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**AIN SHAMS UNIVERSITY  
FACULTY OF ENGINEERING  
DEPARTMENT OF AUTOMOTIVE ENGINEERING**

**Optimization of a Displacement Controlled Linear Hydraulic  
Actuator Utilizing Mechatronics Approach**

A Thesis submitted in the Partial Fulfillment for the Requirement of the  
Degree of PhD in Mechanical Engineering

By

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## **STATEMENT**

This thesis is submitted as partial fulfillment of Ph.D. degree in Mechanical Engineering, Faculty of Engineering, Ain Shams University.

The work included in this thesis was carried out by the author during the Period from 2014 to 2018, and no part of it has been submitted for a degree or qualification at any other scientific entity.

The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others.

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## **List of Publications**

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2. Sherif Elbaz, Moatasem Shahin, Ibrahim Elsherif, Mohamed Abdel Aziz, and Nabila Elnahass “Design and Experimentation of Test Rig to Characterize Hydrostatic Drive for Linear Actuator” IJRET-International Journal of Research in Engineering and Technology, Volume 6, Issue 9; September 2017

## **ABSTRACT**

Displacement controlled hydraulic systems present an effective approach to improve the efficiency of fluid power systems. This approach prevents fluid throttling, which is a major case of power dissipation, by minimizing the use of control valves in circuits. This approach could play an important role in industry and mobile hydraulics in the near future to overcome the problems associated with fossil fuel especially pollution. The work presented in this thesis describes developing, measuring, modeling, and controlling of a displacement controlled hydraulic linear actuator. A practical hydraulic circuit is developed with a small number of common components, and is suitable for many practical applications.

The linear actuator is controlled by changing the swash plate angle of the variable displacement pump which in turn changes the pump delivery. A complete test rig with all necessary instrumentations is designed to measure, monitor, record, and control the hydraulic circuit using mechatronics principals (mechanical, electrical/electronic, and information technology). Model identification is conducted to find the transfer function based on practical measurements. The calculated data were compared with measured results obtained through an extensive experimental program which proved the validity of the model. Two types of controllers are selected and many input signals with different shapes are fed to the system. Good tracking performance is observed between the desired, and the output signals. Experiments are done in different loads to simulate practical conditions and all the data are displayed on line during experiments. Two types of software are used, the first one is made by Visual Basic/Labview packages and the other is done by Matlab Real Time Windows Target toolbox. This work shows a simple solution to the problem arising when using hydraulic cylinders in closed hydraulic circuit which presents a good approach to hydraulic circuit design. Also shows a way to practically identify system transfer function without using analytical methods. During this process, two types of controllers, namely PID and fuzzy tuned PID, were heavily used deployed and compared.



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## NOMENCLATURES

| Symbol      | Description                                 | Unit                |
|-------------|---|---------------------|
| $q_{L1}$    | Flow to load number one                     | $m^3/s$             |
| A           | Hydraulic Cylinder Area                     | $m^2$               |
| $A_p$       | Cross sectional area of a single piston     | $m^2$               |
| D           | piston rod diameter                         | m                   |
| E           | Modulus of elasticity                       | Pa                  |
| F           | Acting force                                | N                   |
| G(S)        | Transfer function in Laplace domain         |                     |
| $G_p$       | Pump flow gain                              |                     |
| J           | second moment of area                       | $m^4$               |
| K           | Reynolds number                             |                     |
| $K_d$       | Derivative gain                             |                     |
| $K_i$       | Integral gain                               |                     |
| $K_p$       | Proportional gain                           |                     |
| L           | Hydraulic cylinder displacement             | m                   |
| $L_k$       | Free buckling length                        | m                   |
| N           | Number of pistons in the machine            |                     |
| $N_B$       | Length of generated PRBS                    |                     |
| n           | Pump angular speed                          | revolution<br>n/sec |
| $n_B$       | Number of bits in the shift register        |                     |
| $N_s$       | Safety factor                               |                     |
| P           | Pressure                                    | $N/m^2$             |
| $P_A$       | Pump Port A pressure                        | $N/m^2$             |
| $P_B$       | pump Port B pressure                        | $N/m^2$             |
| $P_{Boost}$ | Boost pump pressure                         | $N/m^2$             |
| $P_d$       | Discharge pressure of the pump              | $N/m^2$             |
| $P_{do}$    | Steady state discharge pressure of the pump | $N/m^2$             |
| $P_{in}$    | Pump input power                            | Watt                |

