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Improvement of the Statical Behaviour of Pressure Controlled Axial Piston Pumps

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The control of pressure by means of variable displacement pumps is one of the most important tasks in the field of pump control, which is influenced by the properties of the pumps.

Looking for a suitable control concept with good static behaviour, a method is tested which tunes the parameters of a controller. Instancing a variable displacement axial piston pump controlled by a 3/2 proportional valve the improvement will be achieved by fuzzy logic on the one hand and a non-linear approach - adaptation of gain of the classical controller - on the other.

Keywords: servo hydraulic, variable displacement pump, pressure control, conventional-, fuzzy- and nonlinear control structures

0 INTRODUCTION

The main characteristic of an electro-hydraulic pump control system is the presence of an electrical signal path. It requires at least one sensor for the controlled value (in this case: pressure), delivering the feedback to be compared to the electrical or numerical reference in the controller.

The additional expense penalty for the sensor and the control valve is offset by the advantage of flexibility in the structure and parameters of the controller in comparison to hydraulic-mechanical concepts. Thus, the transfer response can be adapted to demands, even in the operational state. Sophisticated control structures can be implemented easily, in the form of computer or microcontroller programs. The layout of the electro-hydraulic pressure control discussed in this paper includes the loading unit, as shown in Fig. 1.

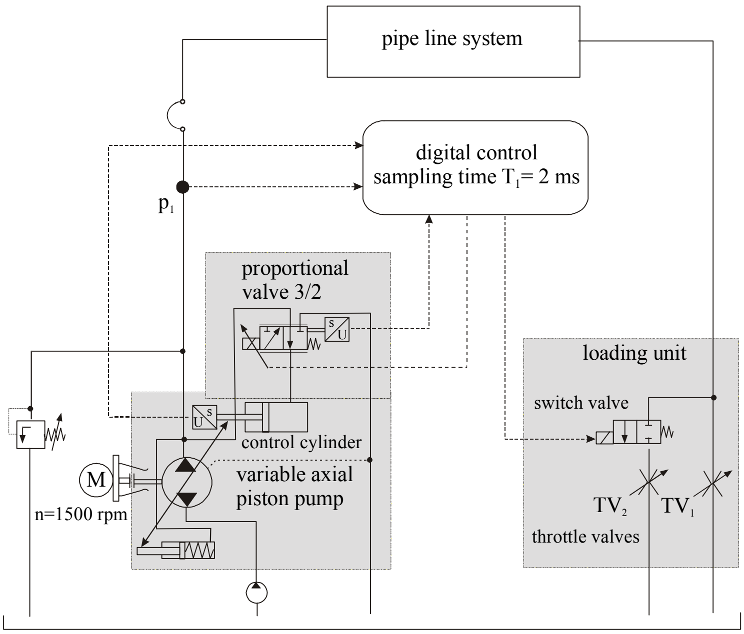

Fig. 1. *Principal layout of the electro-hydraulic pressure control*

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The variable pump is designed to act together with a proportional valve with two metering edges. Compared to a design with a synchronizing cylinder and four metering edges, it is less expensive. However, only inferior static and dynamic performance can be expected.

Hydraulic energy is supplied to the control valve directly from the output port of the pump – with the advantage of simple assembly, as there are no additional components required – but with a drawback of influence on the control loop properties at every change in disturbance value or reference.

The aim of this paper is to present a suitable and more efficient but simple control concept compared to other known methods (see e.g. [1], [2] or [3]) for pressure control of the above mentioned pump including the dynamics of the distribution network and the characteristics of the hydraulic load as well. Control concepts should be improved and developed showing appropriate steady state and dynamic behaviour. Following the trend of increased usage of digital controllers in hydraulics, all the proposed methods are controlled electronically and digitally.

1 THE SIMPLIFIED AND LINEARISED OPEN CONTROL LOOP

The control loop under test can be divided into subsystems of control valve, actuating mechanism, driven mechanism and the hydraulic supply network with the associated load. All subsystems are taken into consideration in the mathematical modelling.

Generally, the dynamical behaviour of such a complex system containing a lot of linear and non-linear dependencies between the different quantities cannot be described by a concise equation or a system of linear differential equations.

A non-linear description of the open control loop for the purpose of theoretical investigation reflects the behaviour much more precisely but leads to an enormous consumption of calculating time on the one hand, and assumes the knowledge of numerous design data which most users do not have (see [4]).

