

Research on Dynamic Response Characteristics Modeling and Adaptive Control Strategy of Electro-hydraulic Proportional Valves

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ABSTRACT Electro-hydraulic proportional valves are critical components in high-precision industrial control systems, where nonlinear dynamics, hysteresis effects, and time-varying disturbances significantly affect control accuracy and system stability. To address these challenges, this study proposes a data-enhanced dynamic-response modeling framework and an adaptive sliding-mode control strategy. A hybrid modeling approach integrating mechanism-based analysis and experimental data fusion is established to characterize nonlinear coupling among electromagnetic force, hydraulic pressure, and spool displacement. An adaptive sliding-mode controller with online gain adjustment is further developed to improve disturbance rejection and parameter adaptation. Simulation and experimental results demonstrate significant reductions in rise time, overshoot, and steady-state error compared with conventional PID control. The framework provides an effective solution for nonlinear system modeling and intelligent control in industrial automation environments.

INDEX TERMS electro-hydraulic proportional valve, adaptive sliding mode control, nonlinear modeling, system identification, intelligent control

I. INTRODUCTION

As a critical control element in high-precision machinery, the dynamic response behavior of electrohydraulic proportional valves directly determines the execution performance and operational stability of the material processing equipment. Enhancing these hydraulic response characteristics is essential for maintaining the mechanical excellence and structural consistency of advanced industrial material distribution systems. The rapid advancement of automated high-precision equipment has led to increasingly stringent requirements for the dynamic characteristics of proportional valves in aerospace, precision manufacturing, and heavy engineering. Nonetheless, the electromagnetic drive linkage within the electro-hydraulic proportional valve possesses hysteresis and nonlinear saturation and the hydraulic flow field is vulnerable to variations in pressure and viscosity of oil and this aspect renders the system to have evident time-varying and strong coupling properties. Such complexity renders it challenging to strike the balance between response speed and control stability by utilizing the conventional linear modeling and constant parameter control techniques. Issues like hysteresis of valve core movement under load variations and multi-disturbances are likely to arise especially under varying loads and such circumstances are

likely to aggravate overshoot to make the overall control performance of the control system even more limited [1,2].

In order to enhance the quality of dynamic control of the electro-hydraulic proportional valves, a technique that integrates high precision modeling and strong control properties is highly demanded. The current literature tends to deal with the single-mechanism models or empirical laws of control and ignore the synergistic effects of friction, hysteresis, and hydraulic compressibility on the nonlinear behavior of the system. To overcome them, this paper develops a dynamic response mathematical model, which is formed by the combination of the mechanistic and experimental data and by implementing it with a better adaptive sliding mode control strategy to attain online parameter regulation and disturbance compensation. Through simulation and experimental verification, the impact of the control strategy on the enhancement of dynamic response characteristics is evaluated to establish a high-precision, stable hydraulic servo control paradigm for advanced manufacturing equipment. This technical approach optimizes the mechanical execution required for material morphology consistency and material spatial distribution, ensuring the industrial excellence of precision production systems.

II. RELATED WORK

In the dynamics modeling of the electro-hydraulic proportional valve, the initial study tended to use mechanism-based analytical modeling that obtained mathematical description model of the system by deriving coupling equations between electromagnetic force, oil pressure and valve core movement. Such models may represent the physical properties of the system, although accuracy of model is reduced during severe nonlinear conditions, since it does not consider various complex properties of the system like friction, hysteresis and temperature variations [3,4]. Over the past few years, the modeling style integrating the two methods has been built up gradually in the model combining data-driven and mechanism-based methods, and this methodology has led to an enhancement in the credibility of the model due to experimental data fitting and parameter identification. Nevertheless, the ability to describe time-varying characteristics in a systematic manner is still limited to the majority of studies, which are restricted to steady state and single operating conditions, thus limiting the dynamic generalization capabilities of the model.

PID control has found extensive application in the study of control strategies that are based on its simple structure and easy parameter adjustment yet its capacity to adapt to nonlinear disturbances and time-varying parameters is lacking. In order to enhance dynamic performance, fuzzy control, genetic optimization and neural network control have been proposed by researchers to have parameter self-adjustment. Nevertheless, these control means are based on substantial quantity of experimental data and training procedures, so it is hard to sustain high response efficiency in the conditions of real time. The sliding mode control has been extensively used in nonlinear systems because of its robust nature, but the classical sliding mode control has disadvantages of chattering in the switching that may lead to core wear and magnified noise in the valve during its long time operation causing instability in the system.

ASMC is a relatively effective improvement scheme that has been shown to yield positive results over the past few years. In this approach, an adaptive law is added to dynamically change the sliding mode gain based on the system error to minimize chattering without compromising the convergence speed and robustness. Other works have used ASMC in hydraulic servo systems, and actuator control, with good results. Nevertheless, the detailed study of the nonlinear compensation nonlinear hysteresis of the electro-hydraulic proportional valves in terms of systematic models has not been accomplished [5,6]. Although, most of the current models have not incorporated features of the experimentally derived models with the mechanistic model parameters, and there are no integrated formulation of control-modeling collaborative design models. It has turned out to be a key cutting-edge direction in enhancing the dynamic functioning of proportional valves.

