Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 17 (2014) 835 – 840

www.elsevier.com/locate/procedia

Variety Management in Manufacturing: Proceedings of the 47th CIRP Conference on Manufacturing Systems

Control system for electro-hydraulic synchronization on RBPT

Olukorede Tijani Adenuga[a*], Khumbulani Mpofu[a]

[a*, a]*Tshwane University of Technology, Industrial Engineering Dept, Pretoria, 0001, South Africa*

* Corresponding author. Tel.: +27611123706; fax: +27-012-382-4847. *E-mail address:*olukorede.adenuga@gmail.com

Abstract

In industrial manufacturing systems, situations are often encounters in which motion with two, three or more hydraulic cylinder actuators need to be synchronized. The need for the design of a reconfigurable bending press tool (RBPT) control system prompted the research in the development of an automatic and synchronized system, suitable for press tool operations. The system had to de designed to be versatile in raising and thrusting of multi- cylinders with odd numbers. This paper describes the concept of the design of the control system that will allow the controlling of pressure, flow and synchronous cylinder movements, accompanied by position readings measured by position sensors. The system will work simultaneously; with a maximum assembled of units working together, typically in a number that fits the operation's needs. The aim of the proposed controller is to develop a position control system that incorporates features of a modular controller interfacing with position sensors and detecting the position of the hydraulic cylinder rod through commercially-of-the-shelf (COTS) components.

Keyword: Reconfigurable Bending Press Tool; Proportional Integral Derivative; Flexible Manufacturing System; Reconfigurable Manufacturing Tools; Commercial Of The Shelf

1. Introduction

The development of modern industry has encouraged the wide use of lifting platforms in various fields; the need for synchronization accuracy of the lifting platforms has been increasingly demanded. At present, the hydraulic lifting system has been applied to many large-scale lifting platforms and other press machines. High-precision hydraulic synchronization control technology has become the main way to improve lifting synchronization accuracy. Due to the fact that the hydraulic system has a nonlinear, a large time delay, a high inertia characteristic, se of traditional Proportional Integral Derivative (PID) control is difficult to achieve the satisfactory control effect. Electrohydraulic actuators are widely used in modern industrial applications, mainly because they have a high power/mass ratio, fast response, and high stiffness [1], anti-lock braking system [2], hydraulic excavator [3, 14], the investigation of the control of position or pressure of hydraulic actuators is of great interest to both academic and industrial fields. In particular, force and pressure tracking are important for some applications, such as vibration isolation and automotive active suspension, where an almost ideal force actuator is assumed in current research and application. The fundamental existence of limits on simple controllers for force or pressure tracking with hydraulic systems necessitates advanced controllers [4]. To achieve synchronization of the unevenly loaded cylinders, individual control of each cylinder is required with the added flexibility of individually controlled cylinders, [5]; *Hogan et al* looked at the issue of synchronizing unevenly loaded hydraulic cylinders, but did not elaborate on the design of a control algorithm that will explicitly improve the synchronization performance. The proposed of a model-reference adaptive control algorithm together with a cross-coupled controller was by Xiong et. al [6], while Koren [7] and Hogan [15] proved to improve synchronization performance as well as attempt to handle the parameter variation associated with the hydraulic systems. The formulation of the synchronization of multiple motion axes in a geometrical framework and proposed three different

doi:10.1016/j.procir.2014.01.135

approaches to explicitly address the motion synchronization issue was addressed Chiu [8] and Zhang [16].

The purpose of this article is to propose and investigate the design of a control system that addresses some aforementioned points. The paper maintains its argument in the preceding section where we review the literatures. Section 3 explicates on the methodology of using modeling of the control system component simulations and test bench results for proposed RBPT.

