MOTION SYNCHRONIZATION ENHANCEMENT OF MOLD OSCILLATION HYDRAULIC CYLINDERS BY MEAN POSITIONS AND PHASE LOCK LOOPS

By

Eng. George Ibrahim Hany Zaki El Mankabady

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE
in
Mechanical Design and Production Engineering

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2017

MOTION SYNCHRONIZATION ENHANCEMENT OF MOLD OSCILLATION HYDRAULIC CYLINDERS BY MEAN POSITIONS AND PHASE LOCK LOOPS

By
Eng. George Ibrahim Hany Zaki El Mankabady

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE
in
Mechanical Design and Production Engineering

Under the Supervision of

Prof. Dr. Saad Abdelfattah Kassem

Department of mechanical design and production
Faculty of Engineering, Cairo University

Prof. Dr. Mahmoud Galal Rabie

Vice Dean of the Modern Academy for
Engineering and Technology in Maadi

Dr. Mohamed Ahmed El Gamil

Department of mechanical design and production
Faculty of Engineering, Cairo University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2017

MOTION SYNCHRONIZATION ENHANCEMENT OF MOLD OSCILLATION HYDRAULIC CYLINDERS BY MEAN POSITIONS AND PHASE LOCK LOOPS

By
Eng. George Ibrahim Hany Zaki El Mankabady

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE in
Mechanical Design and Production Engineering

Approved by the
Examining Committee

____
Prof. Dr. Saad Abdelfattah Kassem, Thesis Main Advisor

____
Prof. Dr. Mahmoud Galal Rabie, Member

____
Prof. Dr. Mohamed El-Sayed El-Araby, Internal Examiner

____
Prof. Dr. Ibrahim Saleh Mostafa, External Examiner
Chairman of the scientific council of the mechanical engineering branch – Military Technical Collage

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2017

Engineer's Name: George Ibrahim Hany Zaki
Date of Birth: 01/10/1977
Nationality: Egyptian
E-mail: georgeibrahimhany@gmail.com
Phone: 01270169100
Address: 33 Saleh Haky street, Heliopolis
Registration Date: 01/10/2011
Awarding Date: / /2017
Degree: Master of Science
Department: Department of mechanical design and production

Supervisors:

Prof. Dr. Saad Abdelfattah Kassem
Prof. Dr. Mahmoud Galal El Din Rabie
Dr. Mohamed Ahmed El Gamil

Examiners:

Porf. Dr. Saad Abdelfattah Kassem (Thesis main advisor)
Porf. Dr. Mahmoud Galal El Din Rabie (Member)
Vice Dean of the Modern Academy for Engineering and Technology
Prof. Dr. Mohamed Elsayed Elaraby (Internal examiner)
Prof. Dr. Ibrahim Saleh Mostafa(External examiner)
Chairman of the scientific council of the mechanical engineering branch – Military Technical Collage

Title of Thesis:

Motion synchronization enhancement of mold oscillation hydraulic cylinders by mean positions and phase lock loops

Key Words:

Synchronization, electro-hydraulic servo, oscillations, mean positions, phase shift.

Summary:

A new control technique is proposed to improve the motion synchronization of the two hydraulic servo cylinders used to oscillate molds of continuous casting machines. Theoretical and experimental simulations are carried out for a system similar to that frequently used in industry in the absence and presence of the proposed control technique. The proposed controller is a self-tuning controller for master and slave cylinders combined that corrects the mean positions of the two operating cylinders and reducing the phase shift between them to practically acceptable values. The proposed controller showed good performance as it reduces the synchronization errors to practically acceptable values, especially at the higher values of disturbances. Both the theoretical and experimental results confirmed the advantages of using the proposed controller for motion synchronization.

Acknowledgments

I would like to take this opportunity to first and foremost thank God for being my strength and guide during this research work. Without Him, I would not have had the wisdom or the physical ability to do so. He blessed me with dedicated supervisors, they supported me until the conclusion of this work.

I would like to express my deep gratitude to Prof. Dr. Saad Kassem for proposing the subject of this thesis and for devoting much time to reading my work over and over again. His special interest and knowledge enabled to give me the right guidance. He spent much time instructing me, how to search literature, how to collect data, and how to present it, and to write a thesis or a paper. His office door was always open whenever I ran into a trouble spot or had a question about my research or writing.