The pressurization in the hydraulic network is according to the flow balance equation between pump flow Q_P and consumed flow on the load Q_L. If this system is in balance, the pressure p1 remains constant.

Since the characteristic frequency of the control valve is far above of that of the rest of the system (hydraulic pipeline system and load), its behaviour can be assumed to be proportional. Even the actuator mechanism can be seen as proportional with a downstream integrator. The drive of the pump is also proportional:

$$Q_P = \frac{y_1}{y_{1max}} V_{1max}\, n_1 \,. \tag{1}$$

The pipeline system can be considered as a concentrated hydraulic capacity C_H. The leakage of the hydraulic system will be added to the consumer flow Q_L. If the latter can be linearised in a certain operation point, the consumers can be substituted by the characteristic value K_L:

$$K_L = \frac{Q_L}{p_1} \,. \tag{2}$$

The time domain performance of the consumers (in the considered case orifice as load) will be neglected because the dominant time constant of the whole controlled system is mostly larger than that of the consumer's on one hand, and an assumed perfect fast consumer is a more critical case compared to a slower one, on the other.

Another important influence on the pressure control system is the internal supply of the pump's adjustment system. The associated flow firstly depends on the system pressure. Already linearised valve flow can be written as:

$$Q_{V1} = V_{Qu1}\, u_1 + V_{Qp1}\, p_1 \tag{3}$$

with:

$$V_{Qu1} = \frac{\partial QV1}{\partial u1}$$

and

$$V_{Qp\,1} = \frac{QV\,1}{\partial\, p1} \,. \tag{4}$$

Secondly, this flow is always taken from the distribution network in which the pressure is to be controlled leading to the degradation of the control results.

The corresponding block diagram of already linearised and simplified system is shown in Fig. 2.

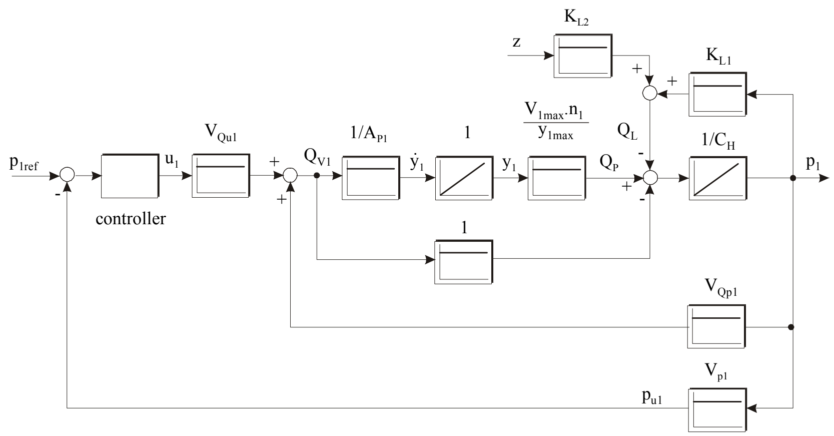


Fig. 2. *Pressure control loop with internal supply of control volume flow*

The output variable of the system is pressure p_1 as a controlled value, and $p_{1,\mathrm{ref}}$ acts as pressure reference input signal (both in form of voltage signals p_{u1} respectively u_1 as controller signal). The dynamical part of the consumer flow ΔQ_L is the disturbance variable z.

Classical PD-controllers (or PDT_1 in the case of digital versions) with proportional and derivative behaviour, are commonly used for the purpose of pressure control, which enables the achievement of suitable reference and disturbance actions of the control loop. Such a solution fulfils the requirements regarding pressure control dynamics, and the simplicity of the controller.

The actuating piston of the pump driven by the 3/2 proportional valve shows integrating behaviour. Hence no steady error signal should appear. Due to self adjusting forces, the spring on the actuating piston of the pump and due to the influence of friction, a small amount of (negative) feedback is added to this integrator resulting in stationary errors. The quality of the control is further decreased by the temperature drift of the hydraulic zero of the proportional valve.

Typical waveforms of pressure in the case of a 35 m pipe line system are shown in Fig. 3 as responses to a reference step as well as to disturbance steps due to switching on and off one throttle valve (TV_2; see Fig. 1) – they correspond to changes in operating point ($\rightarrow OP_1 \rightarrow OP_2 \rightarrow OP_1$).

