Analysis of Adaptive/Learning Control Methods in Cyclic Hydraulic System

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Abstract

By using hydraulic actuators, it is often problematic to design controller that fulfills good control accuracy and stability in wide operation area. Objective of this paper is to design robust adaptive model-based controller. By combining adaptive control law with MBC (Model-Based Controller), it is possible to achieve good performance under varying conditions. In this study the adaptive control law is attained by using the gain scheduling technique with adaptation mechanism. An environment parameter sensitivity analysis is performed to the MBC system. Also the comparison between two different control strategies, ILC (Iterative Learning Control), and adaptive control with MBC, is done. The comparison examines control accuracy and repeatability of control algorithm. These strategies are studied by means of simulations. The simulations are done with co-simulation between AMESim and Matlab Simulink programs, and the model was verified by the experimental tests. As a result, model-based controller is found to fulfill the tracking requirements. The performance with ILC is still slightly better than with MBC. While tuning of the ILC is easier, the calculation load of the MBC is better. This would affect in timing accuracy of the target system.

KEYWORDS: adaptive, learning, model-based, control

1 Introduction

This research was focused on the control design of the EHVA (Electro-Hydraulic Valve Actuation) system. The good performance of the future low emission diesel/gas engines requires accurate timing and control of the gas exchange valves, especially during the changing environment and working point of the engine. The main goal of the design was to achieve as small tracking error as possible and good quality of the position response. Also reliable and accurate measurement of the displacement has important role here. The controller should also have low calculation load in order to improve the timing resolution of the actuator movement. There exist several other studies, for example /1, 2, 3, 4, 5, 6/, where the closed loop control strategies have been studied or compared. Based on this information, a model-based control strategy was chosen in this study. Model-based controllers are used often with digital hydraulic systems /7/, and it has many advantages like possibility to use open loop control system or to use more complex cost functions and thus emphasize wanted control strategy.

2 Electro-hydraulic valve actuation system

The hydraulic diagram of the EHVA system is presented in **figure 1**. This system is part of Wärtsilä W20 engine (bore 200 mm, stroke 280 mm, nominal rotational speed 900 RPM). EHVA system is presented in more details in /1/.

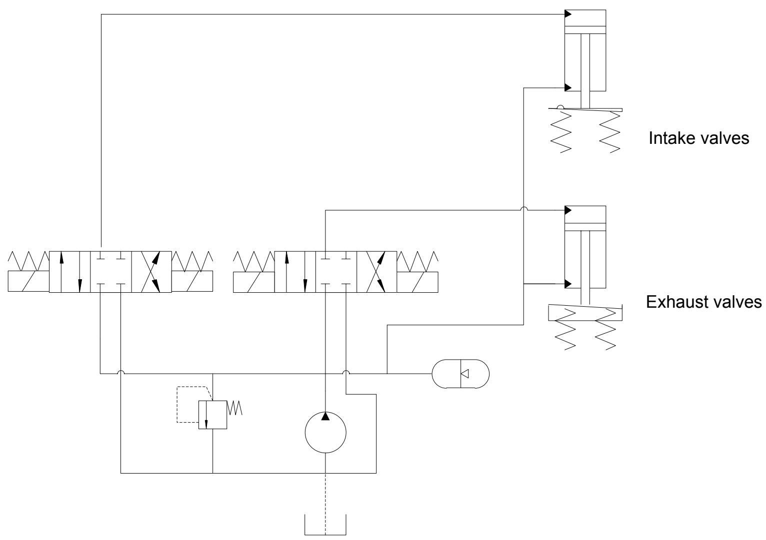

Figure 1: Hydraulic diagram of EHVA

3 Controller Systems

The design of model-based controller requires accurate model of the plant, that the full potential of the controller can be utilized. In a valve controlled system this means that we must be familiar with the characteristic of a control valve. The selection of a control signal is based on a cost function, which minimizes used criterion. The goal of this design is to have a controller, which can be applied in various kinds of processes, where accuracy is demanded.

The second studied controller, the ILC controller, is based on the strategy where parameters of the controller are kept basically constant, but reference signal is modified. The modification is done according to tracking error of previous work cycle. The delay compensator has controller of its own because the ILC cannot provide effective correlation of error caused by delay.

3.1 Model-Based Controller

The controller was based on mathematical model of the control valve. This model-based controller consisted of three parts: model of the control valve, search space and cost-function based control signal selection. Principle of the controller with adaptive control law is presented in **figure 2**.