I would also like also to express my deep appreciation to Prof. Dr. Galal Rabie for taking the time to help me during the writing of this thesis. From him I have learned the importance of producing a good piece of work and putting into it the very best I have. His contribution in suggestions and encouragement, helped me to coordinate my thesis.

I would like to express my deep gratitude to Dr. Mohamed El-Gamil for the useful comments, remarks and engagement through the learning process of this master thesis. He cared so much about my work, and responded to my questions and queries so promptly.

Furthermore I would also like to acknowledge with much appreciation the crucial role of Dr. Taher Salah El-Din who ask for the permission to use all required equipment and the test rig located in Ezz El-Dekhela Steel Company to complete my experimental work. The experimental work would not have been possible without the help of Eng. Mohammed Zagloul and Eng. Mahmoud Omar who helped me during the operation of the test rig.

Finally, I must express my very profound gratitude to my parents for providing me with unfailing support and continuous encouragement throughout my years of study. I would also like to thank my supportive wife, Christine. Her love and helpful spirit have motivated me to achievements beyond my own expectations. Along with her, I want to acknowledge my son Michael and my daughter Martina. Both, are great sources of love and relief from scholarly endeavor.

Dedication

To my parents, my sisters, my wife Christine, my son Michael and my daughter Martina without whom this work wouldn’t be possible.

.

Table of Contents

ACKNOWLEDGMENTS .... **VI**

DEDICATION ....**II**

TABLE OF CONTENTS .... **VI**

LIST OF FIGURES...**XII**

NOMENCLATURE .... **IXII**

ABSTRACT ....**XII**

CHAPTER 1 : INTRODUCTION **1**

1.1. LITERATURE SURVEY 2
1.2. SCOPE OF WORK SECTION 5

CHAPTER 2 : SYSTEM MATHEMATICAL MODEL AND THE PROPOSED CONTROLLER **6**

2.1. SYSTEM DISCRIPTION 6
2.2. TEST RIG MATHEMATICAL MODEL…...…………...……...…..........................8
2.3. PROPOSED CONTROL TECHNIQUE CONCEPT AND DESIGN…....………10
2.3.1 MASTER CYLINDER CONTROLLER DESIGN.....................................12
2.3.2 SLAVE CYLINDER CONTROLLER DESIGN 14

CHAPTER 3 : THEORETICAL INVESTIGATION OF THE CONTROLLER EFFECT ON SYNCHRONIZATION ERRORS………………........20

3.1. EFFECT OF A CYLINDER EXCESSIVE INTERNAL LEAKAGE..................20
3.2. EFFECT OF SERVO VALVE DISTURBED INPUT SIGNAL..........................24
3.3. EFFECT OF SERVO VALVE DELAYED RESPONSE 27
3.4. EFFECT OF COMBINED DISTURBANCES..30
3.5. PERFORMANCE OF CONTROLLERS WHEN DISTURBANCES AFFECT THE MASTER CYLINDER..32
3.6. EFFECT OF CONTROLLERS ON SYNCHRONIZATION ERRORS AT DIFFERENT REFERENCE INPUT SIGNALS..34

CHAPTER 4 : EXPERIMENTAL RESULTS **37**

4.1. EXPERIMENTAL SIMULATION PROCEDURE..38
4.2. EFFECT OF THE MPPLL ON MOTION SYNCHRONIZATION.....................40
4.2.1. SLAVE CYLINDER EXCESSIVE INTERNAL LEAKAGE 40
4.2.2 CASE OF SERVO VALVE DISTURBED INPUT SIGNAL 46
4.2.3 CASE OF SERVO VALVE DELAY IN RESPONSE...…...…………………48
4.2.4. CASE OF COMBINED DISTURBANCES 50
4.3. COMPARISON BETWEEN THEORETICAL AND EXPERIMENTAL RESULTS...52

