MOTION SYNCHRONIZATION ENHANCEMENT OF HYDRAULIC SERVO CYLINDERS FOR MOULD OSCILLATION

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Abstract

A cross coupling control technique (CCC) with a fuzzy logic controller (FLC) is proposed in this work to improve motion synchronization of the two hydraulic servo cylinders used to oscillate the heavy mould of a continuous casting machine. A mathematical model is presented for the system frequently used in industry in which each servo controlled cylinder is driven independently in an accurate closed loop control system. The model validity is verified by comparing results of numerical simulations for mould oscillations using the model, with actual measurements recorded in a steel plant. Effect of disturbances on motion synchronization is depicted theoretically using the mathematical model. A fuzzy logic controller which reduces synchronization errors in cylinders positions to practically acceptable values is proposed and theoretically verified. Measurements carried out on a continuous casting machine in a steel plant confirmed the merits of using the proposed CCC in reducing the synchronization errors resulting from different disturbances.

Keywords: synchronization, hydraulic, servo, cylinder, cross coupling control, fuzzy logic, simulation, plant measurements

1 Introduction

Motion synchronization problem is frequently met when a machine part is driven by two or more actuators, and one actuator is lagging relative to the others. In steel plants this problem is faced, for instance, in continuous casting machines, where the non-synchronized motion of the hydraulic cylinders oscillating the moulds causes production interruption and affects the plant productivity.

Several synchronization techniques are used in practice for position or velocity synchronization control of two or more actuators, the simplest of which are either mechanical or hydraulic. Mechanical synchronization is realized by guiding the driven part mechanically or connecting the actuators through a cabling or linkage design. Hydraulic synchronization is based upon the use of flow dividers (Lisowiski and Brandys, 2000) or e.g. pressure compensated flow control valves. High precision flow divider valves or pressure compensated flow control valves are more suitable for synchronizing hydraulic actuators speeds than their positions due to position biases that might result from different sources.

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To overcome the drawbacks of the mechanical and hydraulic methods of synchronization, electro hydraulic synchronization techniques are used. Three proportional flow control valves were proposed by Li et al. (2001) to synchronize the motion of two hydraulic cylinders in a lift system. A pseudo - derivative feedback controller was applied for velocity control and a constrained step PD controller for minimizing the synchronization error in cylinders positions. Results of experiments showed that the synchronization error using this technique amounted to ± 2 mm. A nonlinear control algorithm was proposed by Sun and Chiu (2002) to synchronize the motion of two servo cylinders of a lift system of 40 kN load carrying capacity. They synthesized the controller through a two - step process using a linear multi input – multi output motion synchronization controller as the outer loop controller and a nonlinear single input – single output perturbation observer - based pressure controller as the inner loop controller of each cylinder. Their experimental results verified the merits of the proposed approach in the application they dealt with. Li, C., et al. (2006) developed a measurement system based on computer visual feedback and adopted a nonlinear control method for controlling the synchronization error of a dual cylinder group electro hydraulic system used in pushing railway bridge machinery. Outer loop and inner loop controllers were designed to handle the disturbances by modifying the conventional PID controller into sectional form.

High quality synchronization of positions of two moving hydraulic cylinders has been realized in practical applications by driving each of the cylinders in an independent and accurate closed loop servo system, with identical input signals (SMS Demag, 2002). Without a cross coupling control technique (CCC) such systems would fail to yield reasonable synchronization when the operating conditions deviate considerably from the design ones. A CCC incorporating a fuzzy logic controller (FLC) was proposed (Moore and Chen, 1995) for motion synchronization control of multiple independent electric servo drivers. The proposed cross coupling controller yielded reasonable results when applied to the case of a two DC motors servo drive system. A FLC and a P - controller were alternatively proposed by Kassem et al. (2008) to establish cross coupling position synchronization of two hydraulic servo cylinders used to oscillate a heavy mould of a continuous casting machine. Results of theoretical investigations showed that the FLC yields better synchronization.

In this paper the effectiveness of a CCC with a proposed FLC regarding position synchronization of the two hydraulic servo cylinders of the hydraulic mould oscillation (HMO) drive and control system is studied both theoretically and practically. For practical investigation purposes the hardware and software of the CCC with the proposed FLC have been connected to the HMO control system in a steel plant, and the system performance was measured in the presence and absence of the CCC. Results of measurements verified practically the merits of using the proposed CCC.

2 System Description and Mathematical Model

The HMO control system used currently in industry is shown diagrammatically in solid lines in Fig. 1. The dashed lines in the figure represent the proposed added CCC Kassem et al. (2008). The hydro mechanical part of the system used in industry consists of two hydraulic servo cylinders (1) and (2) which impart oscillatory motion to the mould (3) of mass M and mass moment of inertia about its center of gravity J. The two cylinders are driven by means of two 3-stage hydraulic servo valves (4) and (5). The electric current supply to each servo valve is given by:

$$I_i = K_{Pu}(x_r - x_i), \text{ during upward motion} \quad (1)$$

$$I_i = K_{Pd}(x_r - x_i), \text{ during downward motion} \quad (2)$$

where, i = 1,2

Since the motion oscillation frequencies in these applications are low and ranging between 4.5 Hz and 5.5 Hz, the equation of motion of the main spool of each servo valve is as follows (Murrenhoff, 2002):

$$\ddot{y}_i + 2D_{vi}\omega_{0vi}\dot{y}_i + \omega_{0vi}^2 y_i = V_{vi}\omega_{0vi}^2 I_i \quad (3)$$

with $|y_i| \le |y_{imax}|$ and i= 1,2

The equations giving the flow rates through the control ports of the servo valves are:

$$Q_{A_1} = A\left(\frac{|P_0 - P_{A_1}|}{R_{m1}}\right)^{0.5} \text{ and}$$

$$Q_{B_1} = A\left(\frac{|P_{B_1}|}{R_{m1}}\right)^{0.5} \text{ for } z \ge 0, \ i = 1,2 \quad (4)$$

$$Q_{A_1} = -A\left(\frac{|P_{A_1}|}{R_{m1}}\right)^{0.5} \text{ and}$$

$$Q_{B_1} = A\left(\frac{|P_0 - P_{B_1}|}{R_{m1}}\right)^{0.5} \text{ for } y < 0, \ i = 1,2 \quad (5)$$

where $A = \dfrac{y_i}{y_{max}}$, $R_{mi} = \dfrac{\rho}{\left(2\alpha_d^2\alpha_{mi}^2\right)}$, an α_d is the coefficient of discharge.