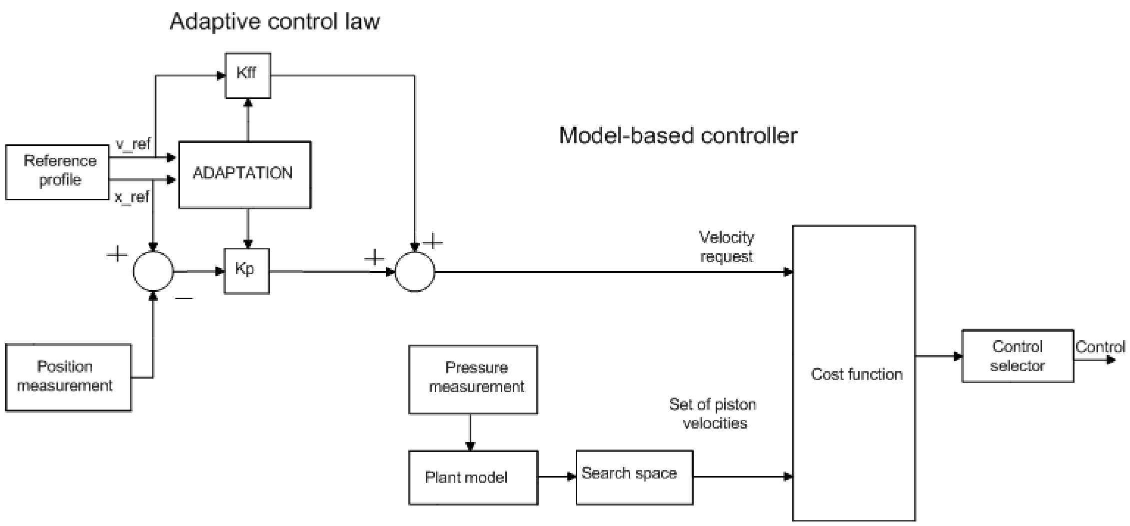

Figure 2.: Schematic of MBC controller

The basic control structure of the system was sum of P-control and Feed-forward loop control. Based on this, the velocity request of the MBC was created. The selection of control parameters was handled by adaptation mechanism, which chose parameters based on reference signal. The MBC calculated different flow rates of the valve, when the opening of the valve was changed. The calculation was based on the equation presented in equation 1.

$$Q = uK_v\sqrt{\Delta p} \qquad (1)$$

The valve opening was a user defined vector, which formed the search space of the controller. Basically it was consisted of discrete steps between 0 and 1. In this study the number of steps was 50. The calculation time of the controller was dependent of the amount of steps. Cost function got set of possible flow rates, which were converted into piston velocities. Cost-function compared these values with velocity request. Used cost-function is presented in equation 2.

$$J = \left| v_i - v_{ref} \right| + W\Delta u \tag{2}$$

3.2 Iterative Learning Controller

Schematic block diagram of the ILC is shown in **figure 3**. The learning equation is presented in equation 3. More detailed description about the function of ILC is presented in /2/.

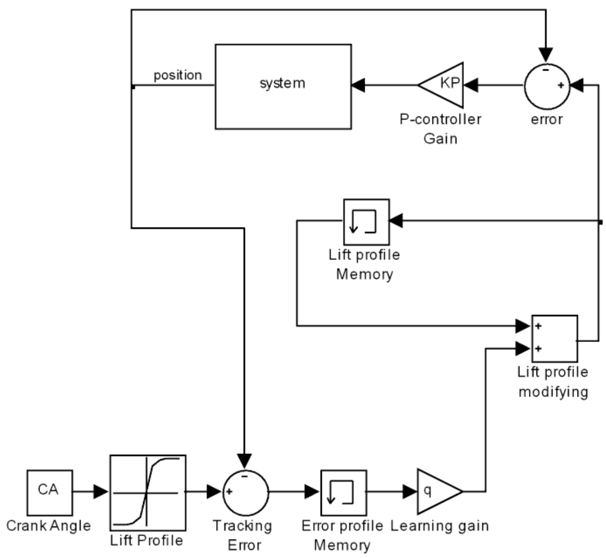

Figure 3: Schematic of ILC controller /2/

$$u_{i+1}(t) = u_i(t) + q\Delta y_i(t). \tag{3}$$

4 Simulations

The simulation model of the system was built in AMESim. In Simulink the controller design is easy to be implemented and hydraulic systems can be easily simulated with AMESim. Because of non-linearities, which exist in EHVA system, adaptive control parameters were needed. This was noticed as a tracking error in the beginning and the end of the movement, if used lift-profile was different.