2. Literature Review

The history of a review regarding the different research areas critical for developing and integrating RBPT and intelligent machines can be related to the concept of Reconfigurable Machine Tools (RMTs) which originated in the early 1990s as a particular trend that evolved directly from the concept of Flexible Manufacturing Systems (FMS) [9]. Machine tools available in today's markets have been designed for flexibility in terms of the types of processes and the geometric complexities of the product that they can manufacture. Hydraulic press brakes is widely used in machinery manufacturing sector such as hydraulic punching, pressing and bending machines, and moulding technology because of its high power/mass ratio, fast response, high stiffness and high load capability. However, the proposed RBPT with automatic control is intended for the small scale industry that will take care of drawbacks such as complex structure, high energy consumption, plentiful heat generation, high noise, serious vibration, high precision requirements of oil filtrating and throttle losses at the control valves.

2.1 Position control system

The position control system may be subdivided into the controller module, electro-hydraulic subsystem and the position sensors. The position limit switches, are fixed on the body platform, to detect the inclination of the piston of the hydraulic cylinders and send a voltage signal to the interfacing circuit. The controller module of the position control system shown in fig 1, uses a closed loop control for the spool position of the proportional directional control valve based on the position feedback of the hydraulic cylinder piston. The varying voltages, which are applied to the solenoid of the proportional valve, change the flow of the hydraulic fluid that passes into the hydraulic cylinder. This will cause a change in the rod stroke of the hydraulic cylinder and consequently the position of the hydraulic cylinder shafts will be affected. Hence the controller detects the error between the set point and the measurement of the hydraulic shaft variable position. The synchronized cylinders have their own individual linear reporting device. This device sends an analogue / digital signal back to the controller, telling the controller exactly where the cylinder is along its stroke. The proportional hydraulic directional control valve commands the cylinders through the flow divider to move to a certain position and thereby ordered cylinders to extend or retract the cylinder.

3. Methodology

The issue of synchronizing electro- hydraulic cylinders can be addressed in three approaches. The simplest approach is to design a flow-divider circuit that will maintain the same cylinder velocity by maintaining the same flow rate to the cylinders. The performance of the synchronization is dependent upon the performance of the fluid and the consistency of the hydraulic components.

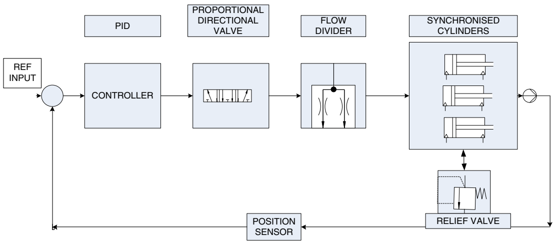

Fig 1: Position control system for the electro hydraulic cylinder synchronisation on RBPT

Another approach is to mechanically connect the hydraulic actuators through either cabling or other linkage design. The drawback to mechanical synchronization is the added system weight and complexity as well as the limitation to the operation range of the equipment. Compared with pure hydraulic and mechanical approaches, electro-hydraulic synchronization provides a flexible alternative. With the electro-hydraulic system, synchronization control strategies can be designed to handle uneven loading as well as uncertainties and external disturbances associated with the hydraulic system [10]. Synchronization at the end of the cylinder stroke is a must, or an additive accuracy error can be expected with each stroke. In applications where the mechanisms between the three cylinders turn out to be too rigid, operating inaccuracy will cause the eventual lock-up of the system, with potential damage to the mechanical structure. The use of a flow divider with only cartridges for three parallel hydraulic cylinders being driven only in one direction with unequal speeds can be accomplished with cylinders of equal displacement using the 33:67 ratios. Cylinders with unequal displacement ratios that match the 33:67 flow divider ratios can be operated at the same speed, within the accuracy limits of the flow divider and the cylinders' volumetric efficiency.