CHAPTER 5 : CONCLUSION AND FUTURE WORK..**54**

REFERENCES **55**

APPENDIX A: CROSS COUPLING CONTROL USING FLC **57**

List of Figures

Figure 1.1: Layout of a continuous casting machine ……………………………………...……..2
Figure 1.2 :Schematic diagram of the control system with the arithmetic mean of ……4
the synchronized cylinders displacements as the command value
[Dariusz Grzybek and Piotr Micek, 2010]
Figure1.3: Hydraulic oscillation control system [Kassem et al, 2012]………………....5
Figure 2.1: Main parts of the test rig.………………………………………………………7
Figure 2.2: Control loops of one couple of operating and load cylinders...……………8
Figure 2.3: Cylinders oscillations in the presence of disturbances……....……………10
Figure 2.4: Cylinders oscillations in the presence of disturbances after reducing …….11
S_1 and S_2
Figure 2.5: The local and the proposed controllers ……………..……....……………12
Figure 2.6 :Recording of the maximum positive amplitude.………..…...………….. 13
Figure 2.7 :Recording of the maximum negative amplitude …....…………………...... 13
Figure 2.8 :Calculation of the mean position S_1……....………..……...…………..... 13
Figure 2.9 : The Simulink blocks of MCC...……...…....…………..…....…………... 14
Figure 2.10 :Calculation of time at which each cylinder crosses zero position…......... 14
Figure 2.11 :Calculation of the time lag (Δt)……………………….........………..…. 15
Figure 2.12 : The Simulink blocks of SCC………...…...………...…...……………..... 15
Figure 2.13 : Connection of the proposed controller with the local controller ……..... 16
Figure 2.14 : Operating and loading cylinders …..…...………...…...……………..... 17
Figure 2.15 : Signal block diagram of operating cylinders..……...…...……………..... 18
Figure 2.16 : Flow chart describing the proposed controllers..................................... 19
Figure 3.1 : Displacements of servo cylinders and the synchronization error e at 21
K_{L2}=2x10^{-10}m^5/Ns when using the local controllers only
Figure 3.2 : Displacements of servo cylinders and the synchronization error e at 21
K_{L2}=2x10^{-10}m^5/Ns when using the (MPPLL)
Figure 3.3 : Displacements of servo cylinders and the synchronization error e at 21
K_{L2}=2x10^{-10}m^5/Ns when using the (FLC)
Figure 3.4 : Synchronization errors at K_{L2}= 2x10^{-10}m^5/Ns when using ……..……22
different controllers
Figure 3.5 : Displacements of servo cylinders and the synchronization error e at 22
K_{L2}=4x10^{-10}m^5/Ns when using the local controllers only
Figure 3.6 : Displacements of servo cylinders and the synchronization error e at 23
K_{L2}=4x10^{-10}m^5/Ns when using the (MPPLL)
Figure 3.7 : Displacements of servo cylinders and the synchronization error e at 23
K_{L2}=4x10^{-10}m^5/Ns when using the (FLC)
Figure 3.8 : Synchronization errors at $K_{L2} = 4x10^{-10}m^5/Ns$ when using ……..……23
different controllers
Figure 3.9 : Variation of maximum synchronization errors with various values ……..24
of internal leakage coefficient when different controllers are used
Figure 3.10 : Displacements of servo cylinders and the synchronization error e at 25
K_{r2} = 0.5 when using the local controllers only
Figure 3.11 : Displacements of servo cylinders and the synchronization error e at.......25
K_{r2} = 0.5 when using the (MPPLL)