4.1 Sensitivity analysis

Investigated parameters were supply pressure, dead volume between control valve and actuator, and diesel-engine cylinder pressure load.

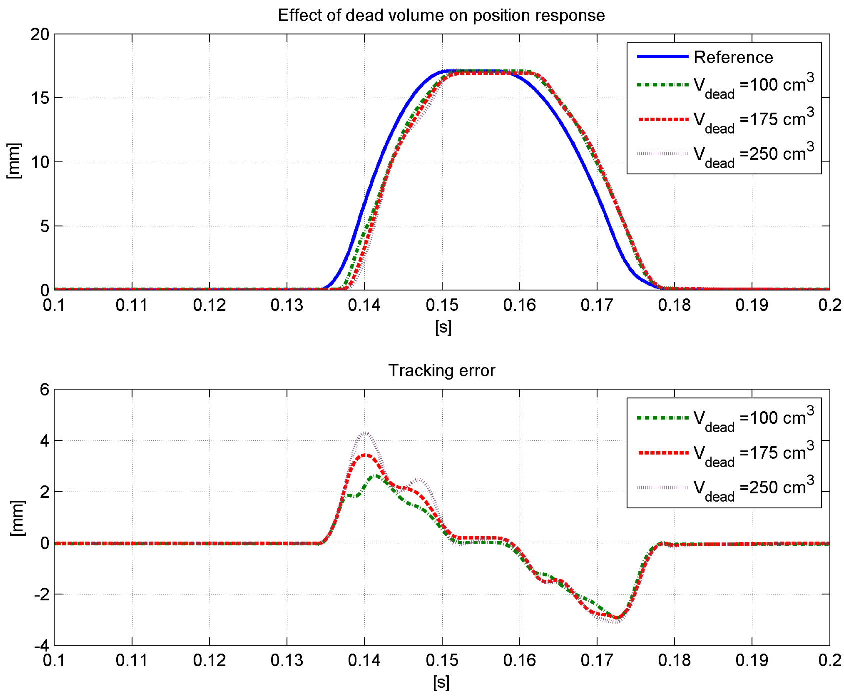

Figure 4: Position responses with different dead volumes.

From the simulations it could be seen that change in hydraulic cylinder dead volume was the most significant error source (**figure 4**). Primarily it affects the pressurizing time of the system, which was reflected into system delay. Changes in supply pressure or diesel-engine load did not affect significantly. The effect of resolution of the valve states and controller update time on position response, are presented in **figures 5 and 6**. Because relatively fast movement of the system, both parameters were affecting to the tracking error, if width of the steps were increased.

In **figure 7** is presented position responses of the system with MBC. The tracking error was reduced significantly by using delay compensation. In some cases it could be possible to achieve even better results by using separate delay compensation for opening and closing of the valve. In **figure 8** is presented position responses of ILC. The delay was already compensated and learning was fully done. As it can be seen, the shape of original reference profile was modified significantly. Tracking error between target reference and actuator displacement has reduced well inside desired range.