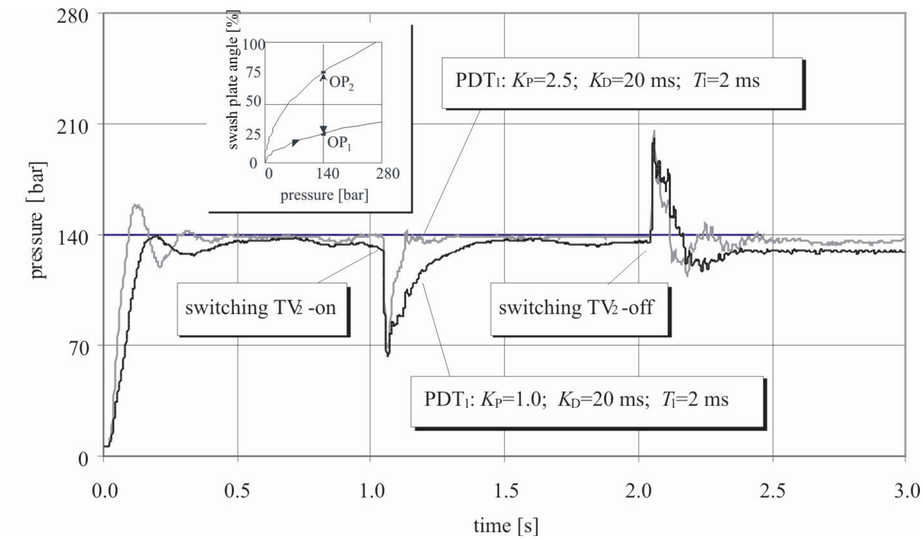


Fig. 3. *Influence of controller gain to the steady state error signal*

A common digital PDT_1-controller is used in the examples presented in Fig. 2. In all the cases presented in the work, the applied sampling time T_1 was 2 ms.

In the case discussed here, the throttle valves are adjusted in such manner that at the working point OP_1, the pump tilts out to deliver 25% of maximum flow, and 75% in OP2 .

The solid line presents an optimal pressure waveform with a relatively large steady state error when using low controller gain. The second, dashed line shows the behaviour at a higher controller gain achieved under the same operating conditions as in the first case. As a consequence of increased controller gain, the steady state error has decreased, but the compensation of the transient response is improper. A similar issue appeared on variations in pipelines lengths.

The solution to the above problem, for achieving an optimal pressure plot with appropriate dynamic behaviour without many steady state errors, is to be found by (adaptive) variation of the controller's proportional gain K_P .

In cases in which control parameters have to be changed due to variations in the parameters of the process, an adaptive system can be superimposed to the basic control loop, which tunes the adjustable parameters of this basic controller according to the process-changing properties. In this way the overall performance of the system can be improved, in spite of fluctuating process characteristics.

In principle, the design of an adaptive control system is divided into three steps: In the first one (identification) the changing open loop parameters will be identified directly or indirectly. In the second step (decision) control parameter changes will be determined, while in the third (modification) a basic controller will be adapted.

In conventional control engineering three basic structures are known, depending on how these steps are realized – the principle of controlled model-reference adaptation with a parallel model *or* without a model-reference *or* the principle of a feedback-less adaptation.

As an alternative to the above-mentioned approaches, which are all somewhat expensive, an attempt was made to develop an effective structure with maximum simplicity with the main goal the steady state error to minimize.

As the first step towards the above defined design goal, it was attempted to reduce steady state errors by a measure based on fuzzy logic. The principle then adopted will be realized in a conventional non-linear way and extended by a mechanism to compensate for changing load characteristics (influencing parameter K_D), in the second step. The result is a hybrid adaptive fuzzy control structure.

2 PRESSURE CONTROL WITH THE FUZZY CONTROLLER

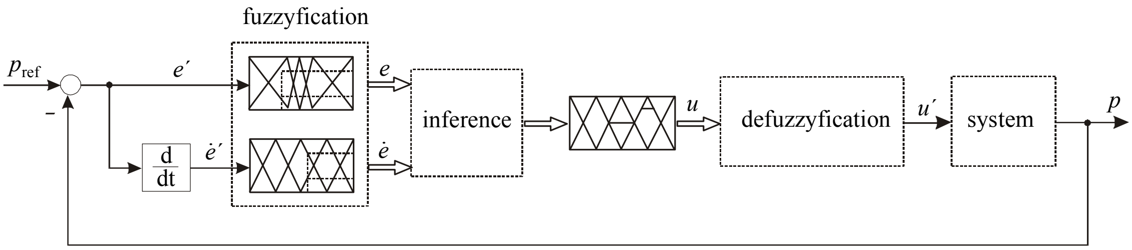
The conventional analysis of processes with mathematical methods is mainly based on the theory of linear and time-invariant systems. This theory becomes less accurate as the process becomes more and more complex and non-linear in nature, because the models that can be found for such systems are insufficient or highly simplified (chapter 1). Experience tells us that a part of these processes can successfully be controlled within the technical limits by an expert acting heuristically. Therefore, the expert uses methods and strategies based on intuition, experience and acquired knowledge.

