Experimental Study of Motion Synchronization of Hydraulic Servo Cylinders for Moulds of Continuous Casting Machines Oscillation

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Abstract

This paper reports the details of a test rig as well as results of experiments conducted to investigate the effect of using a cross coupling controller (CCC) on motion synchronization of two hydraulic servo cylinders. The drive and control system of the two cylinders in the rig is similar to that used frequently nowadays to oscillate the heavy moulds of continuous casting machines. In these systems each of the two cylinders is driven independently in an accurate closed loop control system. The accuracy of position synchronization of the two cylinders is affected in practice by disturbances that have detrimental effects on motion synchronization and may eventually lead to unpredictable production interruptions. A CCC with either a fuzzy logic controller (FLC) or a Proportional (P) controller had been proposed. It showed theoretically to reduce synchronization errors (SE) due to disturbances to practically acceptable values. During experiments each of the two servo cylinders had been loaded with almost constant load by means of two other hydraulic servo cylinders to simulate the mould weight. The experimental results showed that the FLC yields better motion synchronization compared with the P controller.

KEYWORDS: synchronization, cross coupling controller, fuzzy logic, proportional, servo, cylinders, valves, test rig.

1. Introduction

A motion synchronization problem occurs when an actuator leads or lags the other actuators in a group of actuators driving a body. This problem is usually met in continuous casting machines employed in steel plants, where the non-synchronized motion of the actuators oscillating the heavy moulds may cause production interruption and affect the plant productivity.

The Hydraulic Mould Oscillation (HMO) system frequently used nowadays in steel and other plants incorporates two hydraulic servo cylinders, each driven independently in a closed loop control system, with the two command signals of the two systems being identical /1/. This system fails in practice to yield the required position synchronization accuracy when the operating conditions deviate considerably from the design conditions.

In order to alleviate the effects of the disturbances on motion synchronization, Kassem et al. /2/ proposed adding CCC to the currently used control system. Using a derived mathematical model they showed theoretically the detrimental effects of the different disturbances on motion synchronization. A FLC and a P controller were alternatively applied within the CCC and proved to have a positive effect on position synchronization in the presence of disturbances, with the FLC yielding a better performance. In a recent paper /3/ a comprehensive analysis of the effect of the CCC with FLC on position synchronization accuracy of the two servo cylinders had been both theoretically and practically investigated. The CCC with FLC had been connected to the HMO electronic control system employed in the Flat steel plant of the Al-EZZ Dekheila Steel Co. Two types of disturbances were introduced during mould oscillation. System performance was measured in the presence and absence of the CCC. Both the theoretical predictions and the measurements taken in the plant confirmed the merits of the proposed techniques.

Due to economical considerations, the time allocated for conducting experiments on the plant continuous casting machine is usually limited. A test rig was consequently designed, constructed and used to carry out further investigations of the proposed CCC. An important objective of the test rig was also to allow testing of proportional and servo valves and cylinders of different sizes and manufacture under different loading conditions. Forster /4/ presented a test rig developed for performance investigation of a differential hydraulic cylinder working against a load applied by a double road servo cylinder driven by a two stage directional servo valve. The closed loop force control of the load system was controlled by means of a simple proportional gain.

2. Test rig description

Figure 1 shows the mechanical part of the test rig. In this rig the cylinders (1) and (2) are the operating cylinders. Each of them is driven in an independent closed loop position control system similar to that used frequently nowadays to oscillate the moulds of the continuous casting machines. The rig is equipped with other two servo cylinders (3) and (4), called the loading cylinders, which are used to load cylinders (1) and (2).