Applying the continuity equation to the cylinders chambers and assuming that the cylinder internal leakage flow rate $Q_{Li} = K_{Li}(P_{Ai} - P_{bi})$, it can be shown that:

$$\dot{P}_{Ai} = \frac{E\left(Q_{Ai} - A_{Ci}\dot{x}_i - Q_{Li} - Q_{LeAi}\right)}{V_{Ai}} \quad (6)$$

$$\dot{P}_{Bi} = \frac{E\left(A_{Ci}\dot{x}_i - Q_{Bi} + Q_{Li} - Q_{LeBi}\right)}{V_{Bi}} \quad (7)$$

where, I = 1, 2, $V_{Ai} = A_{cl}\dfrac{h}{2} + A_{Ci}x_i$, $V_{Bi} = A_{Ci}\dfrac{h}{2} - A_{cl}x_i$ and Q_{LeA} and Q_{LeB} represent the external leakages from chambers A and B respectively.

The equation of motion of each hydraulic cylinder piston is:

$$m_i\ddot{x}_i = \left(P_{Ai} - P_{Bi}\right)A_{Ci} - d_i\dot{x}_i - F_i, \quad i = 1,2 \quad (8)$$

and the equations of motion of the mould are:

$$F_1 + F_2 - Mg = M\ddot{x}_M \quad (9)$$

$$F_1L_1 + F_2L_2 = J\ddot{\theta} \quad (10)$$

where $x_M = (x_1L_2 + x_2L_1)/L$ and $\theta = (x_1 - x_2)/L$.

Since the maximum allowable deviation between x_1 and x_2 is limited in practice to 1 mm when the distance L between the driving cylinders is 5000 mm, the maximum allowable inclination angle of the mould is 0.011 °. Due to the mould symmetrical design, and since its angles of inclination during motion are quite small, the center of gravity of the mould and its contents can be assumed to be in the middle; namely $L_1 = L_2$. The set of equations from (1) to (10) represent the system mathematical model.

The validity of this model has been checked by comparing the theoretical results of a simulation run, carried out in Matlab Simulink environment using the model, with measurements taken on a continuous casting machine in a steel plant when the plant was running and the input signal was in the form $x_r = 3.5 \sin(29.5\,t)$ m. The parameters and constants adopted during the simulation run were those of the plant; namely:

