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Robust Control of Fuel Control Servo System using Sliding Mode & Experimental Validation

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***Abstract*—Sliding Mode Control (SMC) technique controlling a Fuel Control Servo System (FCSS) for a developmental Aero-gas turbine engine is presented. As a part of Software-In-The-Loop Simulation (SILS), a closed loop performance studies are carried out with both FCSS model and SMC controller model. Further validation of SMC performance is carried out through experimental demonstration as part of Hardware-In-The-Loop Simulation (HILS) where the real-time SMC controller that controls actual FCSS in closed loop. The behavior is of SMC controller is compared with PI controller performance. A simple first order SMC is able to mitigate large parameter variation of plant of SMC in overcoming un modeled dynamics and uncertain disturbances as compared to baseline PI controller.**

***Index Terms*—Electrohydraulic Actuation System, Position control, Sliding Mode Control, experimental validation, Real-time simulation.**

I. INTRODUCTION

Electrohydraulic servo valves (EHSV) are the most critical part of any hydraulic actuation systems. Its use is more prevalent in aerospace and precision applications due to high power to weight ratio, fast response bandwidth and high reliability. Several disadvantages such as contamination susceptibility, small tolerances to avoid leakages are also associated hydraulic systems [1]. An Electrohydraulic actuation system has inherently nonlinear behavior due to fluid interactions. Traditionally, simpler linear models are used for control design with sufficient margins. Most electro-hydraulic actuation systems use PID controllers. The performance rendered by the traditional PID controllers meet the specifications for a narrow operating range only. If the plant dynamics varies vastly due to un-modeled process, variation of sensitive parameters, changes in operation environment etc., it calls for a robust control method to be able to take care of such uncertainties.

Many different control design methods are proposed in literature that ensures performance robustness. This paper discusses first order Sliding Mode Control (SMC) [2] for position control of a fuel control of a developmental gas turbine engine.

II. FUEL CONTROL SERVO SYSTEM MODEL

The FCSS under consideration is a Fuel Control System for a developmental aero-gas turbine engine. The FCSS consists of a LP pump, HP pump, Fuel Metering Unit and spill valve. An Electro-Hydraulic Servo Valve (EHSV) is used for actuation of the Metering valve and a LVDT is used as position feedback for closed loop position control. A schematic of a typical FCSS along with experimental setup is as shown in Fig.1.

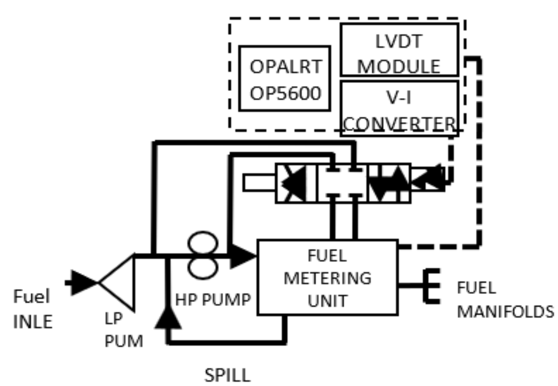

Fig.1 FCSS Schematic and experimental setup

The fuel is metered into engine by a closed loop valve position control for modulation of metering orifice, across which the pressure is maintained constant. For control of position in closed loop, only the position dynamics are considered. A second order transfer function-based model is derived experimentally and is validated against a theoretical reduced order model. The modeling and reduction employed is out of scope of this paper.

Equation 1 indicates the transfer function of EHAS used for validation of SMC implementation in simulation, before implementing on a real-time computer for experimental validation.

$$\frac{x(s)}{i(s)} = \frac{1.5}{0.02s^2+s} \quad (1)$$

Where, x denotes the valve position and i denotes the EHSV drive current input.

Typically, linear transfer function models are used for design of controllers and verified on a nonlinear plant model.

III. SMC CONTROL LAW DERIVATION

The SMC design methodology involves two phases. The first phase is to design or choose a sliding manifold/sliding surface through which the desired dynamic performance of the controlled system is prescribed and the second is to design a switched control law necessary to drive the plant states to the sliding manifold and maintain it on the surface upon interception with sliding surface while satisfying the generalized Lyapunov stability theory.

A standard Conventional SMC derivation is well established and is described below for the sake of completion [2].