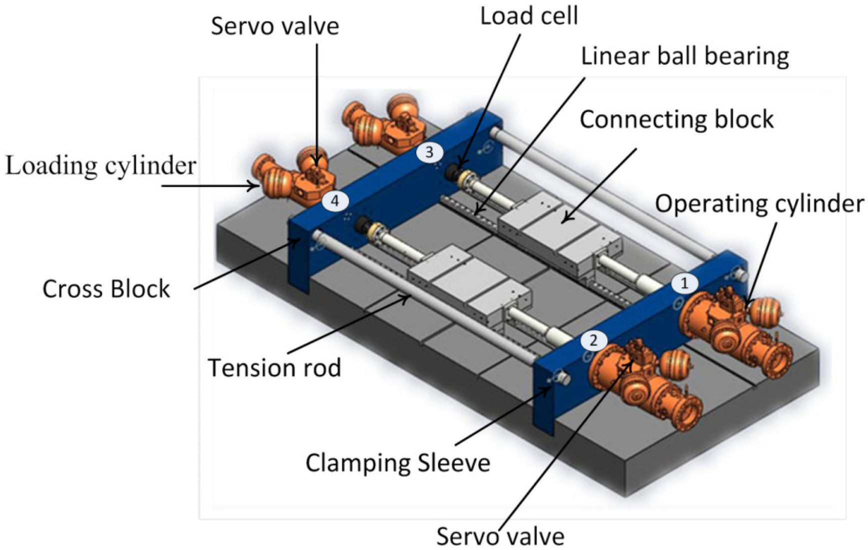

Figure 1: Mechanical part of the test rig

The piston and piston rod diameters of cylinders (1) and (2) are 160 mm and 100 mm respectively, while those of the loading cylinders are 100 mm and 60 mm. The four cylinders have the same stroke of 100 mm, and are mounted horizontally. Each operating cylinder is connected with a loading cylinder via a connecting block of mass 300 kg, which reciprocates horizontally over two rails of linear ball bearings. A load cell of type GTM series K 10kN_160kN /5/ is inserted between each couple of operating and loading cylinders to make it possible to stop system operation in case of an excessive unsafe load. The motion of each operating cylinder is controlled in a closed loop control system by means of a 3-stage hydraulic servo valve type 4WSE3EE16-15/200B8T315K9EM /6/ and the force of each loading cylinder is controlled in a closed loop control system by means of a 2-stage servo valve type 4WSE2DE10-51/90B13ET315K31EV /6/. The force applied by each loading cylinder on an operating cylinder is controlled so as to remain nearly constant and in one direction to simulate the mould weight. In this test rig the control of motion synchronization of the two operating cylinders is analogous to that of the mould oscillation system and even more challenging since the driven masses in the rig are not connected /7/.

Figure 2 shows a schematic drawing of the main components of the test rig. Position control of the operating cylinders is carried out utilizing an interface electronic control card (IEC1) type DS1104 /8/.The actual position of each operating cylinder is measured via a positional transducer type WLH100 /9/. The transducer output signal is processed to the signal block diagram of Matlab Simulink through the analogue digital converter (ADC) of the IEC1 then compared with the reference signal x_r. The resulting error is multiplied by a gain K_{p01}, converted to analogue signal via a digital analogue converter (DAC) and processed to the servo valve. The load pressure of each loading cylinder is measured via a pressure transducer type EDS344-3-250 /10/. The signal resulting is processed to the signal block diagram in Matlab Simulink through the ADC of an interface electronic control card DS1104 (IEC2). It is then compared with the reference signals F_{r3} and multiplied by the proportional controller gain K_{pl1}, converted through the DAC and processed to the corresponding servo valve /7/.