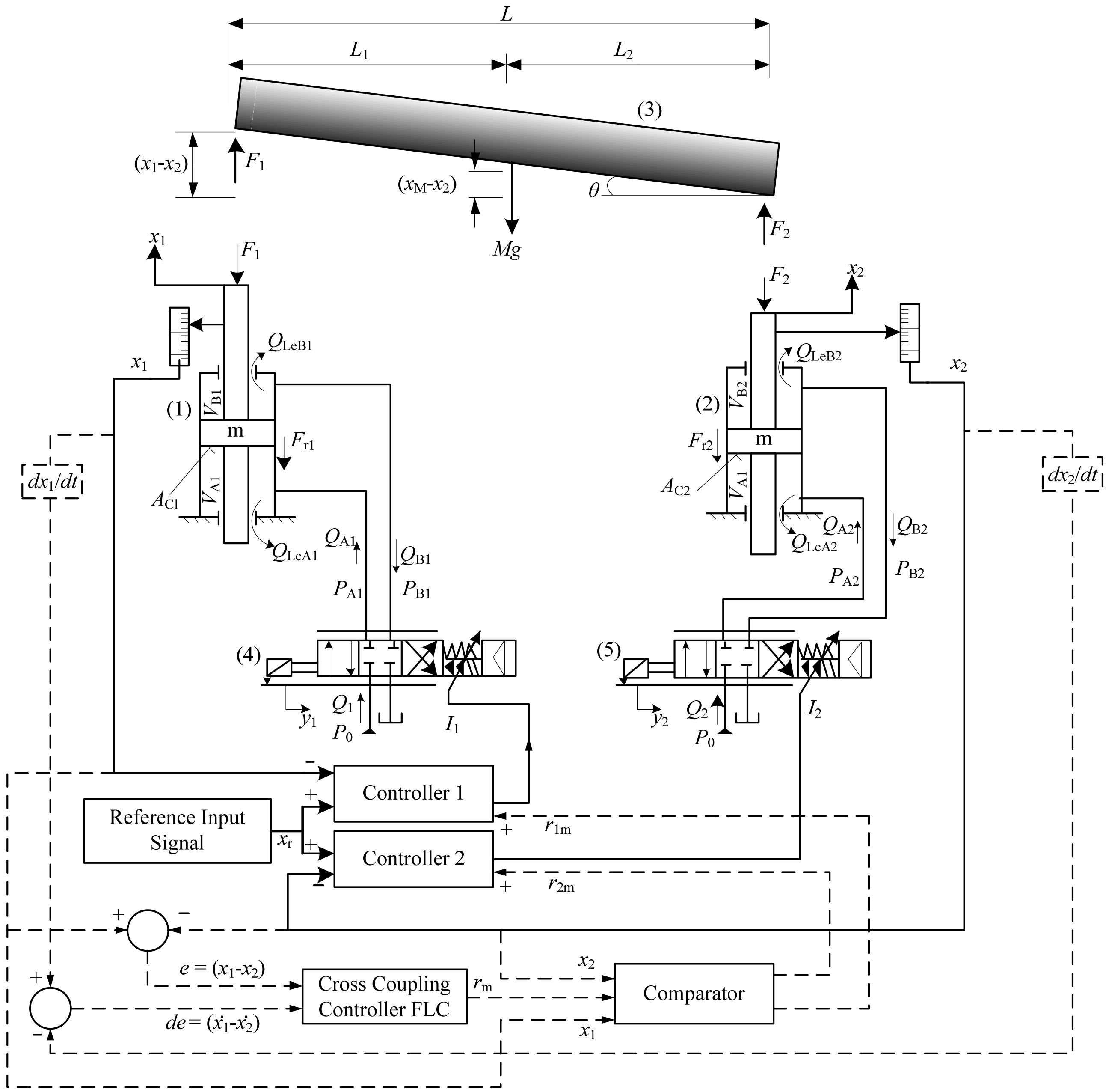

Fig. 1: *Hydraulic mould oscillation control system*

M = 25000 kg, m = 200 kg, J = 54.6 x 10^3 kgm^2, P_0 = 25 MPa, A_{Ci} = 219 x 10^{-4} m^2, d = 1.75 x 10^5 Ns/m, E = 1.4 x 10^9 Pa, D_v = 0.7, ω_{0v} = 816.4 rad/s, K_L= 8 x 10^{-12} m^5/Ns, K_{pu}= 35 %/mm, and K_{pd}= 24 %/mm.

Figure 2 shows a comparison between the theoretically obtained results and the actual measurements taken in the plant when CCC is not present. Good agreement between the results is evident, with the maximum deviation in the peak values being less than 6 % and the phase shift nearly equals 0.003 s. Since the cycle time in this case is 0.212 s, the phase shift between the theoretical and practical results is less than 1.5 %. The small deviation in the peak values and phase shift confirms the validity of the model.

3 Effect of Disturbances on Motion Synchronization

Under the design working conditions the described HMO control system currently used in industry; namely the system without CCC and with

K_{pu} different from K_{pd}, yields practically well synchronized motion for the two cylinders. After periods of operation it has been recorded that the motion of the two cylinders turn out to be non synchronized due to the influence of various internal and external disturbances affecting the system. Motion non synchronization had been attributed in many cases to the increase of one of the cylinders internal leakage. Effect of increase of a cylinder internal leakage on synchronization can be studied theoretically by assigning values to K_{L2} higher than K_{L1}. Figure 3 shows the displacements x_1

and x_2 of the two cylinders and the resulting synchronization error $SE = x_1 - x_2$ when $K_{L1} = 8 \times 10^{-12}$ m^5/Ns and K_{L2} is increased to 180 x 10^{-12} m^5/Ns. The synchronization error is seen to attain a maximum value of 1 mm.

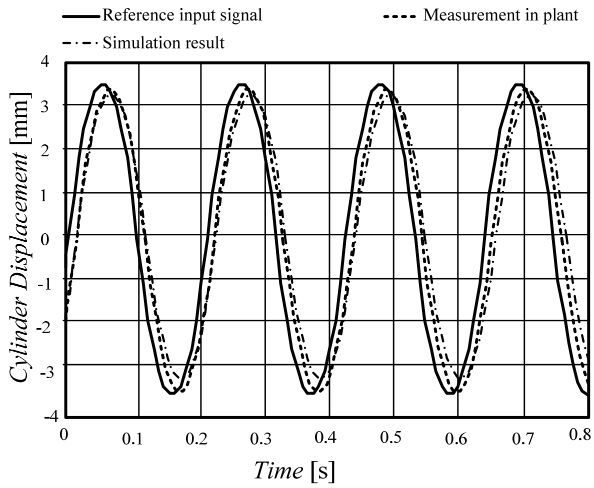

Fig. 2: *Comparison between theoretical results and measurements in a steel plant*

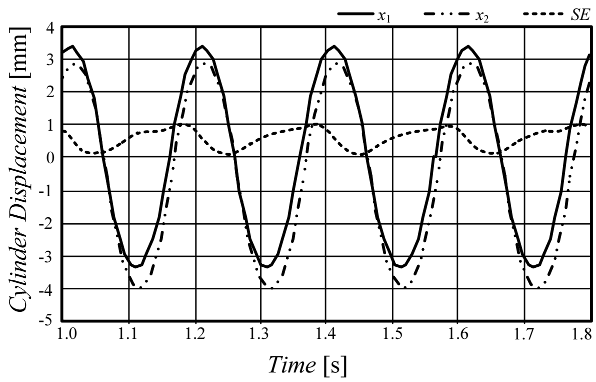

Fig. 3: *Cylinders displacements and Synchronization error (SE) at: K_{L1}= 8 x 10^{-12} m^5/Ns and K_{L2}= 180 x 10^{12}m^5/Ns*

A servo valve disturbed input signal also causes non synchronized motion. It occurs in practice due to reasons such as malfunctioning of a valve electronic control card, bad contacts in a plug-in connector, or else, which results in reducing the value of the control signal fed to the servo valve. This case can be investigated theoretically by multiplying the input current to one of the servo valves by a factor K_{rs}, which is less than unity. Figure 4 shows the displacements of the cylinders and the resulting synchronization error when K_{rs2} = 0.6 for servo valve (5). The figure shows that *SE* amounts to a maximum value of 0.85 mm.

Combined disturbances might occur also in practice when, for instance, a cylinder internal leakage increases and the input signal of a servo valve is disturbed. Figure 5 shows the displacements of the two cylinders and the synchronization error when K_{L2} = 120 x 10^{-12} m^5/Ns and K_{rs2} = 0.75, while K_{L1} = 8 x 10^{-12} m^5/Ns and K_{rs1} = 1. The recorded maximum value of *SE* in this case is seen to amount to 1.2 mm.

