{1_S}). The attenuator (p_{2_S}) is gas loaded with a certain impedance at its inlet. In a first step this impedance is chosen to be very high, i.e., the accumulator has no effect. This is studied in order to demonstrate its necessity for decoupling. In Fig. 13 the simulation result with a high inlet impedance ($Z = \frac{20\,bar}{1\,l/min}$), i.e., quasi without any accumulator is illustrated. Similar to the drive line, large pressure pulsations are excited in the supply line due to the digital valve switching, which is realized by a hyperbolic tangent spool movement at a switching time of $2ms$. Due to the fast opening of the valve the supply pressure drops down in accordance with the pressure waves in the drive line. In this context the flow rate into the drive

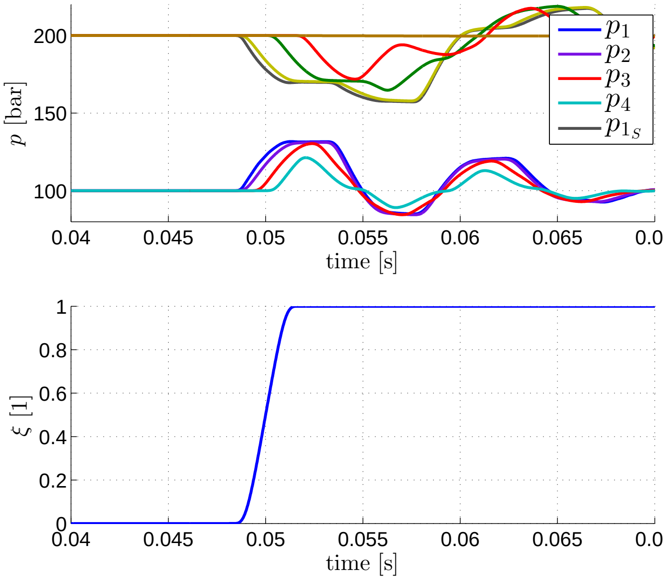

FIGURE 13. HYPERBOLIC TANGENT VALVE OPENING CONSIDERING A SUPPLY LINE

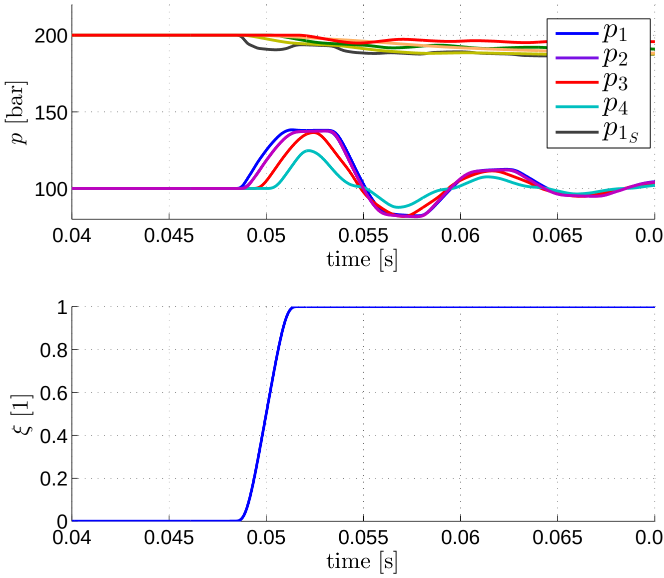

FIGURE 14. DECOUPLING OF THE SUPPLY LINE

line is reduced, since the pressure difference at the valve is lower. Thus, it takes more time to reach up the desired flow rate in the drive line required by the load. In contrast to the pressure breakdown due to the valve opening, closing the valve causes a large pressure overshoot, which may also lead to additional noise.

In order to avoid the mentioned problems a gas loaded accumulator with a low impedance at its inlet and closely located to the valve edge must be installed. If the distance between the accumulator and the valve cavity is larger, i.e., in case of a larger parasitic inductance, increased pressure pulsations at high frequency must be expected as mentioned above. In Fig. 14 the simulation results with a low inlet impedance of the accumulator ($Z = \frac{20\,bar}{100\,l/min}$) are depicted, which shows a well decoupled supply line. The remaining pulsations in the supply line are negligible and the supply pressure at the valve can be assumed to be constant.

Adaption of the Pipe Impedance

Figure 14 shows a damped but ongoing pressure oscillation in the load transmission line. In accordance with this pressure pulsation also fluctuations in the flow rate are present, which may result in unwanted oscillations of the load. The reason for this behavior is, that the used valve is too small for the used pipe diameter or vice versa. Since the wave traveling time through the pipe to the constant pressure boundary and back again is larger than the switching time of the valve ($\frac{2 \cdot l_L}{c_0} > t_S$), a pressure surge according to Joukowsky occurs, which reads

$$\Delta p = Z_0 \Delta q \tag{1}$$

with the impedance of the load line $Z_0 = \sqrt{K\rho}/A$. In this case the amplitude of the Joukowsky pressure surge is independent of the switching time. The flow rate through the valve calculates to

$$\Delta q = Q_N \sqrt{\frac{\Delta p}{p_N}} \tag{2}$$

with the nominal flow rate of the valve Q_N at the nominal pressure drop p_N. The idea is now to adapt the valve size Q_N to the load line impedance Z_0 such that the reflected wave has exactly the magnitude of the Joukowsky surge. Consequently, the outgoing pressure wave induces half of the stationary flow rate according to Eq. (1), which means $1/4(p_S - p_L)$ pressure drop at the valve. When the incoming pressure wave arrives at the valve again, the full flow rate causes full pressure drop $(p_S - p_L)$ at the valve. Thus, the Joukowsky surge is supposed to have a magnitude of $3/4\,(p_S - p_L)$, which suggests to impose the relation

$$\frac{1}{2} Q_N \sqrt{\frac{p_S - p_L}{p_N}} = \frac{3}{4} \frac{(p_S - p_L)}{Z_0} \tag{3}$$

at least under the assumption of negligible friction, which is fairly well justified for many reasonable pipe dimensions. Then

