Research Article

The Prescribed Fixed Structure Intelligent Robust Control of an Electrohydraulic Servo System

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1. Introduction

Electrohydraulic Servo System (EHSS) are extensively used in industrial automation applications because of their small size to power ratios, fast response to input, reliability, ability to handle large force or torque and their continuous, intermittent, reversing, and stalled operation without damage. Due to these characteristics and their automated material handling tasks, applications of Electro Hydraulic Servo System actuators are not limited. EHSS are being used in high-performance industrial applications such as in insulator fatigue test device, a unique composite cylinder consisted of three chambers and two pistons, with fractional order PID control [1]. This system has another sliding mode control-based application in vehicle’s active suspension [2]. Similarly, feedback-based electrohydraulic systems enhanced their application in automobile, active steering and brakes system [3], hydraulic elevator [4], robotic manipulator [5], and in civil engineering as well.
Importance of these systems increased with the passage of time for many practical control applications as mentioned above. In all the above application, models of these systems contain nonlinear dynamics. The dynamic behaviour of EHSS becomes non-linear due to non-linear pressure-flow relationship, friction effect, orifice dynamics, and stiffness of fluid [6]. A wide bandwidth implying small time constant, high fidelity control, and precise accuracy is required for all applications that are mentioned above. Classical PID controllers are being used widely in industries all over the world, but their design using classical approaches can give precise accuracy if exact model of system is known and also if system has no nonlinearity and parameter’s dynamic behaviour. So, in case where system contains nonlinearity and system’s parameters have dynamic behaviour due to load conditions, the design of suitable controller is an issue. To overcome these difficulties and for precise control of EHSS, various non-linear control strategies are proposed in literature. A non-linear adaptive control and the design of indirect adaptive fuzzy control of EHSS [8] hold the valuable performance in position and velocity tracking. The normal practice is to use non-linear techniques to synthesize controllers for EHSS, whereas linear time invariant (LTI) model-based controllers are more practical because they have fewer complications. To our best knowledge, no work on fixed structure intelligent robust controller of EHSS is presented yet. Another contribution shows that the objective function is optimized intelligently using Genetic Algorithm, where linear fraction transformation (LFT) objective function is formulated in MATLAB. An intelligent Genetic Algorithm has many applications in control systems [9], such as in intelligent optimization of control elements [10]. It has been adopted in many practical applications, such as flight control systems [11], where control elements are tuned using this intelligent technique for optimal and robust response of the systems [12–14].

An LTI model-based linear controller with fixed structure and fixed order is proposed. The problem is formulated in MATLAB, and control parameters are tuned in frequency domain using intelligent optimization. Proposed controller overcomes variations in the performance parameters, i.e., steady state error, over shoot, settling time, and peak time, which are caused by nonlinearity and parameters variations. Conventional $H_2$ and $H_{\infty}$ control techniques [15–18] have been used for many years. These frequency domain-based techniques were used for optimal and robust performance. Now, these conventional techniques have slowed their adoption in practical word because of many constraints, such as complex design, speed of response, control bandwidth, disturbance rejection, and robust stability [19], where controllers with fixed order and fixed structure are more practical. These conventional $H_{\infty}$ controllers become more complex while using higher order complex weights to shape sensitivity $S(s)$ and complementary sensitivity $T(s)$ for improved and desired robust performance. The proposed intelligent robust control has fixed structure that increases its practical importance. The proposed synthesis provided better robust performance in comparison with conventional PID and conventional $H_{\infty}$ control synthesis. The conventional $H_{\infty}$ control synthesis has practical limitations because of their complex structure, whereas the proposed controller is more simple and practical. Due to complex weight-based structure, the conventional $H_{\infty}$ controllers are not composed of simple gains and PIDs, on the other hand proposed synthesis formulated such as gains, PIDs, observer based and complex lead-lag controllers [19], for optimized parameterization of control elements. Since the design of the proposed controller is based on intelligent $H_{\infty}$ optimization and has all above-mentioned advantages, the researchers have focused on the design of fixed structure-based robust control systems for many practical applications. These fixed structure $H_{\infty}$ synthesis can also have control applications for MIMO systems such as Twin Rotor Aerodynamic Systems [20] and can perform well because of their decentralized and fixed-order structure [21]. For the design of proposed prescribed fixed-order controller, the intelligent robust $H_{\infty}$ problem is formulated in MATLAB. The intelligent Genetic Algorithm approach is applied to find the robust parameters of proposed fixed structure $H_{\infty}$ synthesis. The remaining part of this paper is organized as follows: mathematical modelling of EHSS is presented in Section 2. The experiment set-up and experimental model validation results are shown in Section 3. An LTI model through system’s identification is developed in Section 4. Section 5 includes fixed structure and fixed-order $H_{\infty}$ controller, conventional $H_{\infty}$ control synthesis, and classical PID controller. The simulation results with comparison and discussion are presented in Section 6, which clearly show the effectiveness of proposed approach. The conclusion is given in the last section.