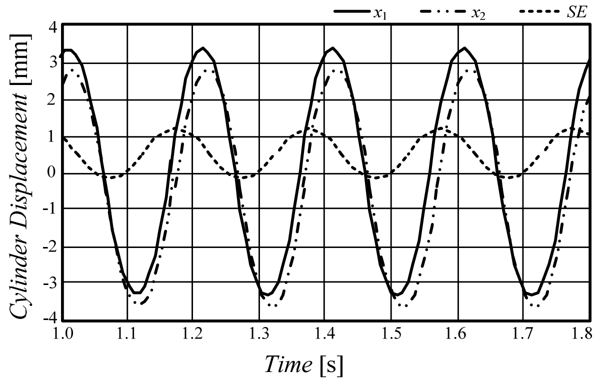

Fig. 4: *Cylinders displacements and SE at K_{rs1}= 1 and K_{rs2}= 0.6*

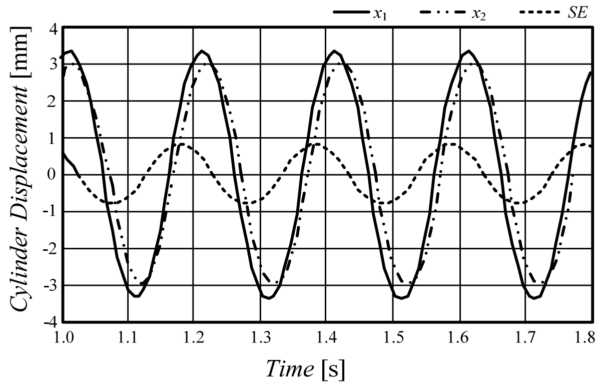

Fig. 5: *Cylinders displacements and SE at: K_{rs2}= 0.75 and K_{L2}= 120 x 10^{-12}m^5/Ns*

4 Cross Coupling Synchronization

The cross coupling controller proposed to improve synchronization is shown schematically in dashed lines in Fig. 1. In this CCC both the position synchronization error $e = x_1 - x_2$ and its rate of change $de = \dot{x}_1 - \dot{x}_2$ are inputs to a fuzzy logic controller (FLC). The FLC maps *e* and *de* to the input of the local control system of the lagging cylinder using only a comparator, which is shown schematically in Fig. 6.

Several trials had been carried out to determine the adequate FLC for the studied case; namely the FLC which achieves minimum synchronization error as well as system stability. Trials with various numbers of membership functions of the “gauss2mf” type, and different numbers of defuzification rules had been carried out. The FLC shown in Fig. 7 was found to fulfill the requirements. It has five membership functions, two inputs *e* and *de* and one output, with the error input values *e* dominant in the output fuzzy sets. The use of *de* showed to contribute to stability and partially to accuracy. In this figure ZR denotes zero, NL and PL denote negative large and positive large respectively, while NS and S denote negative small and positive small.

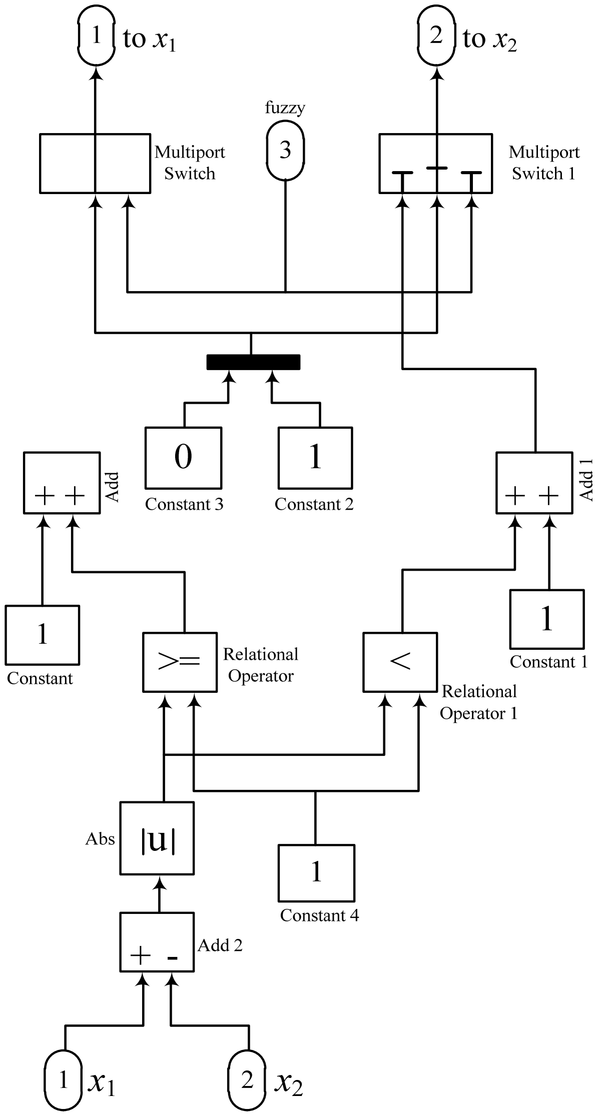

Fig. 6: *Comparator of the CCC*

Table 1 shows the Fuzzy Association Membership (FAM) bank rules. The control surface in this case is nearly linear.