Fuzzy logic (see e.g. [5] to [7] and [9]) offers a suitable mathematical means to express and interpret the expert's heuristic criteria of decision and fuzzy linguistic rules. It is a matter of mathematical modelling to transform the linguistic descriptions of appraisal and evaluation for the algorithmic treatment. This enables the user to develop models for the mathematical description of experience formulated linguistically. In this way fuzzy logic represents an extension to classical (formal) logic.

The pressure controller in this paper is of the PD-Type, but modified in comparison with some usual structures.

Early investigations in the introduction of fuzzy technology were guided by engineering experience but also by an analysis of theory and experiments carried out before (chapter 1). A fuzzy-PD controller was chosen with two input variables: the control error e and its derivative $\dot{e}$, (Δe in digital control), and a single output variable, which is the input voltage u of the control valve. The control loop structure is shown in Fig. 4.

The controllers' three variables hence are treated as linguistic ones and are implemented in thirteen linguistic terms with the abbreviations: NVB(-6) - negative very big, NB(-5) - negative big, NQB(-4) - negative quite big, NM(-3) - negative



real world variables: e', $\dot{e}'(\Delta e')$, u'

fuzzyfied variables: e, $\dot{e}(\Delta e)$, u

Fig. 4. *Structure of pressure control loop with the modified Fuzzy-PD-Controller*

medium, NS(-2) - negative small, NVS(-1) - negative very small, ZO(0) - zero, PVS(1) - positive very small, PS(2) - positive small, PM(3) - positive medium, PQB(4) - positive quite big, PB(5) - positive big, PVB(6) - positive very big. The numbers in parentheses represent the indices for numerical processing.

The development of the rule base was accomplished in accordance with the knowledge of the pressure control dynamic behaviour. In the first step the rules for some selected states had to be stated, after that the rule base was completed by the principle of continuity, that means that changes in the input variables should result in similar changes in the conclusions. The rule base constructed by characteristic rules and expanded by the principle of continuity is shown in Fig. 5.

Δe \ e	*NVB*	*NB*	*NQB*	*NM*	*NS*	*NVS*	*ZO*	*PVS*	*PS*	*PM*	*PQB*	*PB*	*PVB*
NVB	*NVB*	*NVB*	*NVB*	*NVB*	*NVB*	*NVB*	*NVB*	*NB*	*NQB*	*NM*	*NS*	*NVS*	*ZO*
NB	*NVB*	*NVB*	*NVB*	*NVB*	*NVB*	*NVB*	*NB*	*NQB*	*NM*	*NS*	*NVS*	*ZO*	*PVS*
NQB	*NVB*	*NVB*	*NVB*	*NVB*	*NVB*	*NB*	*NQB*	*NM*	*NS*	*NVS*	*ZO*	*PVS*	*PS*
NM	*NVB*	*NVB*	*NVB*	*NVB*	*NB*	*NQB*	*NM*	*NS*	*NVS*	*ZO*	*PVS*	*PS*	*PM*
NS	*NVB*	*NVB*	*NVB*	*NB*	*NQB*	*NM*	*NS*	*NVS*	*ZO*	*PVS*	*PS*	*PM*	*PQB*
NVS	*NVB*	*NVB*	*NB*	*NQB*	*NM*	*NS*	*NVS*	*ZO*	*PVS*	*PS*	*PM*	*PQB*	*PB*
ZO	*NVB*	*NB*	*NQB*	*NM*	*NS*	*NVS*	*ZO*	*PVS*	*PS*	*PM*	*PQB*	*PB*	*PVB*
PVS	*NB*	*NQB*	*NM*	*NS*	*NVS*	*ZO*	*PVS*	*PS*	*PM*	*PQB*	*PB*	*PVB*	*PVB*
PS	*NQB*	*NM*	*NS*	*NVS*	*ZO*	*PVS*	*PS*	*PM*	*PQB*	*PB*	*PVB*	*PVB*	*PVB*
PM	*NM*	*NS*	*NVS*	*ZO*	*PVS*	*PS*	*PM*	*PQB*	*PB*	*PVB*	*PVB*	*PVB*	*PVB*
PQB	*NS*	*NVS*	*ZO*	*PVS*	*PS*	*PM*	*PQB*	*PB*	*PVB*	*PVB*	*PVB*	*PVB*	*PVB*
PB	*NVS*	*ZO*	*PVS*	*PS*	*PM*	*PQB*	*PB*	*PVB*	*PVB*	*PVB*	*PVB*	*PVB*	*PVB*
PVB	*ZO*	*PVS*	*PS*	*PM*	*PQB*	*PB*	*PVB*	*PVB*	*PVB*	*PVB*	*PVB*	*PVB*	*PVB*