2. Mathematical Modelling

2.1. Description of the System. EHSS has an electrohydraulic actuator, hydraulic control valve, hydraulic pump, and a controller. The hydraulic actuator is a cylinder, which provides linear motion through piston and hydraulic control valve regulates the flow of fluid. The hydraulic pump contains electrohydraulic motor to transfer from electrical energy into mechanical and then into hydraulic energy. Typically, electrohydraulic valves are servo or proportional. According to [22], the electrohydraulic actuator is a double-acting cylinder driven by single-stage four-way spool. The ports of cylinder are connected to valve and oil flow through orifice valve is controlled by spool displacement. Hence, the piston position could be controlled by controlling the fluid flow into and out of the cylinder chamber, delivered to the load. A hydraulic system consists of four-way control valve, a double-acting cylinder, and a load with mass $M$ attached to the piston, which is shown in Figure 1.

The mathematical model used in simulation shows the relationship between fluid flow through orifice and pressure delivered to load [16] is given as

$$4 \frac{dP_L}{d\beta_e} = -Ax - C_t P_L + Q_L,$$

where

$P_L$ = Load Pressure, $C_t$ = Total Coefficient Leakage.
\[ \dot{x}_1 = x_2, \]
\[ \dot{x}_2 = \frac{1}{m} (-k{x}_1 - b{x}_2 + A{x}_3), \]
\[ \dot{x}_3 = a{x}_2 - \beta{x}_3 + \gamma \sqrt{P_L} - \text{sgn}(x_4)x_3x_4, \]
\[ \dot{x}_4 = -x_4 + \frac{K}{t} u. \]

In above mathematical model, \( \text{sgn}(x_4) \) represents the forward and reverse motion of spool and states, input, flow rate constants, and system parameters for the EHSS are taken from equation (5).

States and Input.
\( u \) = The input current to the servo valve.
\( x_1 \) = The translational position of piston.
\( x_3 \) = Pressure delivered to the load.
\( x_4 \) = The translational position of the value.

2.2.1. Flow Rate Constant.
\[ \alpha = \frac{4B_e A}{V_t}, \]
\[ \beta = \frac{4C_{tm} B_e}{V_t}, \]
\[ \gamma = \frac{4C_d B_e v}{V_t \sqrt{d}}. \]

2.2.2. System Parameters.
\( K \) = DC Gain of Servo Valve.
\( m \) = Mass of Actuator.
\( b \) = Damping Constant.
\( k \) = Spring Constant.

The Simulink-based non-linear model constructed using state space model of equation (5) to represent the dynamics of system is shown in Figure 2. The open loop response for the non-linear SIMULINK model is shown in Figure 3. The parameters values used for the model with abbreviations and units are given in Table 1. These parameters values are also available in laboratory electrohydraulic system manual. Whether the state space Simulink model inherits the key components of system dynamics, model is also validated experimentally. The input and output data for model identification are generated experimentally. The experimental validation results are shown in the next section.

3. The Experimental Set-Up of EHSS with Model Validation Results

The hydraulic set-up EXPV1-EH is used for experimentation purpose. The experimental set-up is consisted of following:

(i) Hydraulic pump that transforms electrical energy into mechanical energy by use of electrical motor and then transforms it into hydraulic energy. This hydraulic pump can build pressure up to 850PSI. Synthetic oil is used as hydraulic fuel.

(ii) Double rod cylinder with stoke length 10 inches.

(iii) 4/2 Bidirectional proportional control valve (REXROTH 4WRAE6E12-11) with operating range of ±10V DC.

(iv) Linear position transducer (BALLUF BKD-S11-FU-15) with operating range is 0 to 10 VCD

The proportional valve is hydraulically plumbed, and it actuates through power electronics circuitry. The position of spool inside the proportional valve controls the flow of fluid into and out of the chamber. A magnet is coupled with linear transducer, and it is mounted on aluminium rail of double rod cylinder. The experimental set-up of EHSS is shown in Figure 4.