|                 |   |            |
|-----------------|---|------------|
| $P_{L1}$        | Pressure inside cylinder one                                    | $N/m^2$    |
| $P_{L2}$        | Pressure inside cylinder two                                    | $N/m^2$    |
| $P_{Ls}$        | Load sensing pressure   | $N/m^2$    |
| $P_{Ls}$        | Load sensing pressure   | $N/m^2$    |
| $P_{out}$       | Pump output power   | Watt       |
| $Q$             | Pump flow   | $m^3/sec$  |
| $Q_d$           | Volumetric flow rate out from the discharge chamber             | $m^3/sec$  |
| $q_{L2}$        | Flow to load number two   | $m^3/s$    |
| $Q_{po}$        | Steady state volumetric flow rate from the pump                 | $m^3/sec$  |
| $R$             | Yield strength of the piston rod material                       | $N/m^2$    |
| $r$             | Piston pitch radius   | m          |
| $S_e$           | Hydraulic cylinder max extracting velocity                      | m/sec      |
| $S_r$           | Hydraulic cylinder min extracting velocity                      | m/sec      |
| $s$             | Laplace operator  |            |
| $T$             | Total length of generated PRBS                                  | sec        |
| $v_g$           | Pump displacement volume per revolution                         | $cm^3/rev$ |
| $V_h$           | Fluid volume in the discharge chamber                           | $m^3$      |
| $Vol_{diff}$    | Volume difference between the cylinder piston side and rod side | $m^3$      |
| $\Delta P$      | Pressure difference   | $N/m^2$    |
| $\eta$          | Efficiency  |            |
| $\eta_v$        | valve efficiency  |            |
| $\varepsilon_p$ | Overall Efficiency  |            |
| $\omega$        | Angular velocity of input shaft                                 | rad/sec    |
| $\alpha$        | Swash plate angle   | rad        |
| $\lambda$       | slenderness ratio   |            |
| $\mu$           | Volumetric efficiency   |            |
| $e$             | Error   |            |
| $e(t)$          | Change of error   |            |

## LIST OF ABBREVIATIONS

| Abbreviation | Description                      |
|--------------|----------------------------------|
| A/D          | Analog to Digital                |
| AI           | Analog Input                     |
| AO           | Analog Output                    |
| BTU          | British Thermal Unit             |
| CBV          | Counter Balance Valve            |
| D/A          | Digital to Analog                |
| DAAPP        | Dual-Acting Axial Piston Pump    |
| DAQ          | Data Acquisition                 |
| DC           | Displacement Controlled          |
| dc           | Direct Current                   |
| DCA          | Displacement Controlled Actuator |
| DSP          | Digital Signal Processing        |
| ECU          | Electronic Control Unit          |
| EFM          | Electro-hydraulic Flow Matching  |
| EM           | Electrical Motor                 |
| EP           | Electro Proportional             |
| FFT          | Fast Fourier Transform           |
| FGS          | Fuzzy Gain Scheduling            |
| FSW          | Fuzzy Set-point Weighting        |
| FTPID        | Fuzzy Tuned PID                  |
| GA           | Genetic Algorithm                |
| HM-LS        | Hydraulic Metering Load Sensing  |
| IAE          | Integrated Absolute Error        |
| ICE          | Internal Combustion Engine       |
| I/O          | Input Output                     |
| IMC          | Internal Model Control           |
| lpm          | Liter per minute                 |
| LS           | Load Sensing                     |