In this paper, we will analyse the hydraulic control system for synchronization of three hydraulic split rams cylinders that are coupled through a linkage to an iterated load of between 0 to 6 tons. The total load on the beam will comprise of the uniform load from the three hydraulic cylinders and self-loading from the self-weight of the beam. Figure 2 shows a schematic of the upper beam, C1-C3 stands for hydraulic cylinder piston centres and can be reconfigured to any odd cylinder number such as 5, 7, etc. To get three equal outputs with the use of spool-type flow dividers, one with unequal outputs, say 33.3% and 66.7%. Send flow from the 33.3% side to power the first actuator. Send flow from the 66.7% side to an equal-flow divider. Flow from the equal flow divider outlets is now 33.3% of total pump flow, so all three outputs are the same. Noticed that these circuits cannot handle reverse flow, reverse flow through a spool-type flow divider will lock up one actuator when return pressure differs at the outlet ports. It is required that relief valves and equalisation pressure lines are incorporated into the hydraulic circuit to overcome these challenges while a Commercial Of The Shelf (COTS) PID controller is also considered to add a jerk feed-forward/backward to the control loop of the RBPT design, If the model for the actuator is known exactly, and no disturbances occur, then, theoretically, one could control a directional hydraulic actuator perfectly without using closed-loop control. Jerk is the derivative (rate of change) of acceleration. Feed forwards are estimates of what the control outputs should be to the valve to achieve a target velocity, position and jerk.

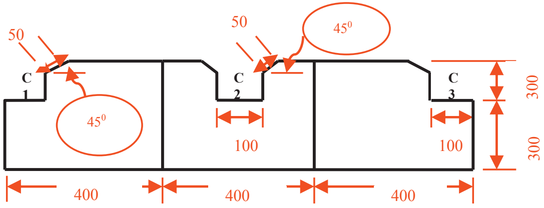

Fig. 2: RBPT upper beam configuration

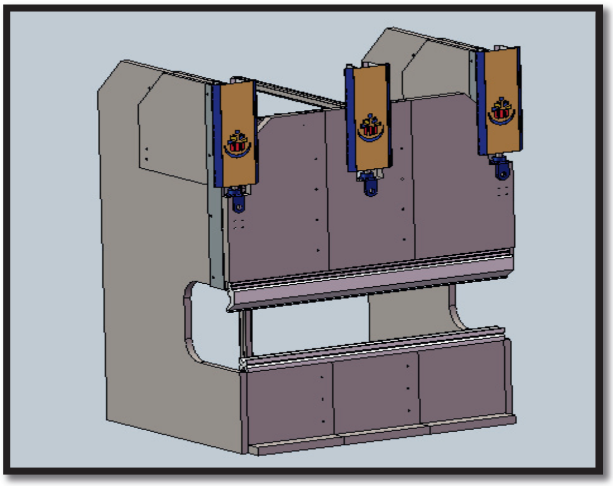

Fig. 3: Pictorial view of the proposed RPBT

The valve should be opened up proportionately to the target position, and a position feed forward will function in this respect. So there may not be need to wait for the PID to respond to an error. Closed-loop hydraulic control adds feedback to the hydraulic circuit through the addition of position and pressure sensors to the system, providing real-time data on system state like position, its derivatives and forces. This enables rapid, precise, repeatable, and (most importantly) automated position and force control of hydraulic actuators. A number of simple applications can be configured using open-loop control, but quality requirements and high-throughput demands make closed-loop motion control and electro-hydraulic controllers the preferred approach.

The three cylinders are powered by a 40 litre hydraulic power unit of 3KW, 8MPA pressure, and 6.85 litres/min flow rate for each cylinder. It is controlled by one proportional directional control valve feeding 3-way adjustable flow control valves by splitting the flow into 33:67 ratios and subsequently supplying the one cylinder with 33 per cent of flow, while 67 per cent is split into two remaining cylinders at 33 per cent flow. Pressure regulation is controlled by three pressure relief valves with an appropriate check valve for non-return flow and nozzles for equalisation.