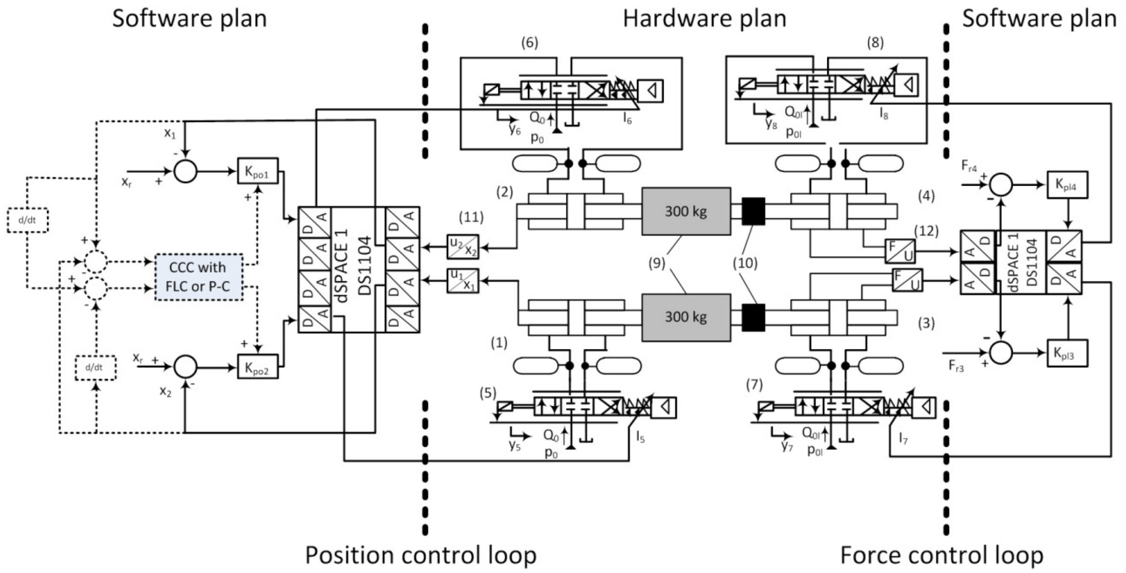

Figure 2: Schematic Layout of the test rig

The proposed CCC is shown in dashed lines in Fig. 2. The CCC includes either a P controller or a FLC. The input to the P controller is the synchronization error $e = x_1 - x_2$, and the gain of this controller is selected during experiments to yield the best synchronization. The inputs to the FLC are the position synchronization error e and its rate of change $de = \dot{x}_1 - \dot{x}_2$. The FLC maps e and de to the input of the local control system of the cylinder with the lagging response through a comparator, which directs also the output of the P controller to the lagging cylinder. The used FLC algorithm is depicted in **Fig. 3** and **Table 1**.

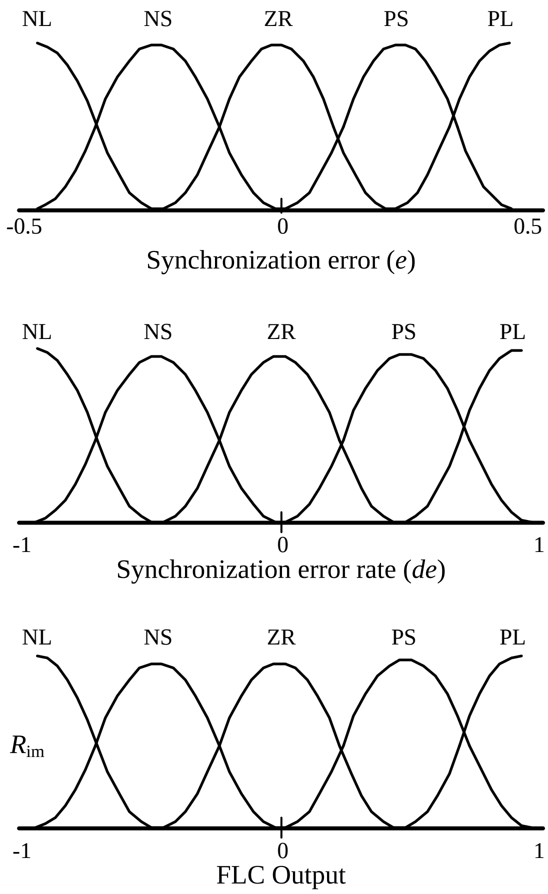

Figure 3: FLC input / output membership functions

e / de	NL	NS	ZR	PS	PL
NL	NL	NL	NL	NL	NL
NS	NS	NS	NS	NS	NS
ZR	ZR	ZR	ZR	ZR	ZR
PS	PS	PS	PS	PS	PS
PL	PL	PL	PL	PL	PL

Table 1: Fuzzy control rules

The signal block diagrams used during experiments for position control of the operating cylinders as well as for the force control of the loading cylinders are shown in **Figs. 4** and **5** respectively /7/.