Figure 3.12 : Displacements of servo cylinders and the synchronization error e at K_{r2} = 0.5 when using the (FLC) 25
Figure 3.13 : Displacements of servo cylinders and the synchronization error e at K_{r2} = 0.35 when using the local controllers only 26
Figure 3.14 : Displacements of servo cylinders and the synchronization error e at K_{r2} = 0.35 when using the (MPPLL) 26
Figure 3.15 : Displacements of servo cylinders and the synchronization error e at K_{r2} = 0.35 when using the (FLC) 26
Figure 3.16: Variation of maximum synchronization errors with the disturbed input signal factor K_{d2} ...27
Figure 3.17 : Displacements of servo cylinders and the synchronization error e at K_{d2} = 10 ms when using the local controllers only 28
Figure 3.18 : Displacements of servo cylinders and the synchronization error e at K_{d2} = 10 ms when using the (MPPLL) 28
Figure 3.19 : Displacements of servo cylinders and the synchronization error e at K_{d2} = 10 ms when using the (FLC) 28
Figure 3.20 : Displacements of servo cylinders and the synchronization error e at K_{d2} = 10 ms when using the local controllers only 29
Figure 3.21 : Displacements of servo cylinders and the synchronization error e at K_{d2} = 10 ms when using the (MPPLL) 29
Figure 3.22 : Displacements of servo cylinders and the synchronization error e at K_{d2} = 10 ms when using the (FLC) 29
Figure 3.23: Variation of maximum synchronization errors with with various values of delay factor K_{d2} when using different controllers ..30
Figure 3.24 : Displacements of servo cylinders and the synchronization error e under the effect of combined disturbances when using the local controllers only 31
Figure 3.25 : Displacements of servo cylinders and the synchronization error e under the effect of combined disturbances when using the (MPPLL) 31
Figure 3.26 : Displacements of servo cylinders and the synchronization error e under the effect of combined disturbances when using the FLC 31
Figure 3.27 : Instantaneous synchronization errors at K_{d2} = 5 ms, K_{r2} = 0.7 and K_{L2} =1.3e-10 m^5/Ns when using different controllers 32
Figure 3.28 : Instantaneous synchronization errors at $K_{L1} = 3.5x10^{-10} m^5/Ns$ when using different controllers ……...33
Figure 3.29 : Instantaneous synchronization errors at a disturbed input signal $K_{r1} = 0.35$ when using different controllers ……....33
Figure 3.30 : Instantaneous synchronization errors at a delay in response $K_{d1} = 12$ ms when using different controllers ……...........33
Figure 3.31 : Instantaneous synchronization errors at combined disturbances when using different controllers 34
Figure 3.32 : Variation of maximum synchronization errors under the effect of a combined disturbances action at maximum amplitude equals 3.5 mm using different controllers …...35
Figure 3.33 : Variation of maximum synchronization errors under the effect of a combined disturbances action at maximum amplitude equals 5 mm using different controllers …...36

Figure 3.34 : Variation of maximum synchronization errors under the effect of a …...36
combined disturbances action at maximum amplitude equals 6 mm
using different controllers
Figure 4.1: The test rig………………………………………………………........…....37
Figure 4.2 :Main components of each operating control loop position control.…….... .38
Figure 4.3: Interface between operating cylinders and position closed loop software ..39
Figure 4.4 :Simulation of internal leakage during operation......…...…....………….…...40
Figure 4.5 : Displacements of servo cylinders and the synchronization error e ………41
at Q_{L2} =18 L/min when using the local controllers only
Figure 4.6 : Displacements of servo cylinders and the synchronization error e ………41
at Q_{L2} =18 L/min when using the (MPPLL)
Figure 4.7 : Displacements of servo cylinders and the synchronization error e ………41
at Q_{L2} =18 L/min when using the (FLC)
Figure 4.8 :Synchronization error at Q_{L2} = 18 L/min for cylinder 2 ......………..….... 42
Figure 4.9 : Displacements of servo cylinders and the synchronization error e ………42
at Q_{L2} =25 L/min when using the local controllers only
Figure 4.10 : Displacements of servo cylinders and the synchronization error e ….….43
at Q_{L2} =25 L/min when using the (MPPLL)
Figure 4.11 : Displacements of servo cylinders and the synchronization error e ……..43
at Q_{L2} =25 L/min when using the (FLC)
Figure 4.12 :Synchronization error at Q_{L2} = 25 L/min for cylinder 2.........………….. .44
Figure 4.13 : Displacements of servo cylinders and the synchronization error e ……..44
at Q_{L2} =29 L/min when using the local controllers only
Figure 4.14 : Displacements of servo cylinders and the synchronization error e ……...45
at Q_{L2} =29 L/min when using the (MPPLL)
Figure 4.15 : Displacements of servo cylinders and the synchronization error e ……...45
at Q_{L2} =29 L/min when using the (FLC)
Figure 4.16 :Synchronization error at Q_{L2} = 29 L/min for cylinder 2.......……………….45
Figure 4.17 :Maximum synchronization error at Q_{L2} = 18,25 and 29 L/min...........…....46
Figure 4.18 : Displacements of servo cylinders and the synchronization error e ……...47
at K_{r2} = 0.35 when using the local controllers only
Figure 4.19 : Displacements of servo cylinders and the synchronization error e ……....47
at K_{r2} = 0.35 when using the (MPPLL)
Figure 4.20 : Displacements of servo cylinders and the synchronization error e ……....47
at K_{r2} = 0.35 when using the (FLC)
Figure 4.21 :Instantaneous deviation between cylinders at K_{r2} = 0.35………….…......48
Figure 4.22 : Displacements of servo cylinders and the synchronization error e ……....49
at K_{d2} = 8 ms when using the local controllers only
Figure 4.23 : Displacements of servo cylinders and the synchronization error e ……....49
at K_{d2} = 8 ms when using the (MPPLL)
Figure 4.24 : Displacements of servo cylinders and the synchronization error e ……....49
at K_{d2} = 8 ms when using the (FLC)
Figure 4.25 :Instantaneous deviation between cylinders at K_{d2} = 8 ms...…………...…....50
Figure 4.26 : Displacements of servo cylinders and the synchronization error e …….....51
at K_{r2} = 0.8 and Q_{L2} = 25 L/min when using the local controllers only