For the purpose of model validation simulation is carried out for \( T = 2500 \) samples. In this regard, the commanded input of ±10V AC is applied to proportional valve. The open loop model validation data are also used for developing the linear model. The model identification and validation curve are shown in Figure 5.

4. Linear Time Invariant Mathematical Model of EHSS

The proposed fixed-structure \( H_{\infty} \) synthesis is a nonsmooth optimization, which is directly used to tune the simple linear control elements such as gains, PIs, PDs, and PIDs, where the parameters of such control elements are optimized. An
LTI model containing the dynamics is required first for the application of the proposed technique. The LTI model is also required to be identified for the purpose of designing the $H_{\infty}$ controller and classical PID controllers. The experimental input and output sine wave data of Figure 5 were collected from the system and described in Section 3. Based on the collected data, an appropriate LTI model is identified by experimental data of Figure 5 with the help of System Identification Toolbox in MATLAB. Three models: ARX model, state space model, and discrete time OE model with sampling time of 0.01 seconds are developed. A second-order discrete time OE model:

$$y(t) = \frac{B(z)}{F(z)}u(t) + e(t)$$

with fit to estimation data of 99.61% (prediction focus) is given in equation (7). Then the appropriate model of equation (7) is converted into transfer function form, which is shown in equation (8). The comparison of an estimated LTI model and non-linear model is shown in Figure 6.

$$B(z) = 0.001624z^{-1} - 0.00162z^{-2}, \quad (7)$$

$$F(z) = 1 - 12994z^{-1} + 0.9944z^{-2},$$

$$G(s) = \frac{0.1627s + 0.04292}{s^2 + 0.5593s + 0.07584} \quad (8)$$
5. Controllers Design for Electrohydraulic Servo System

As LTI model is estimated, and a new challenge is to design a suitable controller that could precisely track the commanded input. Three types of controllers are discussed in this paper. These are classical PID, conventional $H_\infty$ controller, and fixed-structure $H_\infty$ controller. There are two controlling variables position and velocity of piston of EHSS. The variable, which is controlled here, is the position of the piston. The performance criteria are defined upon the basis of tracking of commanded signal. However, the system output is evaluated based upon rise time, settling time, overshoot, and steady-state error.

5.1. Classical PID Controller Design. The classical PID controllers are being widely used in industries all over the world because of their simplicity and low cost. If nonlinearity is contained in dynamic model, then classical controllers become less efficient because they do not provide perfect tracking and precise performance parameters. Classical PIDs are not optimized controllers. Classical PID controller using root locus technique is designed in SISO toolbox in MATLAB. An LTI state space model of EHSS of previous section is used for controller design. Time domain and transfer function representations of classical PID controller are given below in equations (9) and (10), respectively. The tuning parameters of classical PIDs are differential gain ($K_d$), integral gain ($K_i$), and proportional gain ($K_p$) and are tuned using classical approaches such as Root Locus and Ziegler Nicholas techniques. The comparison of the Simulink results for PID with proposed controller is given in Section 6.

\[
\begin{align*}
    u(t) &= K_p e(t) + K_i \int_0^t e(\tau)\,d\tau + K_d \frac{de(t)}{dt}, \quad (9) \\
    U(s) &= \left( K_p + K_i \frac{1}{s} + K_d s \right) E(s). \quad (10)
\end{align*}
\]

5.2. Conventional $H_\infty$ Controller Design. $H_\infty$ controller is designed in frequency domain, using smooth $H_\infty$ optimization. Complex weighting transfer functions are used to shape the magnitudes of the closed-loop transfer functions, such as complementary sensitivity $T(s)$ and sensitivity $S(s)$. Here, $T(s)$ is the transfer function between reference input $R(s)$ and output $Y(s)$, whereas $S(s)$ is the transfer function between $R(s)$ and error $E(s)$. The transfers functions of $S(s)$ and $T(s)$ are provided in equations (11) and (12), respectively, where $L$ is the loop transfer function. It is formulated as $H_\infty$ optimal control problem, thus automating the actual controller design by selecting suitable frequency weighting functions on the sensitivity $S(s)$ and complementary sensitivity $T(s)$. For tuning a typical controller, $H_\infty$ norm is minimized, which is the peak value of $S(s)$ or $T(s)$ as a function of frequency. The constraints (peak specifications) for adjusting the controller parameters are given in equation (13).

\[
\begin{align*}
    S &= \frac{1}{1 + L}, \quad (11) \\
    T &= \frac{L}{1 + L}, \quad (12) \\
    \omega_s S_{\infty} &< 1, \quad (13) \\
    \omega_t T_{\infty} &\leq 1.
\end{align*}
\]

Results of Figure 6 shows that the identified model complies the plant behaviour well. In the next section, based on LTI model linear controllers such as PID, $H_\infty$ controller and fixed-structure $H_\infty$ controller will be designed.