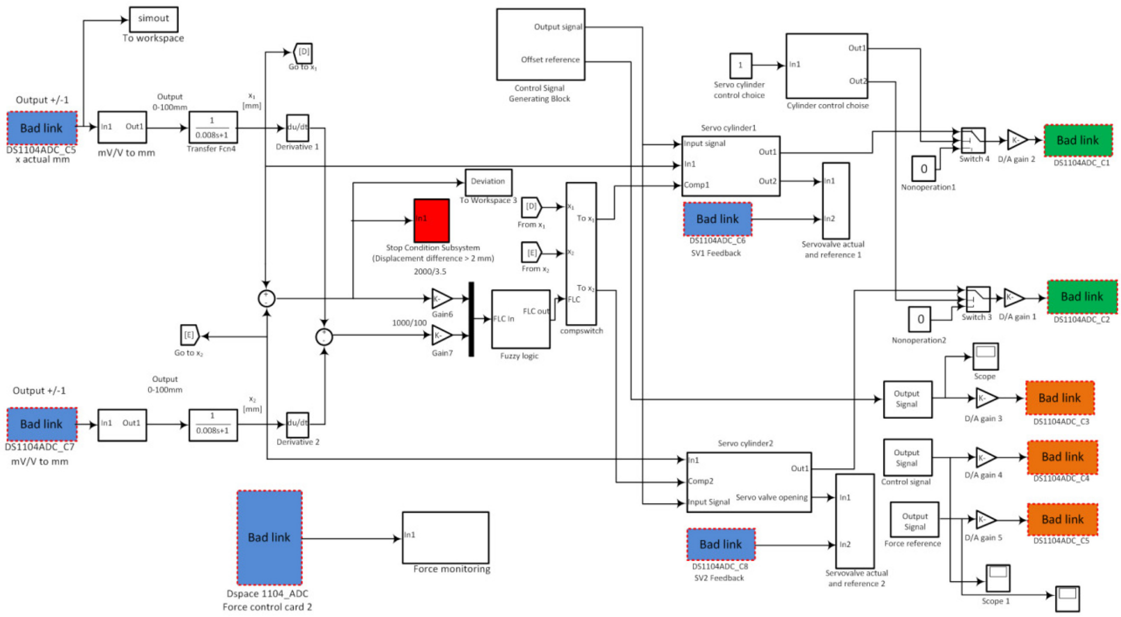

Figure 4: Signal block diagram of operating cylinders position control system with CCC