Table 1: Fuzzy control rules

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

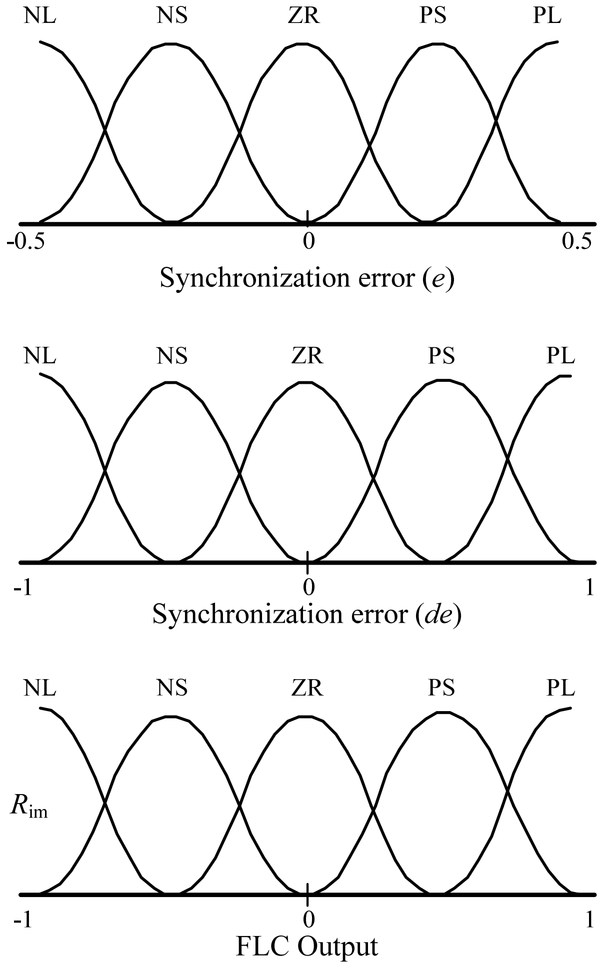

Fig. 7: *FLC input / output membership functions*

The signal block diagram representing the HMO system dynamics as described by Eq. 1 to 10, with the proposed CCC taken into account, is shown in a Matlab Simulink environment in Fig. 8. Numerical simulation runs had been conducted using this signal block diagram to investigate the effect of CCC on performance when various disturbances exist. Initial simulation runs had been carried out to determine the values of the FLC gains namely the error gain K_{eg}, the error rate gain K_{dg} and the fuzzy logic gain K_{fg}. The values of these gains had been found to be $K_{eg} = 570$, $K_{dg} = 10$, and $K_{fg} = 0.7$. The simulation results representing a case of a cylinder excessive internal leakage are shown in Fig. 9 when CCC is applied and when it is absent. The values of the synchronization errors seen in the figure clarify the positive effect of using the proposed CCC, since the synchronization error ranging between 0.12 mm and 1 mm in the absence of CCC is reduced to range between -0.08 mm and 0.4 mm when CCC is applied.

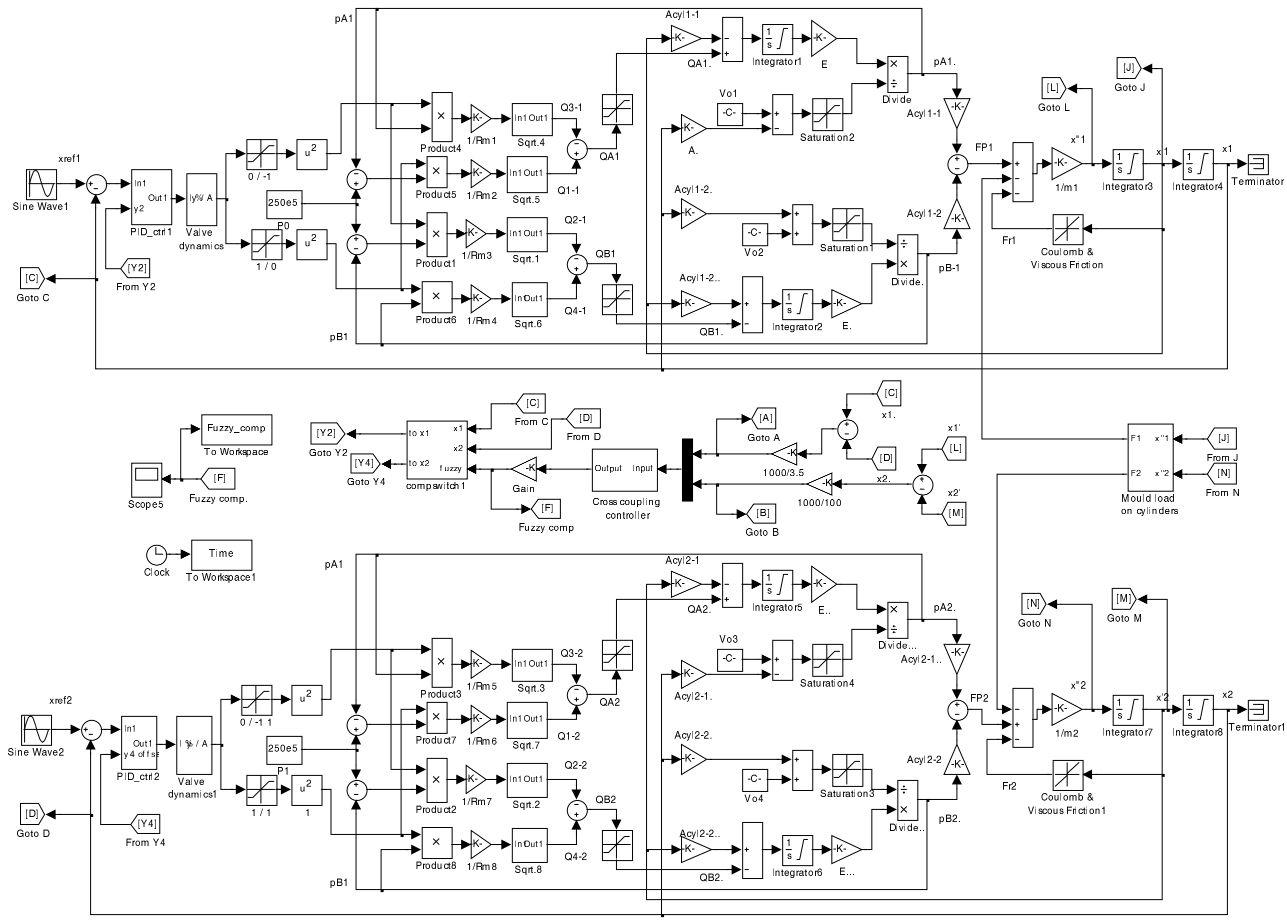

Fig. 8: *Signal block diagram for the HMO control system with CCC*

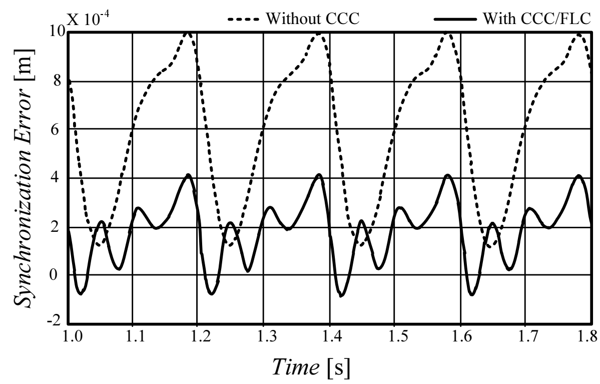

Fig. 9: *Synchronization errors at $K_{L2} = 180x10^{-12}$ m^5/N and $K_{L1} = 8x10^{-12}$ m^5/N*

Further simulation runs had also been carried out to investigate the effect of CCC on synchronization at different values of K_{L2}. The results obtained are presented in Fig. 10 which shows the variation of the maximum value of the *SE* with the variation of K_{L2} in the absence and in the presence of the CCC. In the absence of CCC, the increase of one cylinder internal leakage increases the synchronization error, with the rate of increase of *SE* higher at the higher values of K_{L2}. Applying the proposed CCC is seen to reduce the maximum *SE* at all values of K_{L2} to practically acceptable values. Further, the high rate of increase of *SE* with K_{L2} at the higher values of K_{L2} in the absence of CCC is seen to be zero when the CCC is applied.