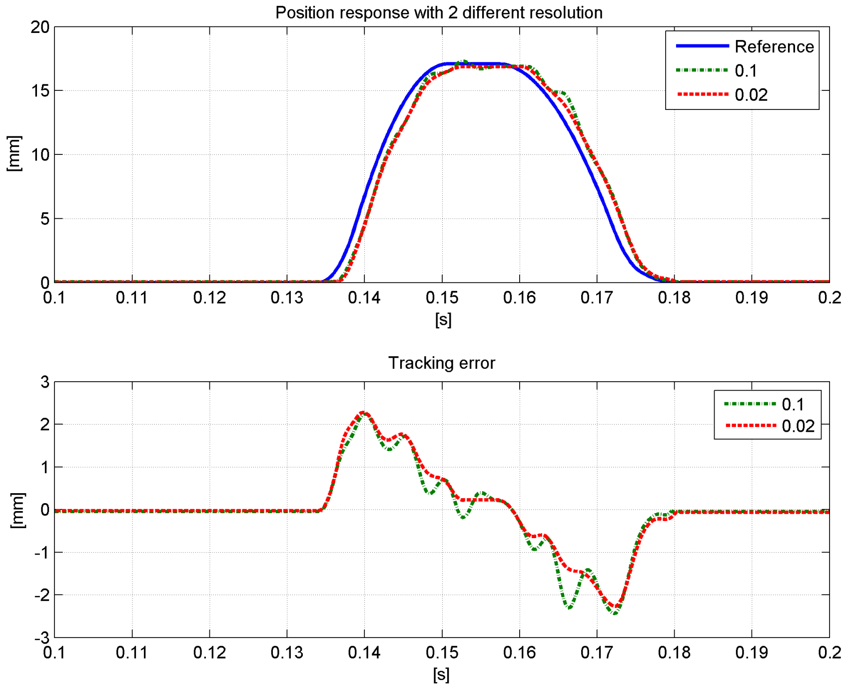

Figure 5: Position responses with 2 different resolution.

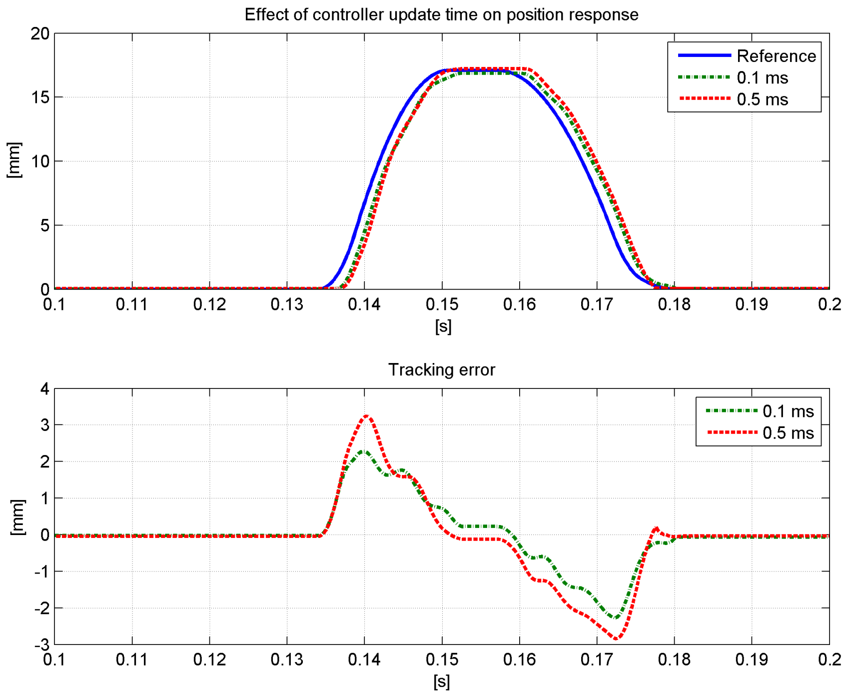

Figure 6: Position responses with 2 different value of update time of controller.