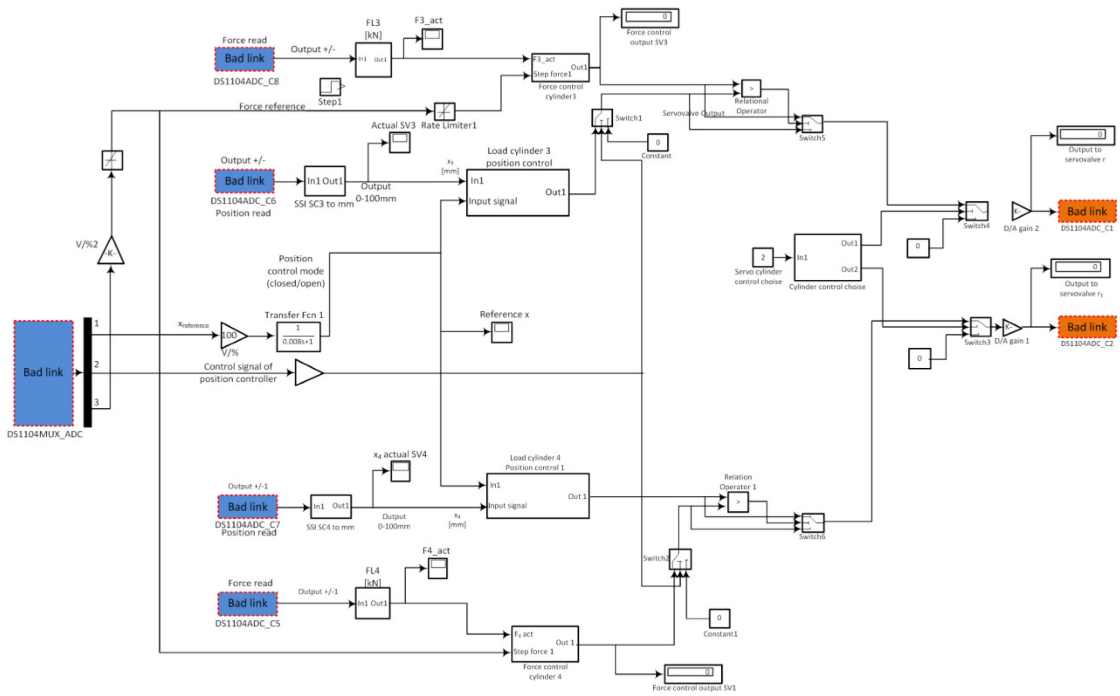

Figure 5: Signal block diagram of loading cylinders force control system

The hydraulic oil tank of the hot strip mill low pressure system in the flat steel plant, of volume 15 m^3, had been used for supplying the servo valves (5) and (6) with oil by means of a pressure - flow compensated axial piston pump of 250 cm^3/rev geometric volume. The pump delivery line feeds three lines P1, P2, and P3. The main pressure line P1 is branched inside the test rig to feed a specially designed block, on which subplates for proportional and servo valves from different manufacturers and of different sizes can be mounted and tested. The lines P1 and P2 are driven directly through the test rig to servo valves 5 and 6 controlling the operating cylinders. Line P3 is an auxiliary line available for other purposes on the rig, e.g. testing external actuators. The servo valves of the two loading cylinders are supplied with hydraulic power from a different hydraulic power supply unit of tank capacity 0.5 m^3 and a pressure - flow compensated axial piston pump of 100 cm^3/rev geometric volume.

3. Experimental results

Experiments had been carried out to investigate the effect of the proposed CCC on motion synchronization when disturbances exist. The two operating cylinders were oscillated during experiments with an input signal x_r = 3.5 sin 10πt mm. The reference input force of the loading cylinders had been set to 45 kN. The resulting force is shown in **Fig. 6**. The loading force is seen to have an average value of 43.5 kN and oscillations with about 4 kN amplitude and 5 Hz frequency.

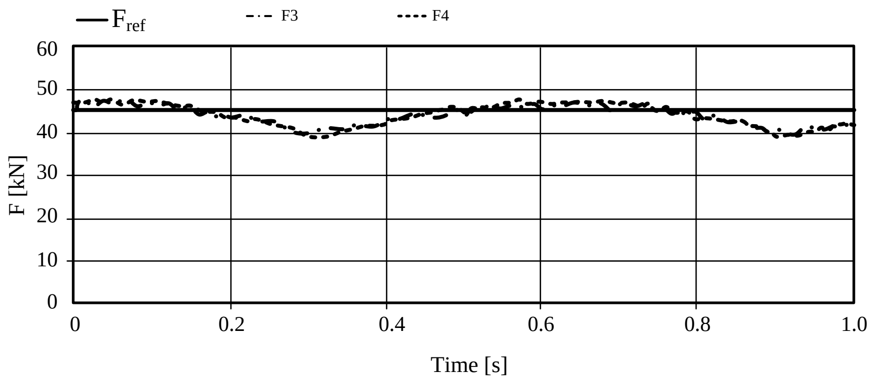

Figure 6: Loading forces of the operating cylinders

One of the cylinders was subjected to disturbances similar to those experienced in practice. The disturbances affecting motion synchronization which are most likely to occur in practice are a cylinder excessive internal leakage, a disturbed input signal to a servo valve, or a combination of these two disturbances. The displacements of the two cylinders had been measured when disturbances are not applied and the CCC is not activated. The results are shown in **Fig. 7**, which shows good motion synchronization of the cylinders. The negligibly small position synchronization errors seen in the figure are due to the deviations in the signal converters zero positions.

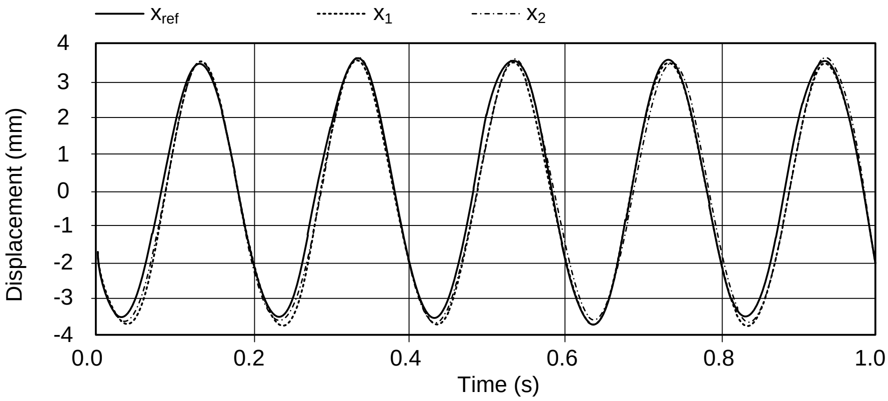

Figure 7: Displacements of the two operating cylinders in the absence of disturbances and without CCC