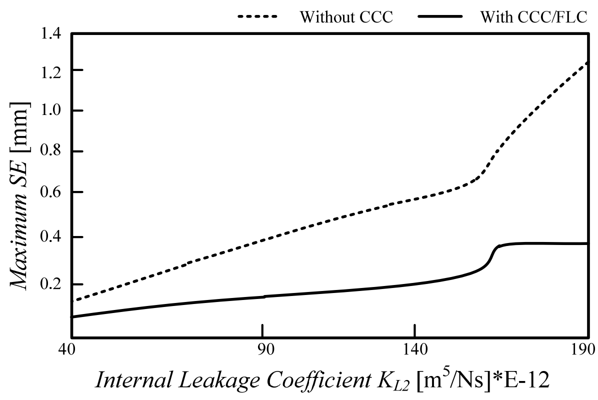

Fig. 10: *Variation of maximum SE with increase of one cylinder internal leakage*

Figure 11 shows the simulation results when one input signal of one servo valve is disturbed; namely when K_{rs2} = 0.6, in the absence and presence of CCC. The figure shows that the *SE* ranging between -0.83 mm and 0.83 mm in the absence of CCC is reduced in its presence to range between -0.27 mm and 0.32 mm.

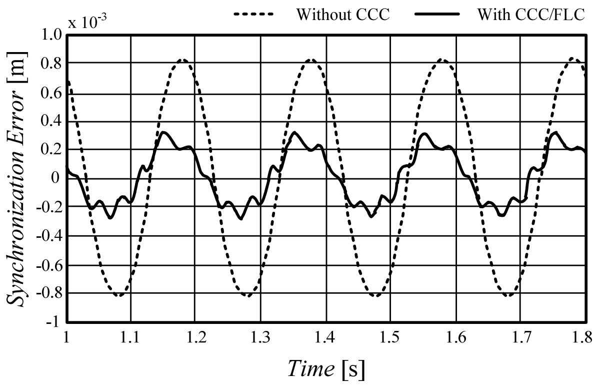

Fig. 11: *Synchronization Error at K_{rs2} = 0.6*

Figure 12 depicts the effect of CCC on the maximum *SE* when K_{rs2} assumes different values. When CCC is not used, the increase of input signal disturbance; namely the decrease of K_{rs}, increases the maximum *SE*. The rate of increase of maximum *SE* is higher at the values of K_{rs2} less than 0.6. Applying the proposed CCC with FLC is seen to reduce the maximum *SE.* The synchronization error amounting to 1.3 mm at K_{rs2} = 0.4 in the absence of CCC is seen to be reduced to the practically acceptable value of 0.7 mm when CCC is used. Figure 13 shows the effect of applying the proposed CCC when the system is subjected to a combined disturbance; namely when K_{rs2} = 0.75 and K_{L2} = 120 x 10^{-12} m^5/Ns. The figure shows that the *SE* which varies between -0.2 mm and 1.2 mm in the absence of CCC is reduced to be between -0.07 mm and 0.34 mm when the proposed CCC is applied.

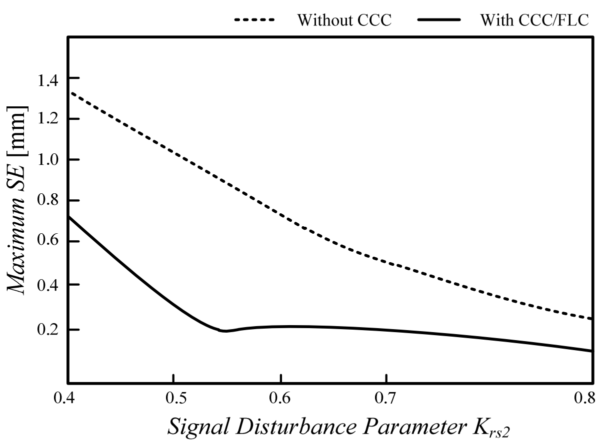

Fig. 12: *Variation of maximum synchronization errors with K_{rs2}*

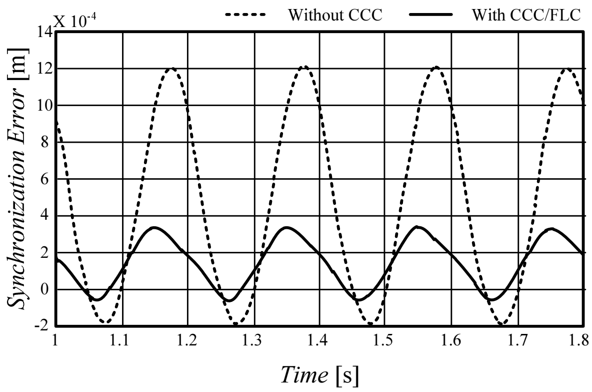

Fig. 13: *Synchronization error at K_{rs2} = 0.75 and K_{L2} = 120 x 10^{-12} m^5/N*

5 Practical Implementation on a Continuous Casting Machine

The effect of the proposed CCC with FLC on motion synchronization has been investigated practically in a steel plant. The CCC has been added to the HMO control system of a continuous casting machine of a thin slab casting line at Al Ezz Al Dekheila Alexandria Steel Company through an interface electronic control card (Dspace, 2007) as shown in Fig. 14. The layout of the HMO electronic control system supplied with the machine is shown in the figure in solid lines, while the dashed lines represent the additional parts of the CCC with FLC.