Figure 4.27 : Displacements of servo cylinders and the synchronization error e ……......51
at K_{r2} = 0.8 and Q_{L2} = 25 L/min when using the (MPPLL)
Figure 4.28 : Displacements of servo cylinders and the synchronization error e ……......51
at K_{r2} = 0.8 and Q_{L2} = 25 L/min when using the (FLC)
Figure 4.29 :Synchronization error between cylinders at Q_{L2} = 25 L/min, K_{r2} = 0.8……52
Figure 4.30 :Comparison between experimental and theoretical results at K_{r2} = 0.35…..52
Figure 4.31 :Comparison between experimental and theoretical results at K_{d2} = 8 ms….53

Nomenclature

a	Reference displacement amplitude of cylinders	[m]
$A_{1/2}$	Restriction areas of cylinder 1	[m^2]
$A_{3/4}$	Restriction areas of cylinder 3	[m^2]
$A_{co1/2}$	Annular cross sectional area of operating servo cylinders 1 and 2	[m^2]
$A_{cl1/2}$	Annular cross sectional area of loading servo cylinders 1 and 2	[m^2]
C_d	Discharge coefficient	[-]
e	Instantaneous position synchronization error	[m]
$\|e_{max}\|$	Maximum absolute value of synchronization error	[m]
E	Oil bulk modulus	[N/m^2]
$f_{1/2}$	Load cylinder force	[N]
F_r	Reference force	[N]
$h_{1/2}$	Stroke of servo cylinders 1 and 2	[m]
i	Electric current	[A]
K_L	Internal leakage coefficient	[m^5/Ns]
K_r	Servo valve delay time	[s]
K_d	Servo valve disturbed input signal	[-]
$K_{Po/l}$	Proportional controller gain for operating and loading cylinders	[-]
k_1	Gain to be adjusted according to the system parameters	[m/A]
m	Mass of cylinder moving parts	[kg]
$p_{A1/3}$	Pressure of servo cylinder chamber A in cylinders 1 and 3	[MPa]
$p_{B1/3}$	Pressure of servo cylinder chamber B in cylinders 1 and 3	[MPa]
P_{sl}	Supply pressure of the loading cylinder servo valve	[MPa]
P_{so}	Supply pressure of the operating cylinder servo valve	[MPa]
V_A	Volume of cylinder chamber A	[m^3]
V_B	Volume of cylinder chamber B	[m^3]
V_v	Valve gain	[m/A]
$q_{A/B}$	Oil flow rate in lines A or B	[m^3/s]
$Q_{L1/2}$	Internal leakage	[m^3/s]
$q_{1/2}$	External leakage at chamber A or B of cylinder 1	[m^3/s]
$q_{3/4}$	External leakage at chamber A or B of cylinder 2	[m^3/s]
S_1/S_2	The actual mean position of the master and slave cylinders	[m]
t	Time	[s]
t_1	Time at which master cylinder crosses the zero position	[s]
t_2	Time at which slave cylinder crosses the zero position	[s]
ω	The frequency of the reference input signal	[rad/s]
ω_o	The frequency of the servo valve	[rad/s]
Xr	Reference input displacement	[m]
x_1	The actual position of master cylinder	[m]
x_2	The actual position of slave cylinder	[m]
x_3	The correction of position of master cylinder	[m]