For applying the proposed CCC the gains of the P controller and the FLC should be determined. On the basis of a theoretical study, not presented in this paper, and experiments conducted on the rig, the gain of the P controller which yields best synchronization in the presence of disturbances was found to be 20% per mm. The corresponding input gains for e and de of the FLC were found to be 0.2 and 0.3 respectively, and the output gain 0.5.

3.1. Effect of a cylinder excessive internal leakage

Internal leakage had been simulated on the test rig by adding a throttle valve followed by a flow meter in parallel with one of the cylinders. The system had been run at different openings of the throttle valve when the CCC is inactivated and when it is applied with either the FLC or P controller. **Figure 8** shows the displacements of the cylinders in the absence of CCC when the throttle valve was opened to allow a flow rate Q_{L2} of 40 l/ min at Δp = 2.5 MPa. **Figures 9** and **10** show the displacements of the cylinders when the CCC is applied.

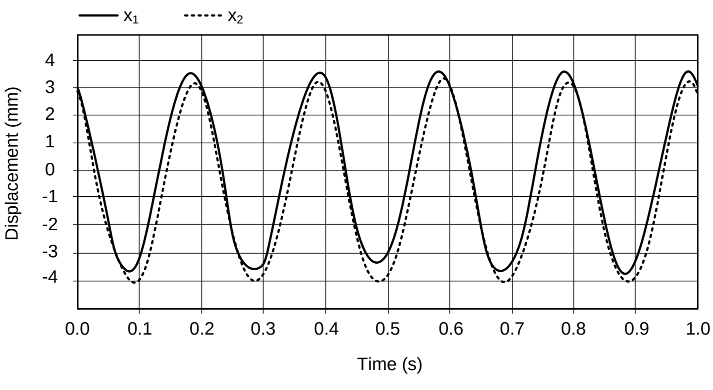

Figure 8: Effect of cylinder excessive internal leakage on cylinders displacements in the absence of CCC (Q_{L2} = 40 l/min)

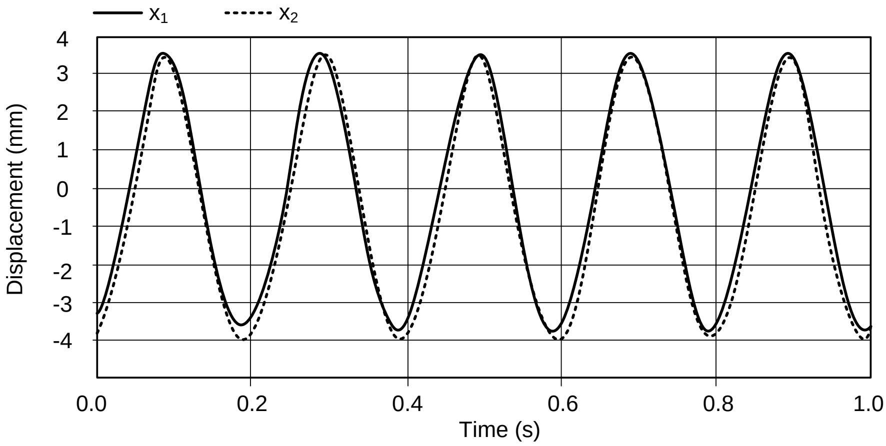

Figure 9: Cylinders displacements when CCC with FLC is applied in presence of cylinder excessive internal leakage (Q_{L2} = 40 l/ min)