Fig. 5. R*ule base of Fuzzy-PD-Controller – linguistic terms*

Another design step is the definition of the value ranges and their scaling (the mapping of values onto the interval [-1, 1] by scaling factors). It should be noted that scaling has its importance primarily in the theoretical treatment and in the numerical simulation. For the real time application it is an additional expense. For the fuzzy algorithm presented in this paper the real world ranges of variables were used directly.

The selection of the variables' ranges itself can be considered as a rather big problem and demands a larger amount of intuition because ranges have to be chosen in a way that system variables can move inside them over most of the operational period. Ranges that are too large, result in coarse effects of the fuzzy controller, whereas too small ranges can even cause instabilities. Scaling factors are comparable to the gain of a conventional controller. The variable's ranges used in this paper are selected as follow:

- range of variable e: [-250, 250] (bar),
- range of variable $\dot{e}$: [-250, 250] (bar/ms),
- range of actuating variable u: [-10, 10] (V).

The scaling factors can be computed by fixing the ranges of variables and parameters K_p and K_D of an underlying classical controller:

$$k_e = \frac{1}{K_P}\ ;\ k_{\dot{e}} = \frac{1}{K_D} \text{ and } k_u = 1\,. \tag{5}$$

By choosing appropriate scaling factors for the linguistic variable e and non-equidistant division of the area of the relevant variable (Fig. 6) the gain of the controller in the direction towards smaller control errors is increased by factor 4. Both limiting gain values are defined experimentally. Lower gain limit (K_{Pmin}) is defined at 5% overshoot over the target value as a result of reference steps. The upper limit (K_{Pmax}) corresponds to the value of gain at the moment immediately before the stability limit is reached. During the control process gain factors close to K_{Pmin} are applied in the case of large control errors and gain factors close to K_{Pmax} in case of small control errors. Consequently, an increasing control error e results in a decline of the K_P parameter from K_{Pmax} to K_{Pmin} in a nearly exponential manner, while parameter K_D is kept constant.

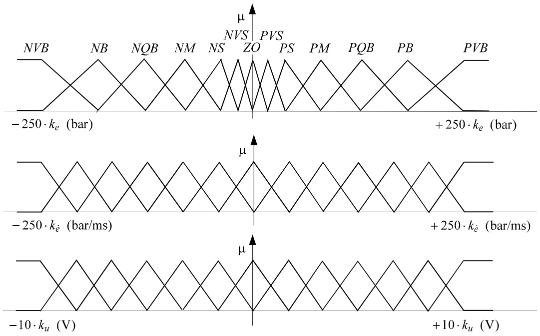


Fig. 6. *Linguistic input variables of the modified Fuzzy-PD-Controller*

Choosing triangular membership functions in the next step results in the fuzzy sets, which are shown in Fig. 6.

Using the principles mentioned before, the pressure control with a variable displacement pump based on the fuzzy controller was implemented.

Fig. 7 now shows the dynamic responses to typical steps in the reference and in the disturbance values (bias point changes $\rightarrow OP_1 \rightarrow OP_2 \rightarrow OP_1$) in the test configuration with 35 m line length. For comparison, the same kind of responses archived with the classical PDT_1 controller are added. Relatively large stationary error which was present at conventional PDT_1-controller is substantially decreased when modified fuzzy controller is applied, while dynamics of transition phenomenon is improved.