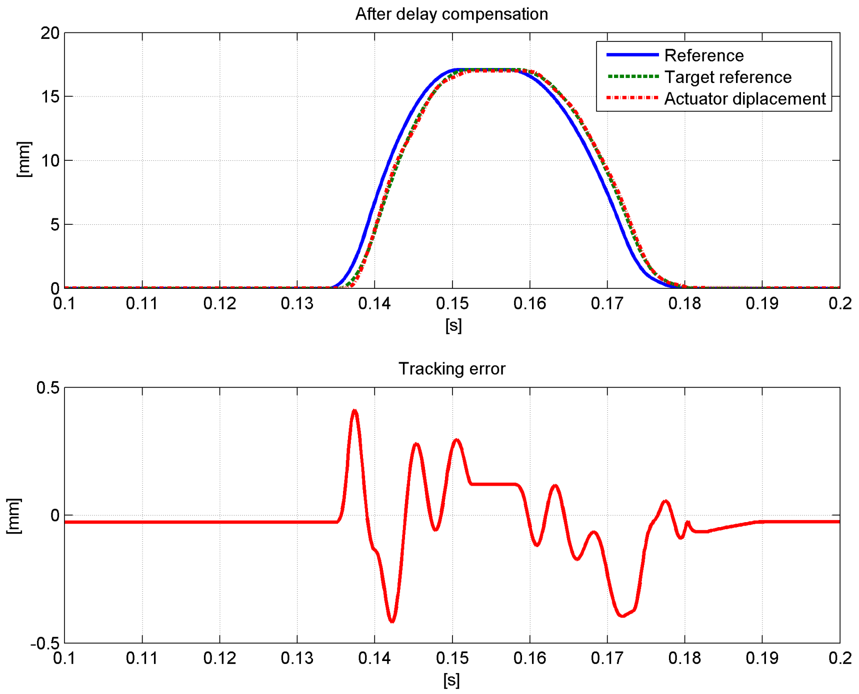

Figure 7: MBC with delay compensation

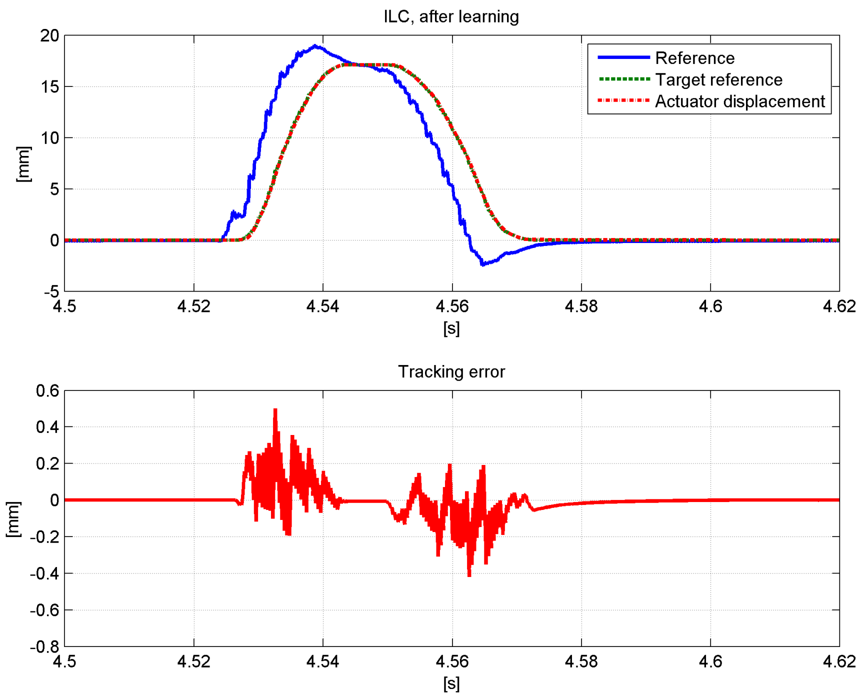

Figure 8: ILC Position response and error after learning

5 Verification measurements

Verification of the simulation model is presented in **figures 9-11**. Used reference signal was a sine wave with transfer function, which made the beginning and end of the movement smoother. In figure 9 it can be seen that the correspondence of measured and simulated position is good. The reasons for the differences are the unknown dead volume of the system, and shorter actual opening distance, which are causing delays in start of the opening/closing. If comparing figures 10 and 11 it can be seen that pressure behavior and control signals were very similar. In figure 11 is presented states for negative and positive direction. Number of states depended on user defined vector. In this study it included 50 possible states for both directions. For example positive state 10 is equal to control signal 0.2, or in a case of negative state, it is equal to -0.2.