![Figure 3: Open loop response at sine input of f=0.1 Hz.](image-url)

Table 1: The physical parameters of non-linear EHSS.

| Name            | Abbreviation | Value   | Unit  |
|-----------------|--------------|---------|-------|
| Supplied pressure | $P_s$        | $5 \times 10^6$ | Pa     |
| Total volume    | $V_t$        | $2.44 \times 10^{-5}$ | m$^3$  |
| Actuator area   | $A$          | $2.4 \times 10^{-4}$ | m$^2$  |
| Effective modulus | $\beta_e$    | $7.60 \times 10^8$ | N/m$^2$|
| Spool displacement | $x_V$       | 0.2     | M     |
| Leakage factor | $C_{cm}$     | $5 \times 10^{-13}$ | m$^3$/Pa.s |
| Discharge factor | $C_d$        | 0.61    | -     |
| Load stream     | $Q_L$        | $2.5 \times 10^{-5}$ | m$^3$/Sec |
| Liquid mass density | $P$          | 870    | kg/m$^3$ |
| Mass and load   | $M$          | 24      | kg    |
computation resources are available, but in general, it is an issue in industrial environment.

5.3. Fixed-Structure and Fixed-Order $H_\infty$ Controller Design. Convention $H_\infty$ controllers are monolithic and have slowed their adoption in industry due to practical limitations. These controllers also have constraints on $H_\infty$ norm regarding design requirements such as speed of response, robust stability, and control bandwidth, and disturbance rejection [19]. The improved results could be achieved by the use of higher order weighting filters, but this leads conventional $H_\infty$ controller to a complex structure. Fixed-structure $H_\infty$ controllers overcome all the above-mentioned limitations. The proposed synthesis is formulated in MATLAB, and optimization of objective function to satisfy the given constraints is done intelligently using Genetic Algorithm. The fixed-structure robust $H_\infty$ problems require only tuning of simple control elements, such as gains and PIDs. Using $H_\infty$ optimization [24–26] in frequency domain. These fixed structure controllers are more practical and perform well in terms of quality of solution and speed of response [19]. Section 5.3.1 represents the standard formulation for fixed-structure $H_\infty$ synthesis, and it also represents the non-tunable (fixed) blocks and tunable control elements. In Section 5.3.2, a brief overview of Genetic Algorithm to optimize the proposed formulation of fixed-structure $H_\infty$ synthesis is presented.

5.3.1. Standard Formulation of Fixed-Structure $H_\infty$ Synthesis. Standard form of $H_\infty$ synthesis is shown in Figure 8, which is composed of two main parts:

(i) The block $P(s)$ is an LTI model of the plant, and it contains all nontunable (fixed) blocks in the control synthesis.

(ii) The prescribed structure and fixed-order control synthesis are put in the second block. This block contains control diagonal elements, which are
Figure 6: Open loop response at sine input of $f = 0.1$ Hz.

Figure 7: (a) Step input tracking, (b) square input tracking, (c) sine input tracking.
presented in equation (14). All these control elements are tuneable in the case of complex MIMO systems. There is only one tuneable control element in the case of SISO system, which is contained in this block. The complex MIMO systems are decoupled due to tuneable diagonal block of control elements. Where every control element $C_i(s)$ is assumed to be an LTI and have a defined structure.

$$
C(s) = \begin{bmatrix}
C_1(s) & \ldots & 0 \\
\vdots & \ddots & \vdots \\
0 & \ldots & C_N(s)
\end{bmatrix}
$$

Robust control theory generally states that all block diagrams representing SISO or MIMO systems could be rearranged into the standard form of Figure 8. Where tuneable blocks are isolated into $C(s)$ and remaining diagonal elements are rearranged into the standard form of Figure 8. Where every control element $C_i(s)$ is assumed to be an LTI and have a defined structure.

$$
C_i(s) = K_i + \frac{K_{id}s}{T_{f}s + 1}
$$

A further challenge is to optimize the scalar parameters of the control elements such as PIDs. These PIDs can be tuned using $H_{\infty}$ optimization [27–29]. The PID controller is parameterized by scalars $K_p, K_i, K_d,$ and $T_f$ as

$$
C_j(s) = K_p + \frac{K_i}{s} + \frac{K_d}{T_f}s
$$

All scalar parameters $K_p, K_i, T_f,$ and $K_d$ are optimized by nonsmooth $H_{\infty}$ optimization. The coefficient $T_f$ is used as a parameter of first-order filter along with the derivative control to make it practical.