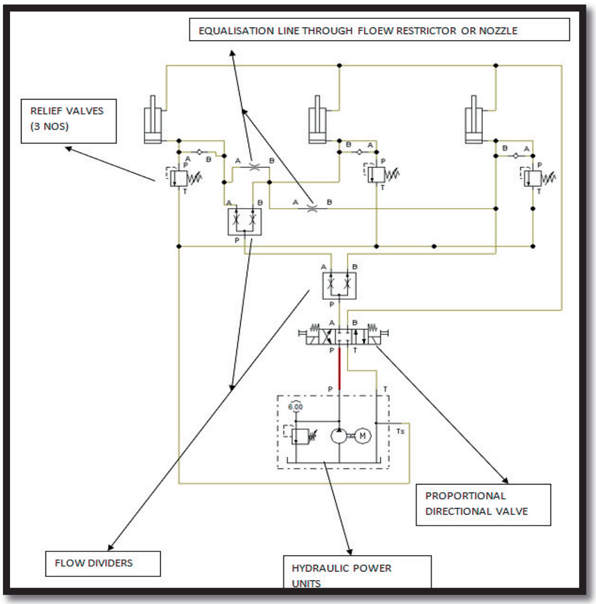

Fig. 4: Control Circuit for Electro-Hydraulic Cylinder

Pictorial view of the proposed RPBT is shown in figure 3, while figure 4 is for 3 cylinders for a nonlinear motion control circuit for an electro-hydraulic cylinder synchronization control proposed to address the synchronization.

3.1.1 Mathematical modelling for proportional directional valve

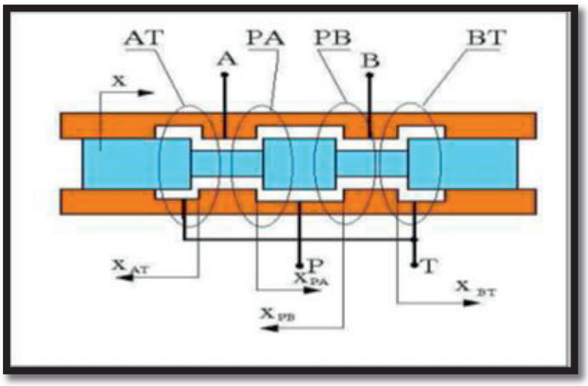

Fig.5: Sectional view of proportional directional valve

The electro-hydraulic proportional valve is in wide use because of its anti-pollution ability, reliability and low cost as comparable with the servo and normal valves, it can also achieve continuous control and fast response. The input signal varies in proportion to the flow direction, pressure of the valve and to the actuator position, speed and force [1, 13].

From Bernoulli's equation, each control orifice is under the effects of the pressure differences between two specific ports of the valve

$$Q_{VA} = C_d \,.\, A_{PA} \,.\, \sqrt{\frac{2}{\rho}}\,(P_s - P_A) - C_d \,.\, A_{AT} \,.\, \sqrt{\frac{2}{\rho}}\,(P_A - P_R) \qquad (1)$$

$$Q_{VB} = -C_d \,.\, A_{PB} \,.\, \sqrt{\frac{2}{\rho}}\,(P_s - P_A) + C_d \,.\, A_{BT} \,.\, \sqrt{\frac{2}{\rho}}\,(P_A - P_R) \qquad (2)$$

Where:

Q_{VA} = flow through the orifice in VA; Q_{VB} = flow through the orifice in VB; C_d = flow discharge coefficient; A_{PA} = orifice area in the PA path; A_{AT} = orifice area in the AT path; A_{PB} = orifice area in the PB path; A_{BT} = orifice area in the BT path; P_S - P_A = pressure differential across the orifice Ps and PA; $P_A - P_R$ = pressure differential across the orifice P_A and P_R; ρ = density of hydraulic fluid

For a solenoid driven proportional directional spool valve, the orifice areas are determined by the displacement of the spool, which is controlled by the solenoid actuating force against the centre springs if the friction and flow forces are neglected. The solenoid actuating force is regulated by the control input voltage signal, u, to the PWM driver of the solenoid valve.

$$A_{Orifice} = U g_d \qquad (3)$$

Where, gd is the gain coefficient of the solenoid drive, and u is the control input voltage signal. Furthermore, the flow discharge coefficient (C_d) is also a function of spool displacement x, which is a function of control signal u. introducing a flow gain coefficient g_F to the orifice equation, the valve orifice equation can be represented as follows.