3 MEASURE TO REDUCE THE STEADY STATE ERROR

A powerful measure to improve the static performance of pressure control is the implementation of a variable, control error dependant, controller gain. At first sight, insertion of two different gain values, a small one for areas of large errors and a bigger one for those of smaller errors, respectively, would be a simple solution. It does, however, bring about a problem related to defining an adequate switching point (according to the size of the control error). If, for instance, the switching point value is set too low and the control error is substantial, the greater of the defined values would not become effective. In contrast, in the case where the switching point is set too high, unacceptable oscillations of the controlled value can occur.

Considering the disadvantages of the above solution leads to the following idea: the controller gain needs to be continuously increased as the control error vanishes and vice versa.

This can be achieved using the following expression:

$$K_P(t) = (K_{Pmax} - K_{Pmin}) \cdot exp(-|e_N(t)|) + K_{Pmin} \qquad (6)$$

where: K_{Pmax} - upper gain limit, applies when $e_N(t) = 0$, K_{Pmin} - minimum gain for the areas of big errors, and $-e_N(t)$ - instantaneous error value, normalized to its maximum.

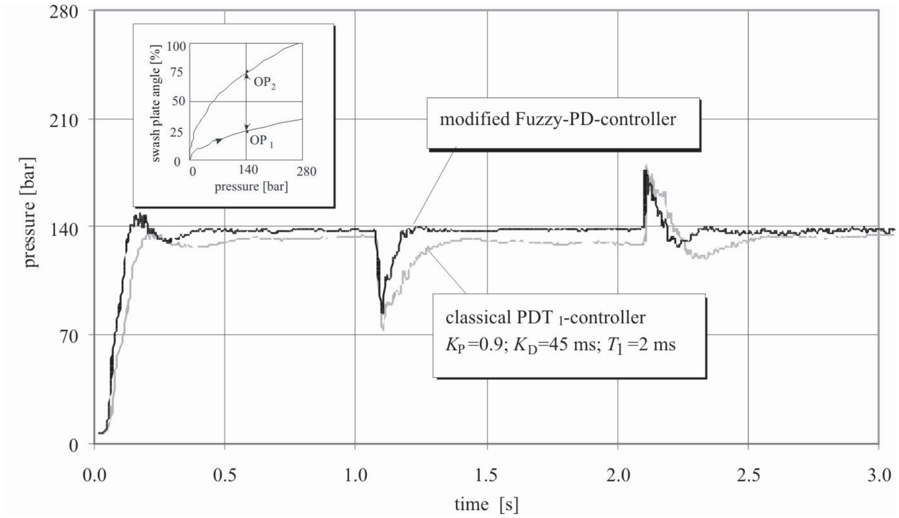


Fig. 7. *Step responses to reference and disturbance variable with modified Fuzzy-PD-Controller*

This form of variable gain value definition including its adaptation to changeable working conditions is particularly suitable for adaptive control structures, which in addition contain different changing loads. Although the application of the K_P parameter enables improvement of steady (and partly dynamic) performance, the problem of adaptation to the various loads and consequently, variable working points, remains unsolved. The K_D parameter of the PD-controller remains constant.

The effectiveness the adaptive controller gain K_P according to Eq. (6), merged into a self-adjusting, hybrid control structure is experimentally proven and presented in Figs. 8, 9 and 10.

Fig. 8 shows dynamic responses to typical steps in the reference and disturbance values (operating point changes $\rightarrow OP_1 \rightarrow OP_2 \rightarrow \rightarrow OP_1$) in a test configuration of 35 m line length (compare with Figs. 2 and 3).

