hydraulic servo actuator. Second, a classical PID controller is designed and tuned using Ziegler and Nichols method according to the Integral Squared Error criteria. Third, a comparative study of the ISA system controllers between classical PID and modified PI-D is performed.

The transient response of the ISA system is obtained and discussed. From the results, it is demonstrated that the modified PI-D controller improve the performance of the system in order to achieve the required settling time with small overshoot and nearly zero steady state error. Adding the modified PI-D controller to the system improves the transient response parameters as the following results:

- Reducing the rise time by 75.11 % (< 1 sec).
- Reducing the settling time by 48 % (< 5 sec).
- Reducing the steady state error by 9.4 % (≈ zero).
- With 0.46 % overshoot of the system (< 0.5 %).

The comparative study between the two controller's configurations showed that the modified PI-D controller is better than basic one in the system output and slower response in presence of disturbance.

In future work, different controllers such as Fuzzy logic controller (FLC) or Genetic Algorithm (GA) could be used to validate the system. It is necessary to develop a suitable hardware system to verify the simulation results in this paper via experimental setup.

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APPENDIX

Nomenclature and the Numerical Values of the Studied System

$A_{a,b,c,d}$	Throttling areas of the port a, b, c and d, m^2
A_{Bp}	By-pass area of the EHSV, m^2
A_P	Cylinder piston area, 12.5 cm^2
Ap_{11}	Resultant subjected area to the pressure on the left poppet, m^2
Ap_{13}	Resultant subjected area to the pressure on the right poppet, m^2
Ap_{21}	Resultant subjected area to the pressure on the left poppet, m^2
Ap_{23}	Resultant subjected area to the pressure on the right poppet, m^2
A_{PL}	Left piston area, m^2
A_{PR}	Right piston area, m^2
Ap_{v1}	Subjected area to the pressure on the left poppet, m^2
Ap_{v2}	Subjected area to the pressure on the left poppet, m^2
A_{Pz}	Piston area of the by-pass valve, m^2
A_{rL}	Left rod side area, m^2
A_{rR}	Right rod side area, m^2
A_s	Spool cross-sectional area, m^2
At_{11}	Throttle area of the left poppet, m^2
At_{13}	Throttle area of the right poppet, m^2
At_{21}	Throttle area of the left poppet of the second DCV, m^2
At_{23}	Throttle area of the right poppet of the second DCV, m^2
A_{th}	Throttle area of the EHSV entrance, m^2
C_d	Discharge coefficient, 0.611
d_f	Flapper nozzle diameter, 0.5 mm
F_{1L}	Seat reaction force for the left poppet, N
F_{1R}	Seat reaction force for the right poppet, N
F_{2L}	Seat reaction force for the left poppet of the second DCV, N
F_{2R}	Seat reaction force for the right poppet of the second DCV, N
f_5	Switching DCV damping coefficient, 300 Ns/m
F_{5L1}	First left seat reaction force, N
F_{5L2}	Second left seat reaction force, N
F_s	Force acting at the extremity of the feedback spring, N
f_s	Spool friction coefficient, 50 Ns/m