$$Q_{VA} \text{ or } Q_B = g_F \, u \sqrt{P_{S-} \; P_R} \qquad (4)$$

$$g_F = C_d \,.\, g_d . \; \sqrt{2/\rho} \qquad (5)$$

Where $gF = is\ the\ flow\ gain\ coefficient$)

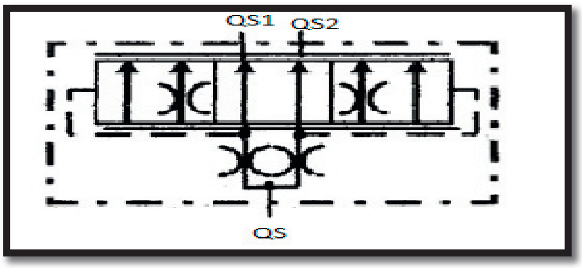

Fig 6: Sectional view of flow divider valve

From [11, 12], the flow Q_S, Q_{s1} and Q_{s2} for an adjustable flow divider valve are,

$$Q_s = C_d A_{orifice} \sqrt{\frac{2}{\rho}}\,(P_A - P_1) \qquad (6)$$

$$Q_{S1} = C_d \, A_{orifice\,1} \sqrt{\frac{2}{\rho}\,(P_1 - P_{A1})} \qquad (7)$$

$$Q_{S2} = C_d \, Aorifice_{\,2} \sqrt{\frac{2}{\rho}\,(P_1 - P_{A2})} \qquad (8)$$

Where A_1 & A_2 orifice is the valve orifice area, C_d is the orifice coefficient, r is the fluid mass density, and SP is the pump supply pressure.

3.2 Model Concepts

3.2.1 Simulation features

To construct virtual prototypes before building a real system brings other options and possibilities on an equipment conception. For hydraulic models, interactive tools and specific software can save hours of fluid flow paths imagination and recreation, as well as the need for consulting experts, which can be saved for more specific questions and practicalities. Even if a real prototype should be built, prototype software previously allows streamlining processes and to identify correct and incorrect options. These tests can however go from small essays of functionality to much more precise levels. Optimization and details related with controls, losses, velocities, etc., can be evaluated in an interesting and inexpensive way. The simulation model built using the *Fluid Sim Hydraulic V Demo Version from Festo Didactic* is presented in figures 7 to 10. In the bottom part of the model; are represented by two processes where each one, is a hydraulic branch with the respective actuator connected for extension and retraction motion.