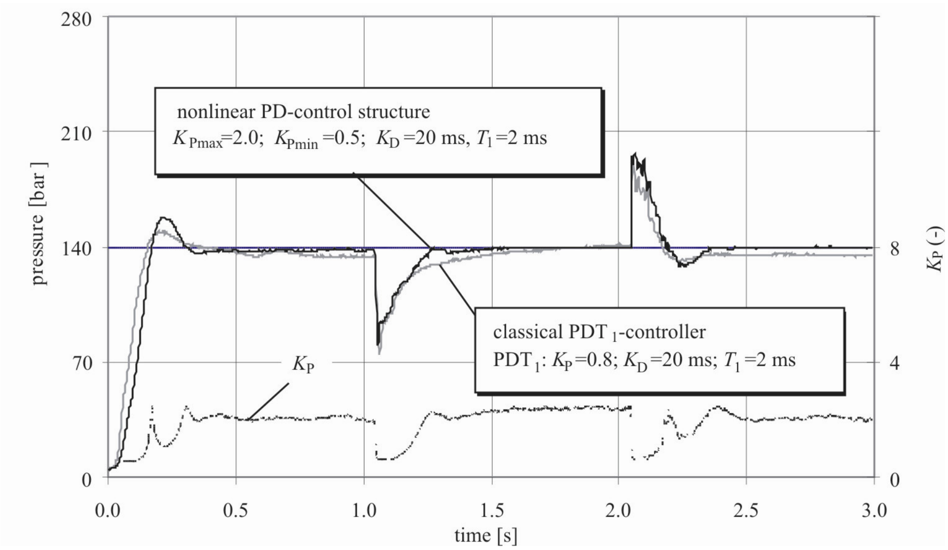


Fig. 8. *Step responses to reference and perturbation variable due to changes in operating point; Comparison classical PDT_1 to nonlinear control structure*

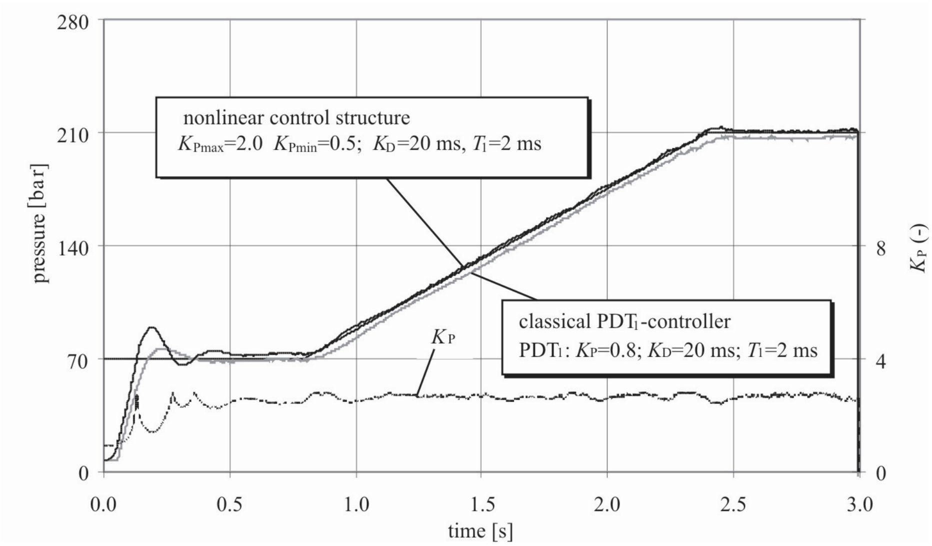


Fig. 9. *Response to a reference ramp; Comparison classical PDT_1 to nonlinear control structure*

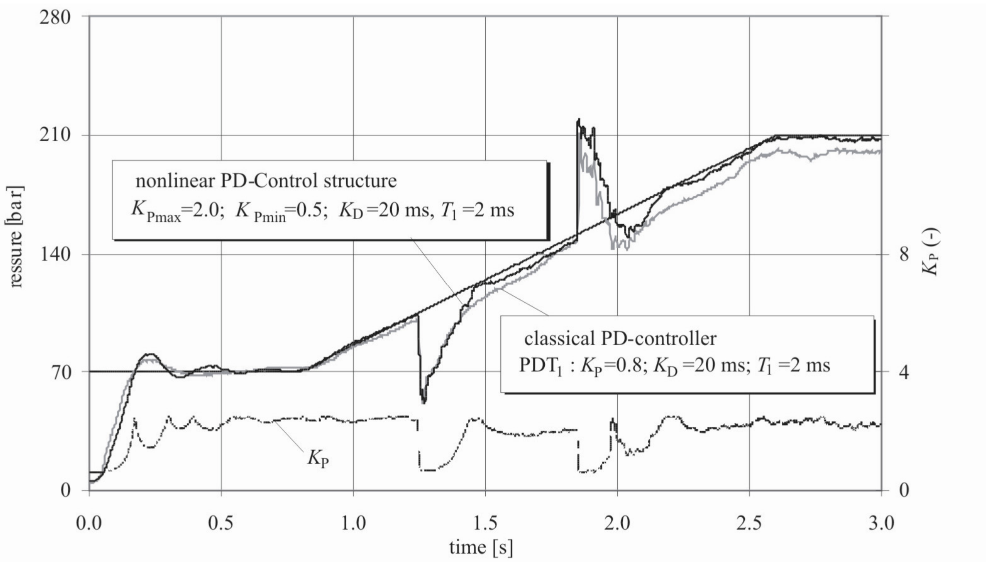


Fig. 10. *Response to a reference ramp combined with steps on the perturbation variable; Comparison classical PDT_1 to nonlinear control structure*