State space description of a second order system with disturbance is as shown below,

$$\dot{x}_1 = x_2 \quad (2)$$

$$\dot{x}_2 = u + f(x_1, x_2, t) \quad (3)$$

$$y = x_1 \quad (4)$$

Where,$f(x_1, x_2, t)$ is the unknown disturbance. This unknown disturbance is assumed to be bounded i.e.$|f(x_1, x_2, t)| \leq L > 0$ (5)

Define a variable called sliding variable,

$$\sigma = g(x_1, x_2) = cx_1 + x_2 \quad (6)$$

If the variable σ is driven to zero by means of a control input u, asymptotic convergence of state variables to zero is assured. Below eqn. shows the corresponding σ dynamics,

$$\dot{\sigma} = cx_2 + f(x_1, x_2, t) + u, \sigma(0) = \sigma_0 \quad (7)$$

The candidate Lyapunov function for σ dynamics can be chosen as,

$$V = \frac{1}{2}\sigma^2 \quad (8)$$

According to stability conditions from Lyapunov theory, for asymptotic stability at σ=0, the conditions below must be satisfied,

a) $\dot{V} < 0 \; for \; \sigma \neq 0$ (9)

b) $V(0) = 0$ (10)

For finite time convergence, the lyapunov condition is modified as

$$\dot{V} \leq -\alpha V^{\frac{1}{2}}, \alpha > 0 \quad (11)$$

The convergence time is inversely proportional to α.The derivative of V is computed as, from (7)

$$\dot{V} = \sigma\dot{\sigma} = \sigma(cx_2 + f(x_1, x_2, t) + u) \quad (12)$$

Define $u = -cx_2 + v$ and substituting in (12)

$$\dot{V} = \sigma(f(x_1, x_2, t) + v) = \sigma f(x_1, x_2, t) + \sigma v$$
$$\leq |\sigma|L + \sigma v \quad (13)$$

Selecting,$v = \rho \; sign(\sigma)$

$$\dot{V} \leq |\sigma|L + \sigma\rho \; sign(\sigma)$$
$$\leq |\sigma|L - |\sigma|\rho$$
$$\leq |\sigma|(\rho - L) \quad (14)$$

From (11) and (8)

$$\dot{V} \leq -\alpha V^{\frac{1}{2}} = -\frac{\alpha}{\sqrt{2}}|\sigma| \quad (15)$$

Combining (14) and (15),

$$\dot{V} \leq |\sigma|(\rho - L) = -\frac{\alpha}{\sqrt{2}}|\sigma| \quad (16)$$

Thus, the control gain can be computed as,

$$\rho = L + \frac{\alpha}{\sqrt{2}} \quad (17)$$

Again from (8) and (11),

$$\dot{V} \leq -\frac{\alpha}{\sqrt{2}}|\sigma| \quad (18)$$

$$\sigma\dot{\sigma} \leq -\frac{\alpha}{\sqrt{2}}|\sigma| \quad (19)$$

The above condition is called as reachability condition and guarantees that the states of the controlled system converge on sliding surface (defined byσ) and stay on the surface thereafter.

For reference tracking, the states for Sliding variable definition are modified to error in output state i.e. $e = y_c - y$. Thus,

$$\sigma = ce + \dot{e} \, , c > 0 \quad (20)$$

Proceeding as above, σ dynamics are given by,

$$\dot{\sigma} = c\dot{e} + \ddot{e}$$
$$\dot{\sigma} = c(\dot{y}_c - \dot{y}) + \ddot{y}_c - \ddot{y}$$
$$= \ddot{y}_c + c\dot{y}_c - f(y, \dot{y}, t) - c\dot{y} - u \quad (21)$$

Define $\ddot{y}_c + c\dot{y}_c - f(y, \dot{y}, t) - c\dot{y} = \varphi(y, \dot{y}, t)$

This Unknown disturbance is assumed to be bounded i.e. $|\varphi(y, \dot{y}, t)| \leq M$

Thus, $\dot{\sigma} = \varphi(y, \dot{y}, t) - u$ (22)

Therefore,

$$\sigma\dot{\sigma} \leq \sigma(\varphi(y, \dot{y}, t) - u) \leq |\sigma|M - \sigma u \quad (23)$$

Selecting $u = \rho\, sign(\sigma)$ for conventional SMC design,

$$\sigma\dot{\sigma} \leq |\sigma|M - \rho sign(\sigma)$$

$$\sigma\dot{\sigma} \leq |\sigma|M - |\sigma|\rho\sigma\dot{\sigma} \leq |\sigma|(M - \rho) \quad (24)$$