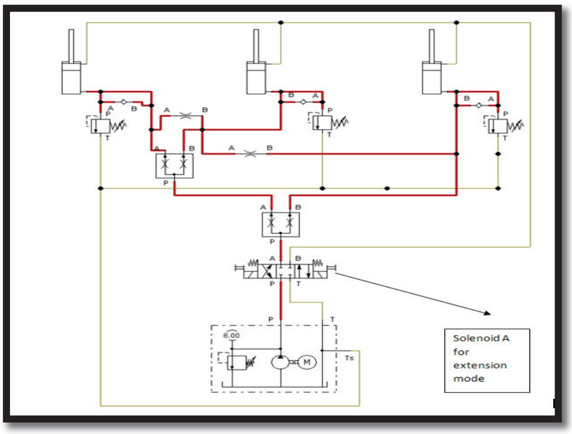

Fig 7: Extension Mode; for 3 Synchronised cylinders

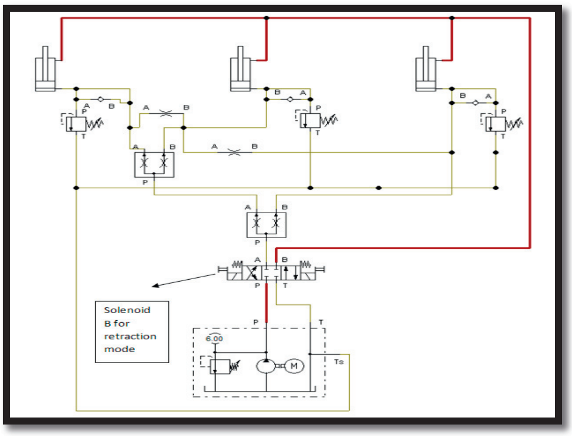

Fig 8: Retraction Mode; for 3 Synchronised cylinders

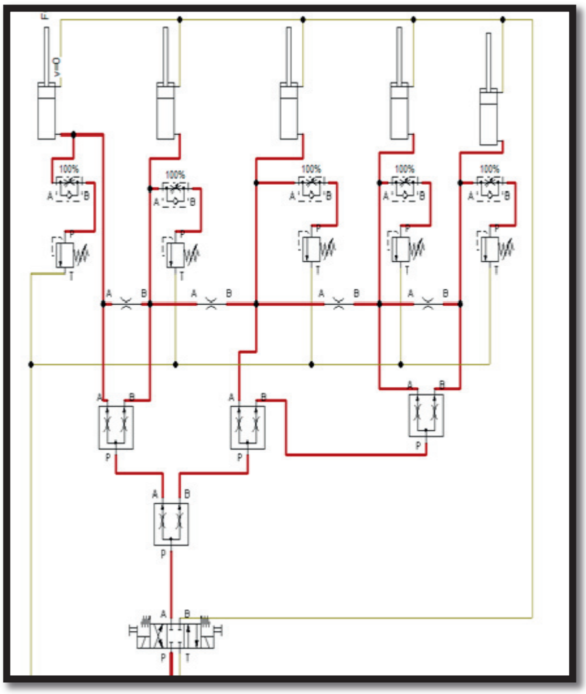

Fig 9: Extension Mode; for 5 Synchronised cylinders

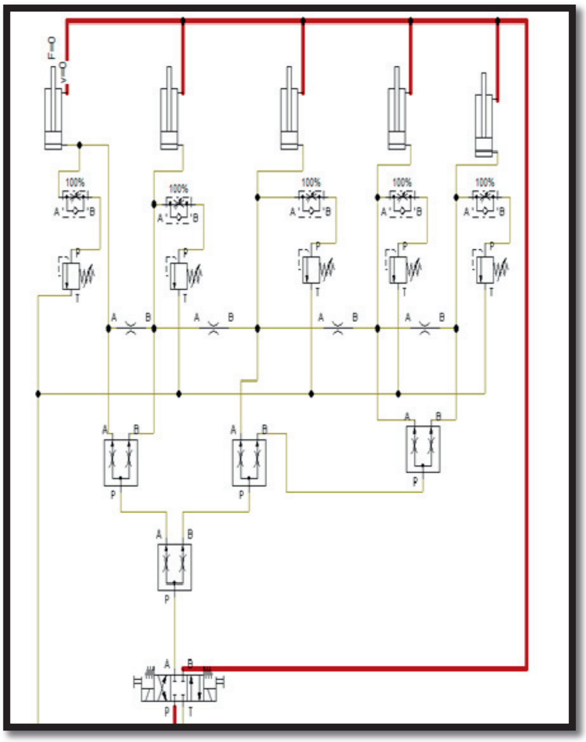

Fig 10: Retraction Mode; for 5 Synchronised cylinder

3.2.2 Simulation Test Results

The cylinders in motion powered by the pump, which is connected to a proportional directional valve which receives signals from a double-acting solenoid which will be inputted by the signals from the controller module through the PID process after feedback or feedforward signal from the sensors. The cylinder is linked with sensors that measure the position and velocity of the movements, as well as the force. The cylinder edge is also linked to the loading value that represents the cylinder acting on the weight of the ram of the RBPT.

The proportional pressure relief valve was here simulated using a valve orifice controlled by a proportional solenoid, which applies the force for the exact opening in order to maintain the desired pressure differential. The considered pressure value can be introduced as a signal for more precise judgement.