During the experiments the two cylinders were brought initially to the mid-stroke position, then oscillated with the reference input signal frequently used in the plant; namely $x_r = 3.5 \sin 10\pi t$ mm. The plant proportional gains during oscillations were assigned the values mostly used in the plant; namely K_{pu} = 35 %/mm and K_{pd} = 24 %/mm. The measurements were taken when one cylinder internal leakage was 3.5 l/min while that of the other was 12 l/min; both being measured at a system supply pressure of 25 MPa. Synchronization errors were first recorded when CCC is not applied, then recorded when it is applied with the parameters of the FLC chosen as: K_{eg} = 570, K_{dg} = 10, and K_{fg} = 0.7. The synchronization errors in both cases are depicted in Fig. 15. The figure shows that using CCC reduces the maximum *SE* from nearly 0.3 mm to 0.2 mm.

Other measurements were carried out in the plant with the assumption of internal leakage increase in the cylinder of higher leakage. This was realized practically by adding a throttle valve and a flow meter between lines A and B of that cylinder.

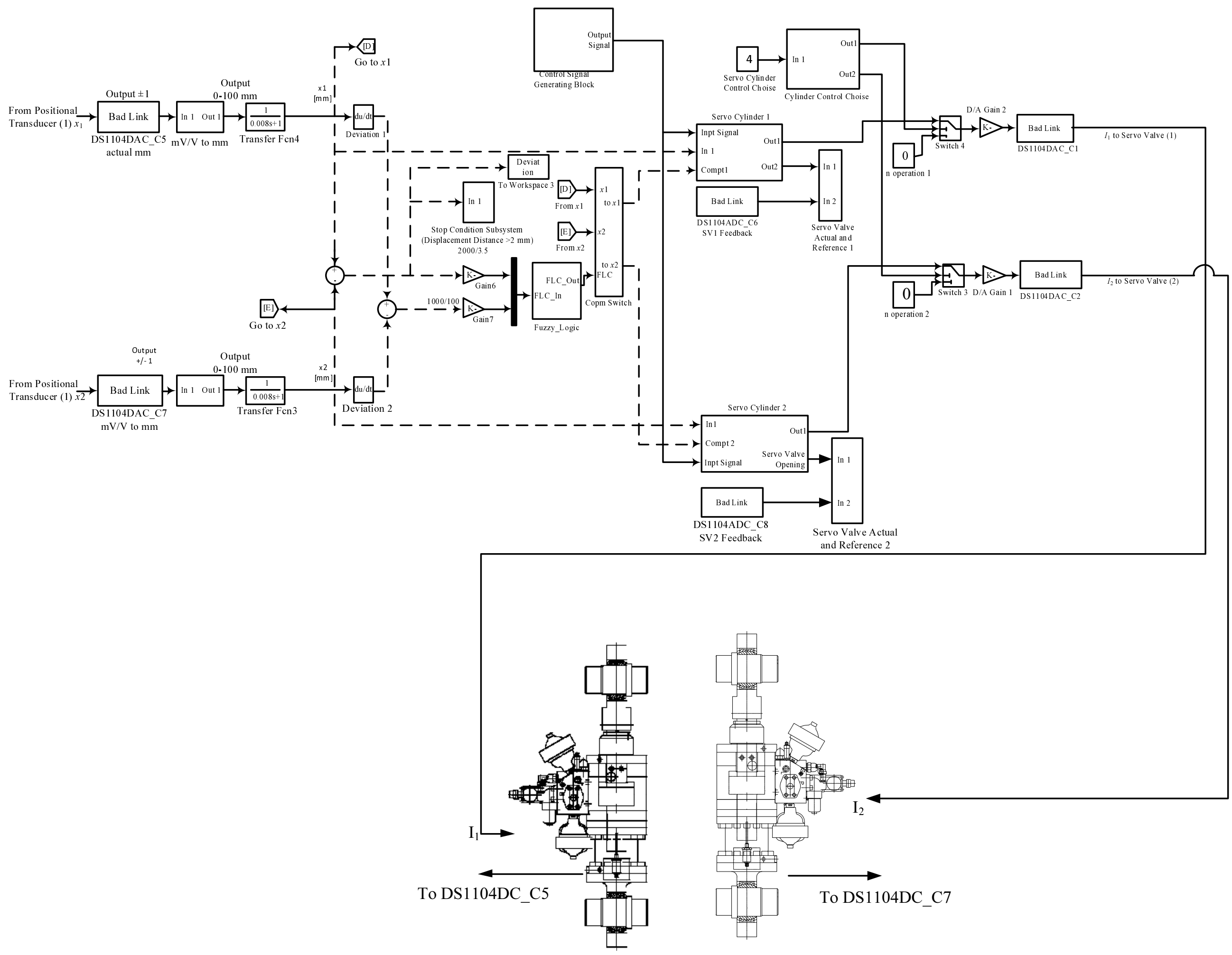

Fig. 14: *HMO electronic control system with the CCC added (MATLAB-Simulink model)*

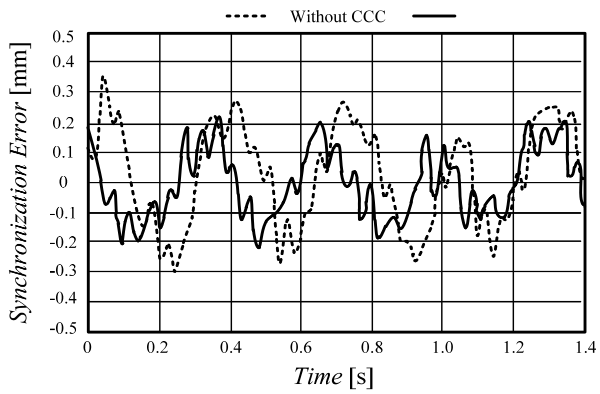

Fig. 15: *Synchronization error when Q_{L1}= 3.5 l/min and Q_{L2} =12 l/min*

The throttle valve was adjusted to allow a 10 l/min maximum flow rate through it during cylinder oscillation, and synchronization errors were recorded during mould oscillation under this condition. The obtained results are shown in Fig. 16, which reveals that the maximum *SE* of value about 0.8 mm in the absence of CCC is reduced to about 0.4 mm in its presence. The recorded higher positive effect of the proposed CCC with FLC when the cylinder internal leakage gets higher confirms the theoretical findings presented in Fig. 10. To investigate the performance of the system when combined disturbances take place, the throttle valve had been closed and the input current to the servo valve driving the cylinder experiencing higher leakage is multiplied by 0.8.