Now, by Sliding Mode reachability condition,

$$\sigma\dot{\sigma} \leq -\frac{\alpha}{\sqrt{2}}|\sigma| \quad (25)$$

Therefore,

$$|\sigma|(M - \rho) = -\frac{\alpha}{\sqrt{2}}|\sigma| \quad (26)$$

Thus,

$$\rho = M + \frac{\alpha}{\sqrt{2}} \quad (27)$$

The SMC law becomes $u = \rho\, sign(\sigma)$, where the control gain ρ depends on the assumed bound of disturbances and the required convergence time.

Further, certain modifications are necessary for implementation purposes. The sliding variable defined for reference tracking contains derivative of error term. For implementation of the current SMC law, the derivative is simply numerically computed using previous iteration data and smoothened by a low pass filter.

For minimization of chattering, a known downside of using SMC, the Signum function is replaced with a sigmoid function. Thus $sign(\sigma)$ becomes,

$$sign(\sigma) \approx \frac{\sigma}{|\sigma| + \epsilon} \quad (28)$$

Where, ϵ is a small positive scalar. The selection of ϵ is a tradeoff between ideal sliding mode performance and smoothness of control effort parameter.

IV. SOFTWARE-IN-THE-LOOP SIMULATION (SILS)

Both FCSS model and SMC model are modeled in MATLAB Simulink ®as shown in Fig.2. The closed loop position control loop simulation also includes sinusoidal disturbance on the position feedback unknown to the controller. Effects of digital controller and signal conditioners are emulated as white noise and quantization noise. A differentiator/ washout filter is used for computing derivative of error term for simulation. The external disturbance added is 50% of the demand reference.

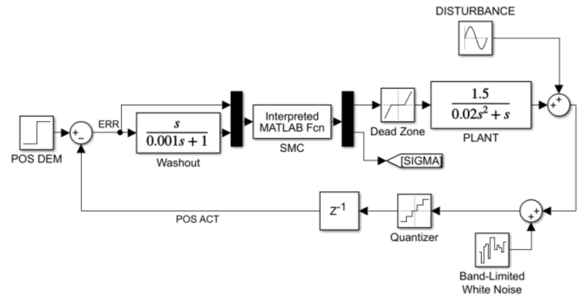

Fig. 2: Simulation block diagram for SMC (Simulink)

First, the simulation is run to compare SMC and PI performance with external disturbance in position state and without dead band, quantization and white noise. The performance of SMC disturbance rejection is compared to that of the traditional PI controller as shown in Fig.3. SMC computed drive current under idle conditions of no noise clearly shows a 'phase advance' as compared to that of PI controller, by the virtue of which SMC provides better disturbance rejection as against PI which only 'reacts' to the built-up error.

Next, dead band, Quantization and white noise are added to emulate a more realistic scenario corresponding to effect of servo valve null, analog to digital converters and signal conditioning circuits respectively. The results are shown in Fig.3 and Fig.4. These effects, together with external disturbance and un-modeled dynamics can be assumed to be lumped by the controller for rejection. The peculiar characteristic of SM Control of high frequency switching is seen on the control effort with minimal effect on the tracking performance.

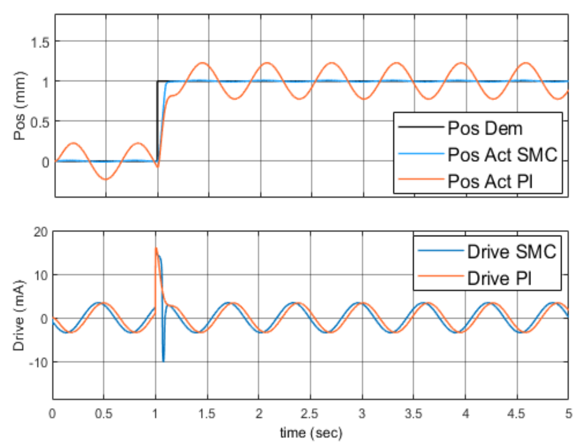

Fig.3 Comparison of SMC & PI performance in simulation without dead band, quantization and noise