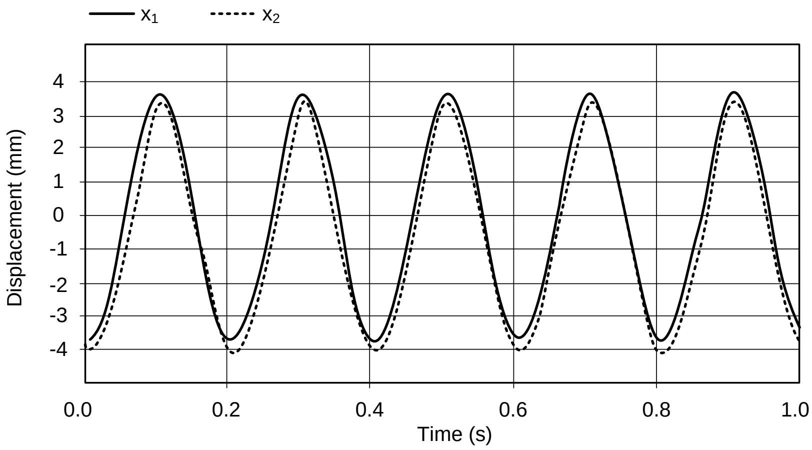

Figure 10: Cylinders displacements when CCC with P controller is applied in presence of cylinder excessive internal leakage (Q_{L2}= 40 l/ min)

The instantaneous position synchronization errors (SE) in the three cases are derived from the foregoing figures, and are presented in **Fig. 11**.

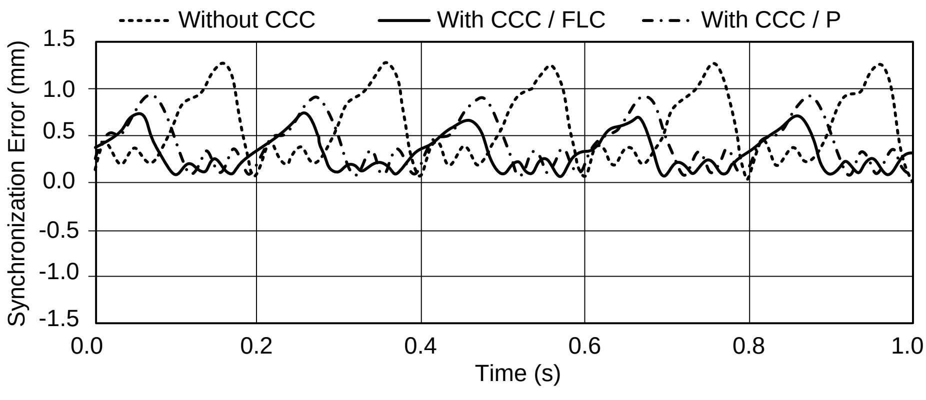

Figure 11: Instantaneous synchronization errors between cylinders 1 and 2 when Q_{L2}= 40 l/min

Figure 11 shows that the maximum value of SE amounts to 1.23 mm in the absence of CCC. This is not an acceptable value in practice. The system is actually stopped when SE reaches 1 mm. This unacceptable value is seen to be reduced to 0.9 mm when the CCC with the P controller is activated and further down to 0.7 mm when the CCC with the FLC is applied.

3.2. Effect of servo valve disturbed input signal

A servo valve disturbed input signal occurs in practice due to a mal-function of the valve electronic control card, bad contacts in plug-in connectors or other causes. This leads to a reduction in the value of the electric current supplied to the torque motor with respect to its correct value. This case is represented on the test rig by multiplying the input current to one of the valves by a factor K_{rs} less than unity. Experiments had been carried out with different values of K_{rs}. **Figure 12** shows the values of SE when K_{rs} for the servo valve of cylinder (2) namely K_{rs2} is equal to 0.3. The positive effect of the CCC is obvious, the maximum error of 1.2 mm in the absence of CCC is seen to be reduced to 0.76 mm when the CCC with the P controller was employed, and to 0.6 mm when it was applied with the FLC.