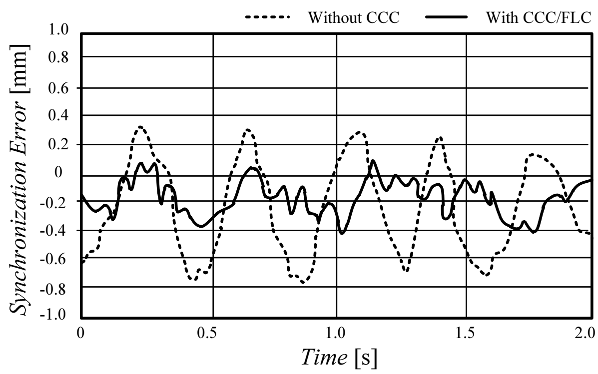

Fig. 16: *Synchronization errors when Q_{L1}= 3.5 l/min and Q_{L2}= 22 l/min*

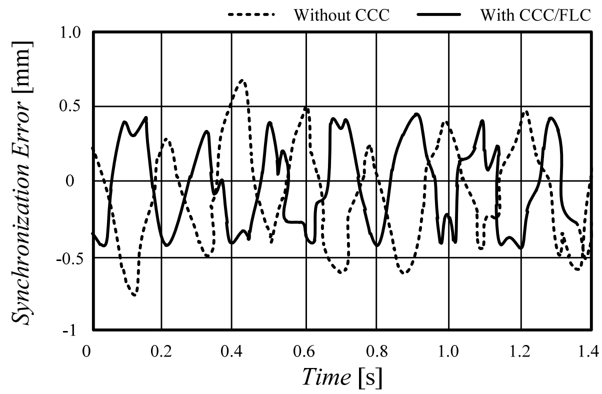

Fig. 17: *Synchronization errors when Q_{L1}= 3.5 l/min, Q_{L2}= 12 l/min and K_{rs2}= 0.8*

Mould oscillations were again initiated and recorded in the absence and presence of the proposed CCC. The recorded synchronization errors in both cases are presented in Fig. 17.

The maximum *SE* in the absence of CCC amounting to about 0.74 mm is seen to be reduced to about 0.3 mm in its presence. The results of the practical measurements shown in Fig. 15, 16 and 17 confirm the theoretical findings regarding the merits of the CCC with the proposed FLC.

6 Conclusion

In this paper a nonlinear mathematical model representing the dynamics of a HMO system frequently used in continuous casting machines is presented. The studied system incorporates two independently driven hydraulic servo cylinders. Model accuracy was verified by comparing results of measurements carried out in a continuous casting machine with computer simulation results based on the model. The detrimental effect of a cylinder internal leakage and a servo valve disturbed input signal on motion synchronization of the two cylinders has been assessed using the system model. A cross coupling control technique with a fuzzy logic controller is proposed to alleviate the problem of non-synchronization. Theoretical studies through computer simulations showed that the proposed cross coupling controller improves motion synchronization and reduces the synchronization errors in the presence of disturbances. Practical implementation of the proposed cross coupling controller in a steel plant verified the theoretical findings. Using the proposed cross coupling controller would consequently improve motion synchronization of the cylinders of HMO systems in the presence of disturbances, and helps avoid unplanned production interruption.

Nomenclature

A	Servo valve port opening ratio	
a_m	Servo valve control port max. opening area	[m^2]
$A_{C1/2}$	Annular cross sectional area of servo cylinder 1or 2 respectively	[m^2]
D_v	Damping ratio of servo valve	
d	Viscous damping coefficient	[Ns/m]
de	Synchronization error rate of change	[m/s]
e	Instantaneous synchronization error	[mm]
E	Oil bulk modulus	[N/m^2]
$F_{1/2}$	Reaction force acting on the piston of cylinder 1 or 2 respectively	[N]
g	Gravitational acceleration	[m/s^2]
$h_{1/2}$	Stroke of servo cylinder 1 or 2 respectively	[m]
I	Electric current	[A]
J	Mould mass moment of inertia about its center of gravity	[kg.m^2]
K_L	Internal leakage coefficient	[m^5/N]
K_{pd}	Gain of proportional controller during mould downward motion	[%/mm]
K_{pu}	Gain of proportional controller during mould upward motion	[%/mm]
K_{rs}	Servo valve response delay parameter	
K_{fg}	Fuzzy logic gain	
K_{eg}	Deviation gain	
K_{dg}	Rate of change of deviation gain	
L	Distance between driving cylinders	[m]
M	Mould mass	[kg]
$m_{1/2}$	Total moving mass of piston of cylinder 1 or 2 respectively	[kg]
$P_{A/B}$	Pressure of servo cylinder chamber A or B respectively	[MPa]
P_0	HMO system supply pressure	[MPa]
P_L	Load pressure	[MPa]
R_{mi}	Hydraulic resistance of servo valve ith control edge	[kg/m^7]
$V_{A/B}$	Volume of cylinder chamber A or B respectively	[m^3]
V_v	Valve gain	[m/A]
$Q_{A/B}$	Oil flow rate in lines A or B respectively	[m^3/s]
Q_L	Internal leakage	[m^3/s]
$Q_{LeA1/2}$	External leakage from chamber A of cylinder 1or 2 respectively	[m^3/s]
$Q_{LeB1/2}$	External leakage from chamber B of cylinder 1 or 2 respectively	[m^3/s]
v_M	Mould speed	[m/s]
$x_{1/2}$	Piston displacement of cylinder 1 or 2 respectively	[m]
x_r	Reference input displacement	[m]
x_M	Displacement of the center of gravity of the mould	[m]
$y_{1,2}$	Main Spool displacement of servo valve 1 or 2 respectively	[m]
y_{max}	Maximum displacement servo valve main spool	[m]

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