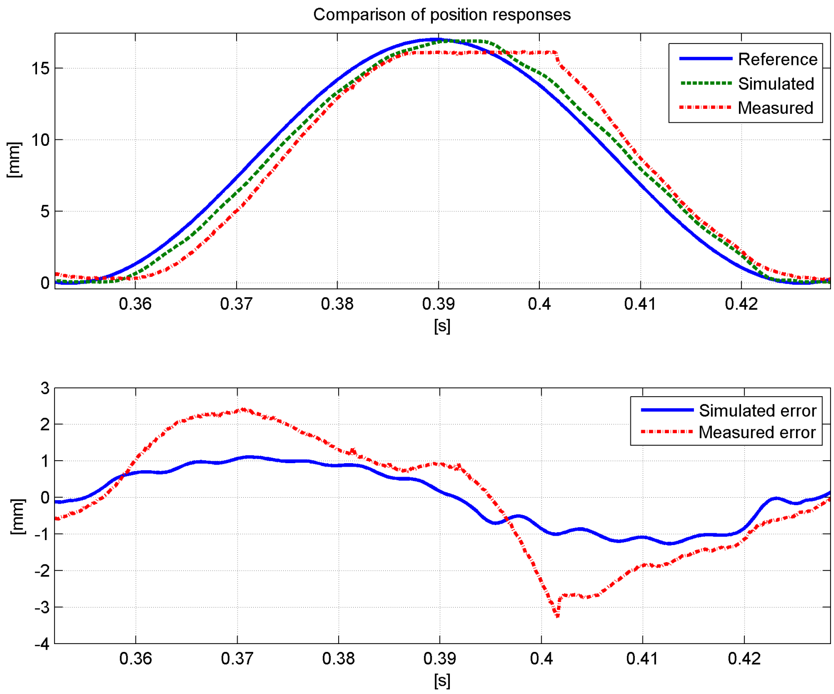

Figure 9: Comparison between simulated and measured results

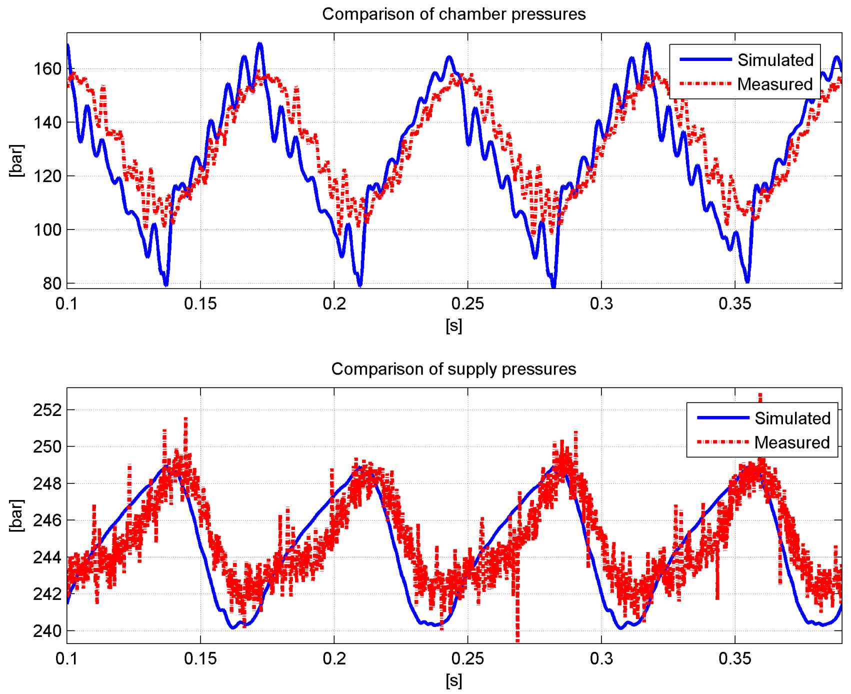

Figure 10: Comparison of system pressures

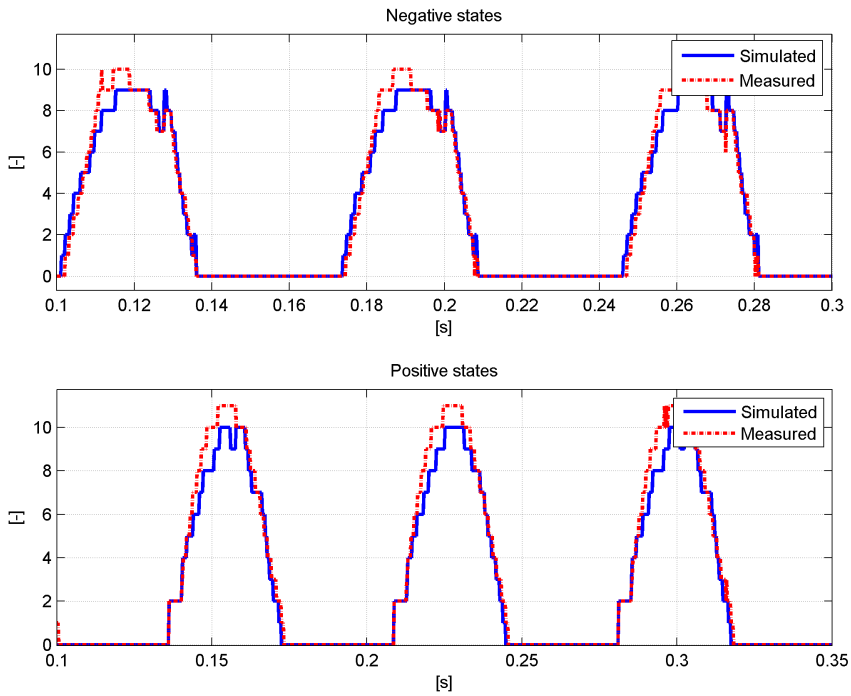

Figure 11: Comparison of control signals

6 Comparison of control strategies

In **table 1** are presented turnaround times of both controllers. It can be seen that ILC required a lot more calculation time than MBC. This was a consequence of automatic tuning, which was much more complex than in case of MBC's user tuned parameters. Turnaround time appeared to be constant during measurements, which can be thought as a one indication of repeatability. If displacement of 10 repeated strokes are measured and investigated, MBC can produce all strokes inside 3 samples (measurement frequency 5 kHz), and ILC inside one sample range (2,5 kHz measurement). But due to turnaround time restrictions, the ILC tests were performed at lower stroke frequency and speed, and thus the results are not fully comparable because the performance of the EHVA is overall better with lower stroke frequencies and speeds.

Control strategy	Turnaround time	Range of repetition
ILC	> 0.2 ms	0.4 ms (@460RPM)
MBC	0.04 ms	0.6 ms (@900RPM)

Table 1: Evaluation of control strategies

Negative aspect of used adaptive model-based controller was that number of parameters was relatively high, and the varying range and behavior must be tuned manually. The work needed to tune the controller, can be done autonomously or by user. If tuning is handled by user then it requires lot more work and time, but it leads possible to a result, where required calculation time is lower. When operation environment is changing or same controller should be applied to other machines, ILC is a convenient choice. The problem with the ILC is related to learning. The decision when to stop learning is important. As earlier studies have shown, ILC has tendency to escalate the error to points, which are not physically possible. Pros of ILC system are easy and automatic running, and small amount of easily tuned parameters.

The pressure compensation feature of MBC seemed to work well, when supply pressure was changed. The biggest error source was found out to be the dead volume of the system. If dead volume was changing a lot from designed value, quality of position response was reduced. In case of ILC the used control law was p-control, which is known to be sensitive for disturbances. However, ILC would be able to modify the reference signal quickly to achieve desired error range again. Other possibility is to use some other control law with ILC, which could improve the quality of position response.