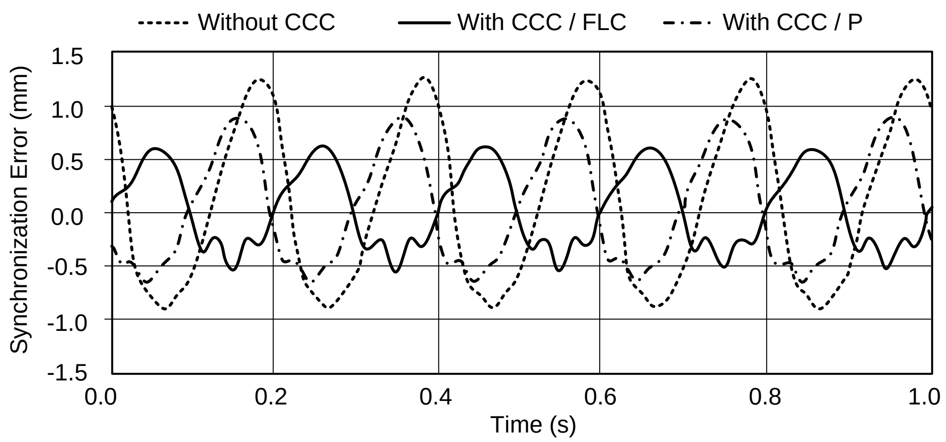

Figure 12: Synchronization errors when K_{rs2} = 0.3

3.3. Combined effect of a cylinder excessive internal leakage and its servo valve disturbed input signal

Figure 13 shows the values of the measured SE in the absence and presence of CCC, when the throttle valve was opened to allow a flow rate of 20 l/ min at Δp = 2.5 MPa and the electric current supplied to the corresponding servo valve was multiplied by 0.7. The advantage of using the CCC is evident from the figure since the maximum SE reaching 0.9 mm in the absence of the CCC is reduced to 0.7 mm when it is applied with the P controller and to 0.6 mm in its presence with the FLC.

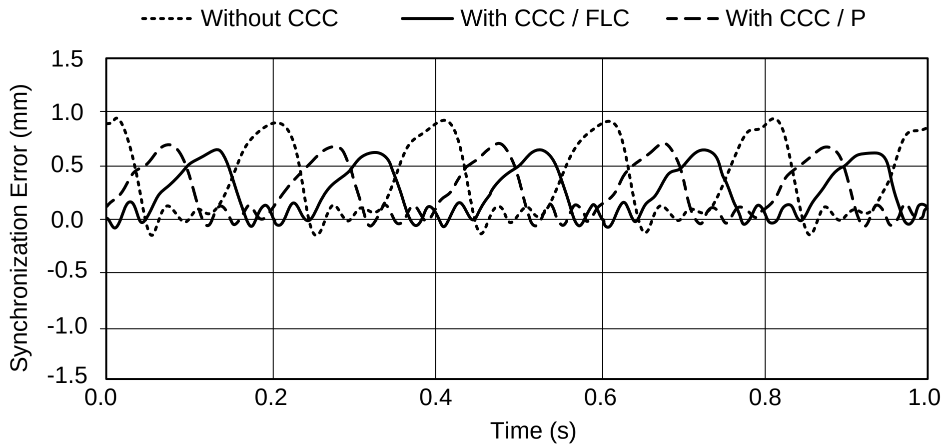

Figure 13: Synchronization errors when Q_{L2}= 20 l/min and K_{rs2} = 0.7

4. Conclusion

A test rig had been designed to investigate experimentally the effect of using a proposed cross coupling controller on motion synchronization of two hydraulic servo cylinders. The cylinders and their control systems represent the drive and control systems used frequently nowadays to oscillate the heavy moulds of continuous casting machines in steel and other plants. The technology prevailing is to drive each cylinder independently in an accurate closed loop control system with the input signal of each cylinder control system identical to the other. The results of the experiments showed the positive effect of employing the proposed CCC on motion synchronization in the presence of disturbances that would otherwise lead to high synchronization errors and would eventually lead to production interruption. The proposed CCC with FLC showed to be more effective than the CCC with P controller.

5. References

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6. NOMENCLATURE

de	synchronization error rate of change	mm/s
e	instantaneous position synchronization error	mm
$F_{r3/4}$	reference force for loading cylinders 3 and 4 respectively	N
I	electric current	A
K_{rso}	response delay parameter of servo valve of operating cylinders	
p_o	supply pressure of test rig load cylinders	MPa
p_s	supply pressure of test rig operating cylinders	MPa
Q_L	internal leakage	l/min

Acknowledgement

The authors would like to express their gratitude to the management of EZDK Co. for providing the funds required to cover the costs of the test rig and for their support.