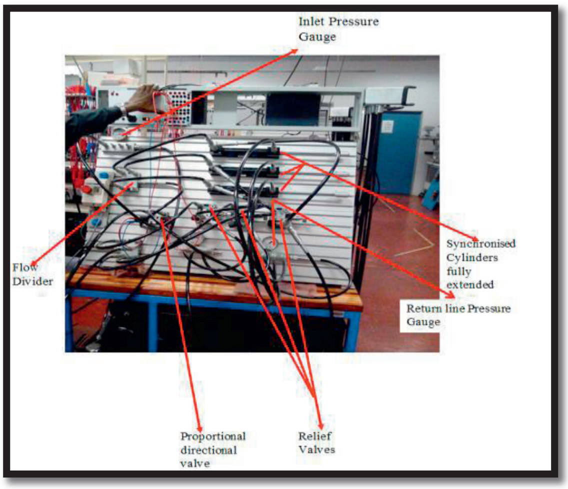

Fig 11a: Extension Mode: 3 Synchronised cylinder Test pictorial views

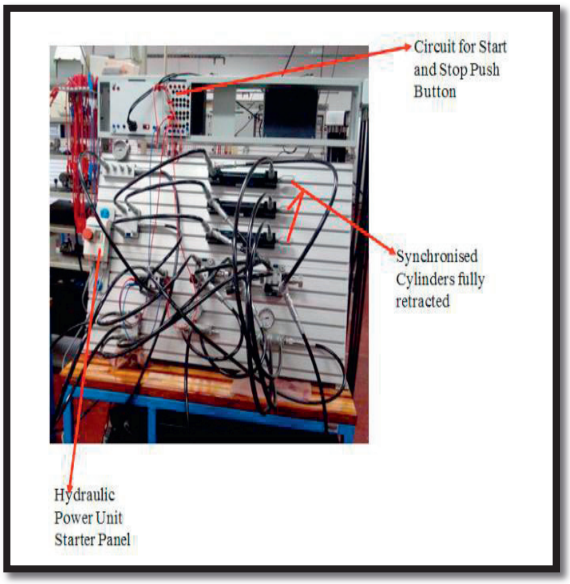

Fig 11b: Extension Mode: 3 Synchronised cylinder Test pictorial views

The simulation test results of the model shown in figure 11 follow some rules in order to optimize the hydraulic process. Hydraulic components should be well selected to detect whether the system will work in real-time capable. A system is real-time capable if the simulation runs before the simulated period counted in real time and is to validate if the simulated results on the *FESTO DIDACTIC TEST BOARD by* connecting all the hydraulic components, consequently saving the cost of real implementation. More important to this study, is the indication given by the simulation time. Even if it is not supposed to run an implementation like this in real-time, the simulation time when running the system is an important factor to measure the computational burden of the simulation system. Real-time simulation of physical systems with various domains (mechanical, electrical, hydraulic, etc.) requires a combination of several factors: model complexity, components choice and settings. What is being outlined here is the arrangement of all this components and the comparison between the desktop simulation and the real-time one. The model setup was designed to avoid unnecessary connections, loops or other unnecessary items as the starting point for having success when running a model. There are many occurrences on a simulation, such as, hydraulic power units, switches, valves, input signals, physical sensors and other physical events that can render challenging conditions during the simulation.

Summary and Conclusion

Two concepts utilised in the specification of RBPT are analysed, and then an approach is proposed in the design, configuration and reconfiguration of these industrial press tools. Authors further go on to present the range of varying configurations that are achievable with these COTS modules. These mechatronic modules can result in structures of press tools that are reconfigurable and the characteristics of the RMS can also be realised as depicted. From the result of the simulation and the laboratory test bench exercises made at mechatronics lab in the Department of Industrial Engineering of Tshwane University of Technology,Pretoria,South Africa, to investigate the performance of the hydraulic control system for the RBPT shows that the control system for the synchronised cylinders was successful.