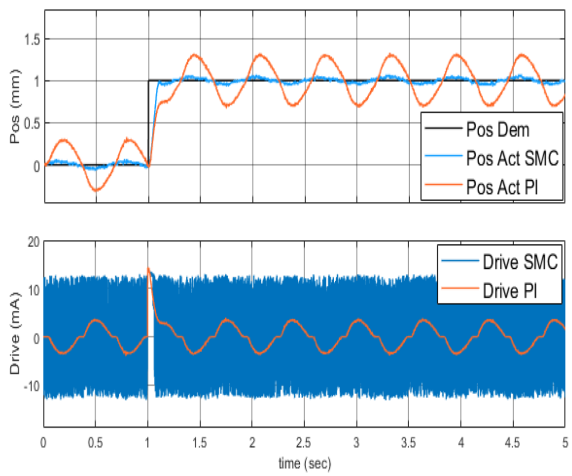

Fig.4 Comparison of SMC & PI performance in simulation with dead band, quantization and noise

V. SILS BASED SIMULATION RESULTS

The closed loop performance studies were carried out with a provision to switch from PI control mode to SMC control mode. The effects of nonlinearities like the dead band, quantization and noise effects are studies and the SMC control performance is found to be insensitive to non-linearities meeting both steady state and transient requirements. These simulations serve as a validation to proceed with experimental implementation on real-time controller and testing on the actual hydro-mechanical system.

VI. HARDWARE-IN-THE-LOOP SIMULATION

The SMC for FCSS is tested in a HILS Rig facility as a part of Modeling and Simulation framework, where the pumps are operated by a prime mover in accordance with the engine spool running speeds. An OPAL-RT® based system act as the real-time SMC controller. The rig setup of fuel supply, piping etc., emulates the standard of preparation as on the developmental gas turbine engine. OPAL-RT OP5600 is a real time computer running Redhat Linux, which has configurable analog as well as digital inputs and outputs. OPAL-RT propriety development environment called RT-LAB integrates Matlab-Simulink developed controller model for the selected target real-time system and provides the necessary software drivers for interfaces. The real-time scheduler, interface Input-Outputs, compiling and deploying controller algorithm is taken care by RT-LAB environment thereby providing a rapid prototyping system for control design evaluation. The SMC controller hardware configuration with Standard COTS based V-I converter and LVDT conditioner modules consistent with corresponding rating and accuracy are chosen and are indicated in Table 1.

Module	Specifications
OPALRT, OP5600, Analog Out, Analog In	Intel Xeon E5, Redhat Linux, 16 bits, +/- 15V, 15mA, 16 bit, +/-20 V,820kHz BW
V-I module, VC2124	+/- 10V input, +/-20mA output, 2.5kHz BW.
LVDT conditioner, Canopus LVDT-DBV	5 wire LVDT 5.3Vrms, 2kHz excitation. +/-10V

Table 1: Hardware configuration of SMC controller

The controller program is designed such that the control logic can be switched online between PI and SMC for online monitoring and to address HILS rig operating safety aspects as shown in Fig.5. The execution sample time for the real time controller is 1ms.

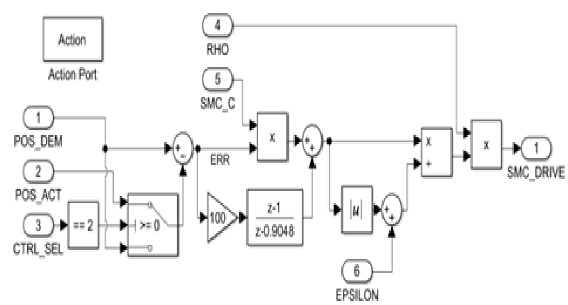

Fig.5 Simulink block diagram of SMC for Real-time implementation

The SMC tuning parameters used are c = 100, ρ = 15 and ϵ =3. The derivative of error is computed numerically using difference of previous iteration and passed through a low pass filter with $\tau = 0.001$sec. The PI loop parameters are k_p=15 and k_i=1. The PI position control loop gains for FCS satisfy the loop performance as per engine stability and operation requirements.

VII. HILS BASED EXPERIMENTAL RESULTS

Fig.6 shows comparison of performance between SMC and PI control. The low frequency oscillations exhibited under PI control are not present for SMC case. These low frequency oscillations in servo system can be caused by numerous reasons, not limited to, contamination, non-symmetrical wear of second stage spool, biased feedback spring to torque motor stage, variation in resistance and inductance of valve torque motor etc. The reasons however are out of scope for current paper. SMC is able to reject these unknown disturbances by high gain and frequency switching action.