5.3.2. The Design of Structured $H_{\infty}$ Synthesis. The controller parameters are tuned in frequency domain to meet typical design requirements. The constraint in the case of SISO system is to minimize the $H_{\infty}$ norm, and it is just the peak values of the transfer functions $S(s)$ and $T(s)$ over the whole range of frequency. The requirements for robust design such as disturbance rejection, attenuation elimination, high control bandwidth, and high stability margins and improved transient specifications can be formulated in the form constraints of equations (18) and (19).

$$
\|W_j(s)T_j(s)\|_{\infty} \leq 1 \text{ where } j = 1, \ldots, M,
$$

$$
\|W_i(s)T_i(s)\|_{\infty} \leq 1 \text{ where } i = 1, \ldots, N.
$$

The proposed robust algorithms are formulated to minimize $H_{\infty}$ norm of $H(s)$ and the standard form of $H(s)$ are given below in equation (20).

$$
H(s) = F_1(P(s), \text{Diag}(C_1(s); \ldots; C_N(s))).
$$

To satisfy design requirements of equations (18) and (19), the suitable higher order complex weighting functions $W_s$ and $W_T$ are chosen to get the desired shape of the transfer functions $S(s)$ and $T(s)$ because order of the proposed synthesis is independent of the order of complex weights. For EHSS $C(s)$ assumed to be a parametric optimized PID controller. The generalized prescribed structure $H_{\infty}$ synthesis model for $H_0$ is constructed in MATLAB as

$$
C(s) = \text{ltiblock.pid}('C', 'pid'); \quad \% \text{tunable PID.}
S = \text{feedback}(1, G(s) * C(s)); \quad \% \text{G(s) is the "s" domain model of EHSS.}
T = \text{feedback}(G(s) * C(s), 1);
H0 = \text{blkdiag}(w_1, s, w_T * T);
$$

where $H0$ is the generalized continuous-time state-space model with 2 outputs, 2 inputs, 7 states, and the block $C$, where block $C$ is a tuneable parametric PID controller. All the parameters of structured robust control synthesis are required to be optimized by minimising the objective function of equation (20), which is done by intelligent Genetic Algorithm. Finally, the generalized synthesis model formulation is converted into the standard form $H(s)$ of equation (20) and to achieve the robust optimized control parameters. The control parameters of robust PID controller are tuned to enforce the constraint less than 1 such as $H(s)_{\infty} \leq 1$, which means the norm of $H(s)$ is minimized.

The proposed optimization is initiated by generating an initial population of possible optimized solutions (individuals). In the context of control elements optimization, these individuals are decoded to obtain desired values of robust
Figure 9: (a) Flow graph for intelligent algorithm. (b) Feedback loop for whole system.

Table 2: The comparison of the performance parameters.

| Techniques               | Rise time (sec) | Settling time (sec) | Overshoot (%) | Steady-state error (%) |
|--------------------------|-----------------|---------------------|---------------|------------------------|
| Classical PID            | 0.9             | 4.2                 | 8.2           | 1.2                    |
| Conventional $H_{\infty}$ controller | 0.19            | 0.23                | 0             | 0                      |
| Fixed-structure $H_{\infty}$ controller | 0.16            | 0.20                | 0             | 0                      |

Figure 10: (a) Step disturbance rejection by H-infinity controller. (b) Step disturbance rejection by fixed-structure H-infinity controller.
control parameters. Search mechanism of this intelligent algorithm is constituted on three main operators: selection, crossover, and mutation.

Genetic Algorithm is focused on optimization of all possible solutions, and it works as

(i) Initialize a population of possible solutions.

(ii) Calculates the fitness values of all individuals by using fitness function.

(iii) Values with highest fitness are selected.

(iv) Cross over and mutation are used to generate the new optimal population.

• Criteria is stopped after finding best optimal solution.

Working of this intelligent algorithm is also shown in signal flow graph of Figure 9(a).

The elementary feedback loop configuration block diagram for the whole system is shown in Figure 9(b), and simulation results of the proposed controller and conventional controllers with comparison are given in next section.