Future work will involve searching for the suitable sizeable work part, hydraulic components, suitable proportional controllers that are modular and the respective press tool components for commercialisation to be integrated into the designed structure. It will also involve the simulation and finite element analysis of the proposed methods. The stability and stiffness tests will also be carried out; issues that will also need to be taken into consideration of are the ramp up time for changing from one configuration to the next. The reconfiguration time and its optimisation becomes a critical issue in the industrial application of these press tools. Thought will also need to be pondered on, with respect to the implications of the modular designer of the press tool to the manufacturing system utilised to develop the modular tool. Aspects in these lines are hinted on [17].

Acknowledgements

O. T. Adenuga and Dr. K. Mpofu thanks Tshwane University of Technology and the National Research Foundation for the privilege to undertake this research.

References

[1] Li G, Khajepour, A. Robust control of a hydraulically driven Flexible arm using back stepping technique. Journal of Sound and Vibration 2005; 280:759–775.

[2] Wu MC, Shih, MC. Simulated and experimental study of hydraulic anti-lock braking system using sliding-mode PWM control. Mechatronics 2003; 13:331–351.

[3] Lee SU, Chang PH. Control of a heavy-duty robotic excavator using time delay control with integral sliding surface. Control Engineering Practice 2002; 10:697–711.

[4] Alleyne A, Liu R. A simplified approach to force control for Electro-hydraulic systems. Control Engineering Practice.2000; 8:1347–1356.

[5] Hogan P, Burrows CR. Synchronizing Unevenly-Loaded Hydraulic Cylinders. Proceedings of the ASME Fluid Power and Systems Technology Division; 1994; 1: pp. 75-80.

[6] Xiong YF, Lequoc S, Cheng RMH. Adaptive Control of a Synchronizing Servo-System, SAE Technical Paper Series1992:1-5.

[7] Koren Y. Cross-Coupled Biaxial Computer Control for Manufacturing Systems. Journal of Dynamic Systems, Measurement, and Control.1980; 102:265-272.

[8] Chiu GTC. Coordination Control of Multiple Axes Mechanical Systems: Theory and Applications to Machining and Computer Disk File Systems, Ph.D. Dissertation, University of California at Berkeley, 1994

[9] Chick SE, Olsen TL, Sethuraman K, Stecke KE, White CC. A descriptive multi-attribute model for reconfigurable machining system selection examining buyer-supplier relationship. Int. Journal of agile mgmt. Systems 2000; 2:33–48.

[10] Sun H, Chiu GTC. Motion Synchronization for Multi-Cylinder Electro-Hydraulic System. Proceeding of IEEE/ASME International Conference on Advanced Intelligent Mechatronics 2001; 8-12 July; Como, Italy.

[11] Jelali M, Kroll A. Hydraulic servo-system modelling, identification and control London, 2003. New York: Springer.

[12] Merritt HE. Hydraulic control systems. New York: Wiley; 1967

[13] Sun H, Chiu GT. Motion Synchronization of Multiple Hydraulic Actuators, IMECE Fluid Power Systems and Technology.FPST- Vol.6, 1999. pp. 147-154

[14] Rong L, Jing L, Chun-geng S, Sen L. Analysis of Electro-Hydraulic Proportional Speed Control System on Conveyer. Procedia Engineering 31 2012; 1185 – 1193 Available online at www.sciencedirect.com. Assessed on 28-10-2013.

[15] Chena C, Liub L, Cheng C, Chiu GTC. Fuzzy controller design for synchronous motion in a dual cylinder electro-hydraulic system 2007.

[16] Zhang Q. Hydraulic Linear Actuator Velocity Control using a Feedforward plus PID controls. Department of Agricultural Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801.

[17] Erixon G, Yxkull A, Arnstrom A. Modularity-the Basis for Product and Factory Reengineering. Annals of the CIRP 1996; 45/1:1 6.

[18] Tchkalov V, Miller S. Parameterization of Directional and Proportional Valves in Sim Hydraulics. Math Works. http://www.mathworks.com/tagteam/63022_Parameterization_Valve_Models_SimHydraulics_PDF.pdf assessed on 28-10-2013.