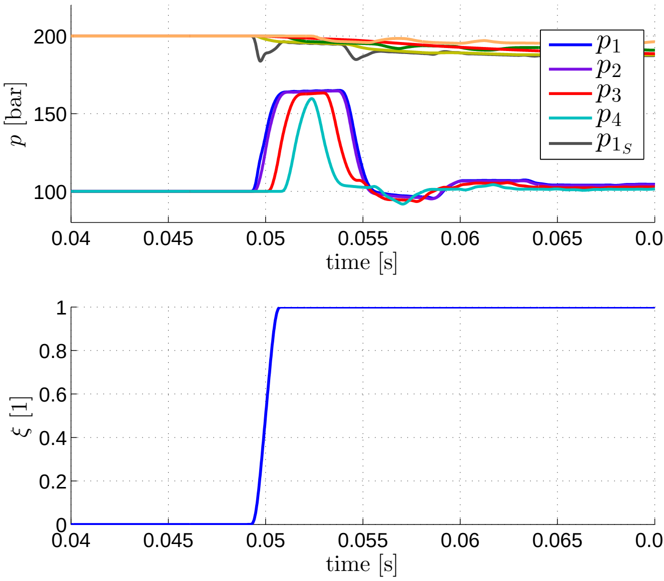

FIGURE 15. ADAPTION OF THE PIPE IMPEDANCE

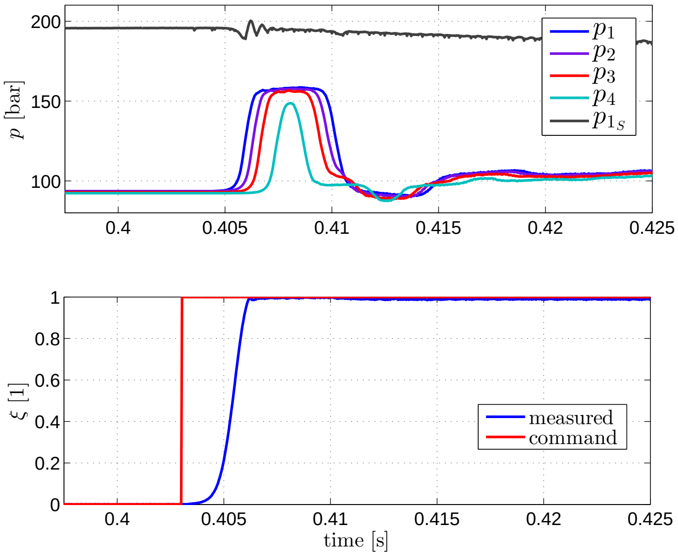

FIGURE 16. MEASUREMENTS OF A DIGITAL VALVE OPENING WITH AN ADAPTED PIPE IMPEDANCE

the pressure surge is annihilated by the reflected pressure wave and no further pressure oscillations remain. It is remarked that for dead end pipes - like, for instance, pilot lines - another relation similar to Eq. (3) exists, which is not treated here. Depending on the need of the application, Eq. (3) can be solved either for the nominal valve size Q_N or the cross-section area of the pipe A, respectively. In Fig. 15 simulation results for a well adapted valve/pipe combination is illustrated. No significant pressure fluctuations occur after the reflected wave reaches the valve again. This effect was confirmed by measurements using a fast switching 2/2-way directional valve according to [11], as depicted in Fig. 16. However, an adaption of pipe and valve does not have any improving effect on valve closing.

SUMMARY AND OUTLOOK

In this paper an analysis of pressure surge effects on the acoustic behavior of hydraulic systems was investigated by simulations. For this purpose different simulation models were used in Matlab/Simulink for calculating the transient responses due to digital valve switching. The time domain simulation results were transformed to frequency domain, where the acoustic effects were evaluated. The investigations show that a ramp opening curve of the switching valve causes a broadband excitation of the connected pipe system. Furthermore, in presence of parasitic inductances the frequency response of the pipe system shows a noticeable resonance peak in the critical frequency area of low threshold in human hearing. The ramp switching represents the opening and closing of digital spool valves, respectively, where the spool edge passes the valve overlap at high speed, which results in a broadband excitation. A smoother switching of the closing element turned out to show a much better frequency response in the critical audible frequency band.

The preferred opening curve can be realized with seat type poppet valves, which do not have any valve overlap. The inertia of the poppet results in a smooth opening curve of the valve. Furthermore, the valve actuation system comprising the necessary power electronics should be capable to manage soft landing strategies with regard to reduce the impact of the poppet and to improve the smoothness of the poppet movement in the closing direction.

Another interesting effect in order to reduce pulsations due to digital switching is the adaption of the valve size to the pipe impedance or vice versa. In a well adapted pipe/valve configuration the reflected wave annihilates the pressure surge due to the valve opening and no further fluctuations remain.

The results in this paper show, that a reduction of pressure oscillations in a certain frequency range may result in a lower excitation of surrounding mechanical structures and, furthermore, in a better noise behavior of digital hydraulic systems. Thus, the investigations form a basis for future valve actuation strategies.

ACKNOWLEDGMENT

This work has been supported by the Austrian COMET-K2 programme of the Linz Center of Mechatronics (LCM), and was funded by the Austrian federal government and the federal state of Upper Austria.

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