6. Comparison of Performance of Controllers with Simulation Results and Discussion

Fixed-structure $H_{\infty}$ control technique applied to electro-hydraulic system is investigated in this paper in light of controller synthesis. An ultimate goal of this scheme is the precise tracking of commanded position, which is a big problem in industries. Classical PIDs due to their low cost and easy handling are widely used in industries, whereas these controllers are not able to precisely handle dynamic behaviour of parameters due to load condition and nonlinearity contained in the system. Conventional $H_{\infty}$ controllers overcome the above limitations, but they also have constraints on speed of response, bandwidth, etc. These are higher order controllers, and their structure is also complex, so that they have practical limitations. Fixed-structure and fixed-order $H_{\infty}$ controllers are optimization-based robust controllers. They are composed of simple optimized control elements, due to this reason they are more practical. Fixed-structure controllers also hold wide bandwidth and precise tracking.

The comparative analysis of three controllers for different reference inputs in the form of simulation results is shown in Figures 7(a)–7(c). And it can be seen from below figures that results of proposed synthesis are quite improved in terms of transient and steady-state response.

Table 2 shows the comparison between all controllers on the basis of transient specifications of Figure 7(a), where simulation results clearly show that rise time, overshoot, and settling time have been reduced in case of proposed controller for step position tracking.

The $H_{\infty}$ controller and fixed structure $H_{\infty}$ controller are optimized and robust controllers so that disturbance rejection figures are given below for both controllers. Where for tracking the rectangular reference position, a step disturbance is applied at time is equal to 2 seconds. Simulation results of Figures 10(a) and 10(b) show that both controllers reject the step disturbance within 0.2 seconds and start again the tracking of reference position.

For parametric uncertainty analysis, bounded parametric uncertainty in nominal plant is considered [30], and linear model is rewritten as in equation (21).

$$G(s) = \frac{k(s + 0.04292/0.1627)}{s^2 + 0.5593s + 0.07584}$$  \hspace{1cm} (21)
where $k = 0.1627$. A wide range of parameter variation $\Delta k$ in nominal parameter $k$ is considered, and an open loop step response is made as is shown in Figure 11(a). This figure clearly shows that for large parametric variations, open loop system may rise unbounded, and this uncertainty will lead it to unstable region.

Because robust controllers are designed to deal with uncertainty, robust controllers make the systems stable despite the uncertain parameters that may cause instability. The proposed intelligent robust synthesis contains a fixed and simple structure that increases its practical importance where non-linear and conventional robust controllers have complex structure [31, 32]. The prescribed structured intelligent robust synthesis performs excellently and makes the system stable despite the wide parametric variations. As results are shown in Figure 11(b), the system’s response makes the stable and desired steady state behaviour despite the wide parametric variations. This figure shows that response contains minor transient overshoot because of unstable parametric variations.

The future direction of this work is the coupling of two proportional hydraulic valves that has an application in industrial pick and bottle filling plant.

7. Conclusion

The proposed technique is compared with classical PID and conventional $H_\infty$ controller. Table 2 shows that a proposed robust control technique gives effective performance regarding transient specifications, disturbance rejection, and robust stability. Another main advantage of proposed fixed structure $H_\infty$ controller over conventional $H_\infty$ controller is its simple and decentralized structure, while conventional $H_\infty$ controllers are complex because of their higher number of states [19]. The proposed fixed-structure $H_\infty$ synthesis also gives better performance as compared to classical or conventional $H_\infty$ controller because it is designed using higher order complex weights and nonsmooth $H_\infty$ optimization, where its order is independent of the order of complex weights and its optimized control parameters are also achieved by nonsmooth $H_\infty$ optimization. The order and defined structure of proposed synthesis is not disturbed by higher order shaping filters so that this fixed structure $H_\infty$ synthesis also performs well in terms of quality solution and response’s speed. These proposed controllers are more practical because they are composed of simple control elements such as gains, PIs, PDs, and PID’s. Their practical applications are not limited for robust control only. It has also been proved in [19], the fixed structure synthesis $H_\infty$ formulation can also tune the decentralized control of complex Multi Input and Multi Output (MIMO) systems to reduce the complexity, which is due to higher order nature of MIMO systems. To our best knowledge, proposed synthesis is designed and implemented for Electrohydraulic Servo System for the very first time, and the proposed synthesis provided better results in comparison with conventional controllers.

Data Availability

All the data are available in the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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