x_4	The correction of position of slave cylinder	[m]
$y_{1/3}$	Spool displacements servo valves 1 and 3	[m]

Subscripts

A	Cylinder chamber A
B	Cylinder chamber B

Symbols

φ	Phase shift	[rad]
ζ	Damping ratio of servo valve	[-]
ρ	Oil density	[kg/m^3]
Δt	Time difference between master and slave cylinders at which both cylinders crosses zero position	[s]

Abbreviations

ADC	Analog Digital Converter
CCC	Cross Coupling Control
DAC	Digital Analog Converter
EH	Electro Hydraulic
FLC	Fuzzy Logic Control
MCC	Master cylinder controller
MPPLL	Mean position phase locked loop
PLC	Programmable Logic Control
PID	Proportional- Integral- Derivative
Ref	Reference
SCC	Slave cylinder controller

Abstract

A new control technique is proposed in this thesis to improve the motion synchronization of the two hydraulic servo cylinders frequently used to oscillate heavy molds of continuous casting machines. Theoretical and experimental simulations are carried out for a system similar to the system frequently used in industry for mold oscillation, in the absence and presence of the proposed control technique, when disturbances exist. The disturbances dealt with are those currently met in practice; namely an increase of cylinder internal leakage, a servo valve disturbed input signal, delay in response or a combination of these disturbances. During simulations the load acting on each cylinder of the system, called the operating cylinder, is simulated by a load applied by another servo controlled loading cylinder. A previously developed and experimentally verified mathematical model is presented for the system, when each operating cylinder is driven independently in an accurate closed loop control system similar to that used in industry. The proposed controller is a self-tuning controller for a master cylinder combined with reducing the phase shift between the two operating cylinders and correcting their mean value of oscillations for reducing the synchronization errors to be less than the practically acceptable values of 1 mm. The controller yielded good performance, especially at the higher values of disturbances. The obtained results are compared with the results obtained when a previously proposed cross coupling control technique with the fuzzy logic controller (FLC) is used. The comparison confirmed the advantages of using the proposed controller on motion synchronization.

Chapter 1 : Introduction

Synchronization of motion of two or more hydraulic actuators is required in many machines and processes. Lagging of one actuator motion with respect to the others would have a detrimental effect on production quality and would cause production interruption. This problem is faced in continuous casting machines used in steel plants. The process of continuous casting of molten steel is carried out by pouring the molten steel into a tundish, which is located above a mold and feeds it with the molten metal, as shown in figure 1.1. The tundish supplies an oscillating mold with molten steel to compensate for the steel that continuously moves out of the mold during the manufacturing process, so as to keep the mold filled to the correct level. The supply of molten steel to the mold must be carried out accurately, and the tundish control system supports doing this task. The steel casting partially solidifies from the mold wall then solidification progresses internally.

The mold in the continuous casting process is water cooled, this helps speed up the solidification of the metal casting to form a protective solidified skin of a sufficient thickness on the outside. The long steel strand uses rollers to move the cast at a constant rate. The rollers guide the strand and assist in the smooth flow of the metal casting out of the mold and along its given path.

Molds used for continuous casting are to be oscillated using oscillating mechanisms. Mold oscillation is necessary to minimize friction and sticking of the solidifying shell, and to prevent shell tearing and liquid steel breakouts, which can cause machine disorder and machine stoppage for cleaning up and repairs. Mold oscillation is achieved either hydraulically or by using motor driven cams. Friction between the shell and the mold is reduced through the use of mold lubricants such as powdered flux. The powder feeder is designed for the automatic distribution of casting powder into the mold to ensure constant uniform mold powder distribution during the process [1].