The situation in Figs. 9 and 10 differs because it introduces a ramp function for the reference value: Fig. 9 shows only the step responses to a reference ramp, Fig. 10 the step responses to a reference ramp combined with a disturbance step where both disturbance actions appear during the ramp time. The changes in the controller parameter values K_P due to the adaptive mechanisms are also presented. The same kinds of responses achieved with the classical PDT_1-controller are added, for comparison. In all the cases the load represents two throttle valves; the applied sampling time is 2 ms.

It is apparent that control with an adaptive K_P controller gain provides fast and well-damped responses of a controlled system, under all operating conditions. The value of the proportional controller parameter K_P changes bases on the current control error.

In comparison with the conventional pressure control systems, the steady state error substantially decreased.

This is especially apparent from Fig. 10, which shows the step responses to a reference ramp combined with a disturbance step, as consequences of operating point changes.

4 CONCLUSIONS

The control of pressure by means of variable displacement pumps is one of the most important tasks in hydraulic control and is particularly demanding because it is heavily dominated by the pump's properties, the operating point, and the load's characteristics.

A suitable controller concept should ensure a good static and dynamic performance respectively to be able to adapt itself online to any changing properties of the control loop. This is especially important when components which do not have ideal properties for control, such as internally supplied 3/2 proportional directional valves and asymmetric swash plate actuators are in use. In the paper two possible effective solutions are presented.

One possibility how to achieve the above mentioned requirements is the use of a fuzzy logic based controller, which was developed and evaluated as an alternative to classical concepts. To reach the goal, an algorithm was created with a PD-like performance. By the use of non-linear properties of the fuzzy controller and a suitable choice of the linguistic input variables, the so modified Fuzzy PD-controller was developed and tested. Its control performance with respect to steady state error reduction is much more efficient than the classical PD-controller.

The second possibility is the use of simple non-linear measure. It is shown that the use of variable gain in a classical PD-controller provides fast and well-damped responses of a controlled system, under all operating conditions. The value of the derived controller gain changes depending on the current control error - the controller gain needs to be continuously increased as the control error vanishes and vice versa.

The implementation of fuzzy logic and the non-linear measures that have been shown to meliorate the static behaviour in the control of variable displacement pumps is the simplest and most effective way to improve pressure control and adapt it to variations in the controlled system. The presented procedure is simple and does not require long calculation times. Following the above experience it can be concluded that both measures could effectively be applied to hydraulic systems especially does with variable loads.

5 NOMENCLATURES

A_{P1} [m^2] - area of actuator piston
C_H [m^3/bar] - hydraulic Capacity
e [-] - error signal of control loop
e' [-] - error signal - real world variable
e_N [-] - scaled error signal
$\dot{e}$; de [-] - derivation of error signal
$\dot{e}'$ [-]- derivation of error signal - real world variable
k_e [-]- scale factor for input variable e
$k_{\dot{e}}$ [-]- scale factor for input variable $\dot{e}$
k_u [-]- scale factor for output variable u
K_D [ms] differential time constant of controller
K_P [-] - gain of controller
$K_{P,min}$ [-] - lower limit of controller gain
$K_{P,max}$ [-] - upper limit of controller gain
K_{L1}, K_{L2} [l/min bar] - characteristic value of load 1, 2
n, n_1 [min^{-1}] - rotational speed of electric motor
p [bar] - pressure [common]
p_{ref} [bar] - reference of pressure
p_u [V] - pressure signal
Q_P [l/min] - pump volume flow
Q_{V1} [l/min] - volume flow of control valve
Q_L [l/min] - load volume flow
t [s] - time
u_1 [V] - drive signal of pump control valve
V_{p1} [V/bar] - gain of pressure transducer
V_{Qp1} [l/min bar] - volume flow-pressure ratio of control pump valve
V_{Qu1} [l/min V] - volume flow-signal ratio of control pump valve
V_{1max} [m^3] - maximum of pump volume
y_1 [m] - displacement of actuator piston
$\dot{y}_1$ [m/s] - velocity of actuator piston
z [-] - perturbation variable [common]

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