The efficacy of SMC is verified for the entire operation range of fuel metering valve with varying pump speed is as shown in Fig.7. As explained in Fig. 5, 'CTRL_SEL' parameter that enables online controller switching between PI and SMC is also shown in Fig.7. Fig.8 shows the detailed changeover between PI and SMC. 'CTRL_SEL' value of '1' indicates conventional PI, whereas a value of '2' indicates selection of SMC.

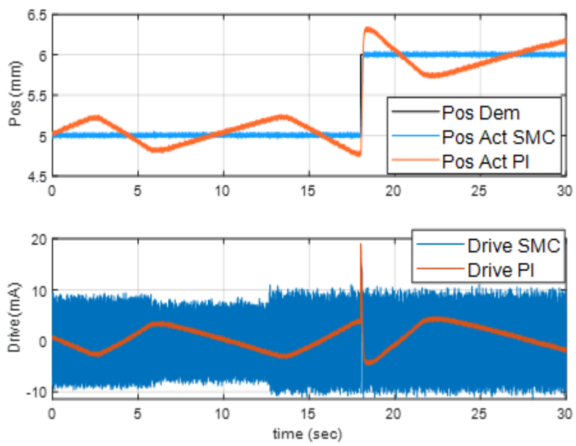

Fig.6 Comparison of SMC and PI performance and control effort

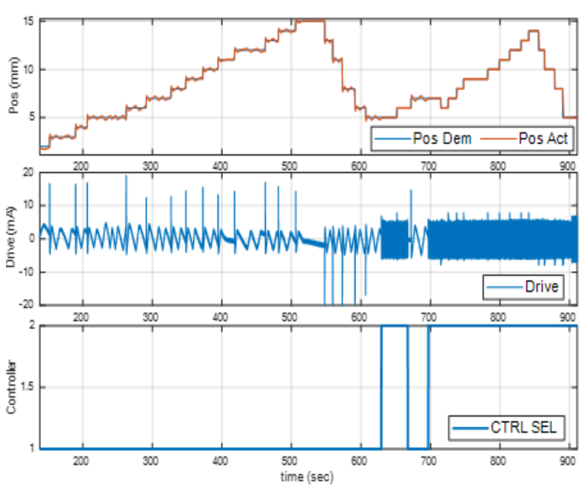

Fig.7 Comparison of SMC and PI performance including control effort for the entire range of valve position control, showing online controller switching

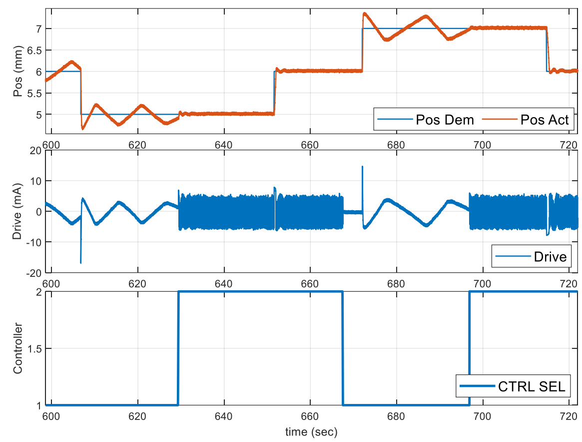

Fig.8 On-line switching between PI and SM controller

VIII. CONCLUSION

Sliding Mode Control is implemented and the performance is compared with conventional PI control. Ability of SMC in rejecting external disturbance is brought out experimentally. Robustness of SMC against unmodelled dynamics and parameter uncertainties is evident from comparison of simulation and experimental results. A simple second order position dynamics model is used for simulation verification and the same SMC design in real-time implementation performs well for a non-linear Fuel Control System. This highlights that SMC design does not required higher fidelity model of the plant for control design. These features of SMC are exploited for control of plant with large parameter variations due to degradation and substantial un-modeled dynamics.

Quantitative analysis of effects of this high frequency switching due to SMC on such electro-hydraulic actuation systems is a further topic of exploration for the authors. These require detailed computation of resonance frequencies of constituent components, their possibility of excitation by SMC action and operational life aspects. Further work can include implantation of more sophisticated methods for control effort smoothening and better error derivative term estimates.

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