F_{S1}	Solenoid force of the first DCV, 200 N
F_{S2}	Solenoid force of the second DCV, 200 N
f_{sm}	Seat material structural damping coefficient, 5000 Ns/m
F_{sR}	Seat reaction forces of the interconnection valve, N
F_{SR1}	Total seat reaction force of the first DCV, N
F_{SR2}	Total seat reaction force of the Second DCV, N
F_{sR5}	Total seat reaction force of the Switching DCV, N
f_v	Spring damping coefficient, 300 Ns/m
f_z	Interconnection valve damping coefficient, 50 Ns/m
f_θ	Damping coefficient, 0.002 Nms/rad
i_e	Torque motor input current, A
K_i	Current-torque gain, 0.556 Nm/A
K_{Lf}	Equivalent flapper seat stiffness, $5*10^{6}$ N/m
K_s	Stiffness of the feedback spring, 900 N/m
K_{sm}	Seat material stiffness, $1 * 10^7$ N/m
K_{sp}	Spring stiffness, 15000 N/m
K_T	Stiffness of flexure tube, Nm/rad
K_θ	Armature rotational angle torque gain, $9.45*10^{-4}$ Nm/rad
L_f	Flapper length, 9 mm
L_s	Length of the feedback spring and flapper, 30 mm
m_5	Switching DCV mass, 0.05 kg
m_p	Piston mass, 10 kg
m_s	Main spool valve mass, 0.1 kg
m_z	Mass of the by-pass valve, 0.02 kg
P_1	Pressure in the first valve chamber, Pa
P_2	Pressure in chamber (b), Pa
P_4	Pressure in the right chamber of the switching DCV, Pa
P_{S1}	Supply pressure of the main system of EHCS, 300 bar
P_{s1}	Supply pressure of the main system of ISA, 300 bar
P_{sL}	Supply pressure to the EHSV, pa
P_t	Return tank pressure, 2 bar
Q_{11}	Throttle flow rate of the left poppet, m^3/s
Q_{13}	Throttle flow rate of the right poppet, m^3/s
Q_{21}	Throttle flow rate of the left poppet of the second DCV, m^3/s
Q_{23}	Throttle flow rate of the right poppet of the second DCV, m^3/s
Q_{41}	Throttle flow rate of the left poppet of the fourth DCV, m^3/s
Q_{43}	Throttle flow rate of the right poppet of the fourth DCV, m^3/s
Q_{Bp}	By-pass flow rate of the EHSV, m^3/s
Q_{th}	Flow rate of the EHSV entrance, m^3/s
R_s	Equivalent flapper seat damping coefficient, 5000 Nms/rad
T_F	Feedback torque, Nm
T_L	Torque due to flapper displacement limiter, Nm
T_P	Torque due to the pressure forces, Nm
V_0	Initial volume of oil in the spool side chamber, 2 cm^3
V_1	Initial volume of chamber (a), 4 mm^3
V_2	Initial volume of left chamber of the switching DCV, 6 mm^3
V_3	Volume of the flapper valve return chamber, 5 cm^3
V_4	Initial volume of right chamber of the switching DCV, 5 mm^3
V_L	Volume of left chamber in the switching DCV, 4 cm^3
x_f	Flapper displacement, m
x_i	Initial Flapper limiting displacement, 30 μm
y_1	First DCV displacement, m
y_2	Second DCV displacement, m
y_5	Switching DCV displacement, m
y_{5iL}	Left initial position of the switching DCV, 0 m
y_{5iR}	Right initial position of the switching DCV, 0.006 m
y_{ciL}	Left initial position of the cylinder piston, 4 cm
y_{ciR}	Right initial position of the cylinder piston, 4 cm
y_i	The initial distance between the right poppet and its seat, 2 mm
y_o	Spring pre-compression distance, 3 mm
z_0	Spring pre-compression distance, 3 mm
A_{Bp}	By-pass area, m^2
F_{SRC}	Seat reaction force of the cylinder, N
K_{FB}	Feedback gain, 0.25 A/m
K_p	Piston loading coefficient, 0 N/m
V_c	Initial volume of the cylinder chamber, 100 cm^3
d_i	Transmission line diameter, 2.5 mm
f_P	Friction coefficient on piston, 1000 Ns/m
i_c	Control current, A
i_e	Torque motor input current, A
i_f	Feedback current, A
A	Throttle area of the flapper nozzles, m^2
B	Bulk modulus of oil, 1.9 Gpa
c	Spool radial clearance
J	Moment of inertia of the rotating part, $5*10^{-7}$ Nms^2
m	Reduced mass of the moving parts of first DCV, 0.01 Kg
P_1	Pressure in the left side of the flapper valve, Pa
P_2	Pressure in the right side of the flapper valve, Pa
P_3	Pressure in the flapper valve return chamber, Pa
Q	Flow rate, kg/m^3
T	Torque of the electro-magnetic torque motor, Nm
x	Main driven spool valve displacement, m
x	Spool displacement, m, [12]
y	Actuating hydraulic cylinder displacement, m
z	Interconnection valve displacement, m
θ	Armature rotation angle, rad
ρ	Oil density, 900 Kg/m^3
ω	Width of the port, 2 mm