7 Conclusions

Based on the simulation and measurement results, both controllers are capable of producing good position response in wide operation area. It was found out that turnaround times varied significantly. Especially ability of the ILC for automatic tuning is a huge benefit. In MBC user has to do tuning by himself which takes a lot of time, if only some of the tuning could be done in advance. The turnaround time of MBC was 0.04 ms and ILC over 0.2 ms. The high value of ILC’s turnaround time was partly explained by additional safety features of the controller. Even though, it clearly requires more calculation capacity than MBC, and the turnaround time of the controller directly affects to the actuator timing resolution.

The improvement of the MBC requires a more accurate model of the plant. Used model was found out to be satisfactory, but more work with model should be done to obtain better results. Better model would possibly reduce number of required control parameters. Disadvantage of more accurate model would possible be the increased turnaround time. Other option is to replace gain scheduling with adaptive structure that can optimize control parameters based on the process and reference signal. In case of MBC separate delay compensation could improve results, because the delay was found out to be different in opening and closing phases.

During the tests, many malfunctions of displacement sensors have been detected. Better sensors for continuous measurement are not available, or they are very expensive and require remarkable changes to the construction. Due to problems in position measurement reliability, also MBC with open loop and proximity sensor measuring would be worth to examine in future /6/.

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Symbols

Q	flow rate of the valve	$[\frac{m^3}{s}]$
u	valve opening 0-1	[-]
K_v	characteristic valve coefficient	$[\frac{\frac{m^3}{s}}{\sqrt{Pa}}]$
Δp	pressure difference over the control edge	[Pa]
J	cost-function	[-]
v_i	set of piston velocities	$[\frac{m}{s}]$
v_{ref}	velocity request	$[\frac{m}{s}]$
W	weight coefficient	[-]
Δu	change of control signal	[-]
i	iteration index	[-]
q	constant learning gain	[-]
Δy	tracking error	[m]