III. METHODS

A. ESTABLISHMENT OF DYNAMIC RESPONSE MATHEMATICAL MODEL

The electro-hydraulic proportional valve dynamic response model is largely assembled around electromagnetic drive mechanism, the hydraulic actuation chamber, and the characteristics of motion of the valve core. The modeling process takes into account a nonlinear dependence of the current in the drive and the electromagnetic force of the coil. The functioning of the magnet field and attraction force with various input currents is experimentally determined and the dynamic map between the electromagnetic force and the input signal is established. Combining the displacement of the valve core with the shape of the throttling orifice, the pressure in the hydraulic chamber is jointly defined. In order to describe the dynamics of pressure, experimentally recorded data of flow-pressure difference is used to define the flow damping and compression characteristic parameters, taking into account the variation in hydraulic pressure difference across the valve core, thereby obtaining a coupled characterization between flow rate and displacement [7,8].

The friction properties were identified by acquiring velocity response data in the friction zones. The developed continuous friction force model incorporates the Stribeck effect to capture the nonlinear transition from static to sliding friction. Furthermore, a temperature-dependent viscosity correction factor is integrated into the friction identification process to account for hydraulic oil property variations under prolonged operation, ensuring high-precision tracking during high-speed processing. Hysteresis effect was modeled by a hyperbolic antisymmetric function indicating the hysteresis loop of the coil. Compared to complex Preisach or Bouc-Wen models, the hyperbolic antisymmetric function is selected due to its superior computational efficiency for real-time control and its ability to provide a smooth, differentiable gradient for the adaptive sliding mode controller. This simplified yet effective representation ensures that path-dependent electromagnetic properties are captured without introducing excessive latency into the control loop. This was then used to develop a hybrid state-space structure. In this framework, the mechanistic coupling equations define the core physical backbone (electromagnetic force, valve core displacement, and flow), while the data-driven residuals—derived from experimental mapping—act as real-time compensation terms that fill the gap between the idealized physical model and the observed nonlinear behaviors. In addition, the flow rate is incorporated as an independent state variable to explicitly decouple the dynamic coupling between transient flow forces and spool motion. This treatment allows the controller to directly compensate for the nonlinear flow-induced disturbances that are often masked when flow is treated merely as a derived output of pressure differentials. The control current was the input and the valve core displacement was the output. Experimental parameters were identified with least-squares identification and optimized with a particle swarm optimization algorithm to make

sure that the time-domain error between the simulation and experimental responses was below 5%. Step and sinusoidal sweep tests were used to verify the model and the dynamic response curves depicted a high level of accuracy with the measured response. The state equations developed were realistic in terms of the time-varying nature and nonlinear nature of the coupling between electro-hydraulic proportional valve [9].

B. CONTROL STRATEGY DESIGN

The adaptive sliding mode control design is grounded on dynamic response model. Control goals include making sure that the position of the valve spool correctly follows the desired command, and that there is stable output in the presence of dynamic disturbances. Examples of external perturbations to the system are electromagnetic hysteresis and disturbed flow of oil. The sliding surface is developed according to the valve spool motion error and error rate variation, which has allowed the control law to modify the response rate and steady-state error concurrently. The switching manifold incorporates a continuous reaching law that provides a smooth transition that minimizes chattering in the high frequencies, hence, preventing oscillation of the valve spool as well as maintaining the speed of the system.

The adaptive gain adjustment actively corrects the model uncertainty and error level in real-time by looking at it and as such, the control gain increases quickly in the initial response stage to provide the dynamic performance and automatically gets closer to the steady-state response to minimize energy use and impact. This gain correction law is not dependent on empirical constants, but it is self adjusting by the evolving tendency of the sliding surface. Its update rate is limited by the integrative nature of the error signal, which results in adaptive compensation of the nonlinearity of the system and time-varying parameters.

The controller structure has a parallel arrangement of the feedforward compensation and sliding mode term. The feedforward channel is used to process linear response, whereas the nonlinear disturbances are processed by a sliding mode channel. To offset the hysteresis in the electromagnetic response, a delay compensating component is added to the signal path to assure that the control signal is in phase across the time domain thereby enhancing the predictability of the core movement of the valve. This type of structural design enables the system to stabilize the tracking of the input signal when subjected to all different loads and changes in pressure.

The Lyapunov direct method is used in stability analysis, in which an energy function is built to show the state of error drifts to the sliding surface in finite time, ensuring that the state remains bound in the long term regardless of the input perturbation. The control law simulations demonstrate that the control law ensures a smooth transition process when various valve core displacement commands are used, and no oscillations or accumulation of overshoot are observed. Control signal rate of change is not excessive and the system

attains high convergence rate and constant output under nonlinear disturbances which means that the adaptive sliding mode control strategy is highly robust and self-adjusting in the balance of the electrohydraulic proportional valve dynamic response.

C. CONSTRUCTION OF EXPERIMENTAL AND SIMULATION PLATFORM

The simulation and experiment platform is based on a dynamic characteristic test bench of electro-hydraulic proportional valve. It has a servo drive power supply, a proportional valve actuator, a hydraulic oil source, pressure sensors, displacement sensors, a temperature monitoring unit, and high-speed data acquisition and control system. The source of hydraulic oil gives an adjustable pressure constant flow environment where the maximum system pressure is 21 MPa and the flow rate is adjusted between 5–20 L/min. The maximum system pressure is measured in real time by a displacement sensor of gating type. The electromagnetic drive unit comprises of a coil current control facility, as well as a power amplifier, which uses a constant current drive scheme in order to enhance input stability. The acquisition and control of the signals and the execution of the commands are done by the dSPACE real-time controller with the main control frequency of 2 kHz and the sampling period of 0.5 ms. This setup allows proper recording of high-speed dynamic variations of the motion of the valve spool.

The simulation model was constructed in MATLAB/Simulink format and there was consistency in the arrangement of the experiment. Oil compressibility coefficient, core mass of the valve and damping parameters were experimentally determined. Three kinds of input signals were employed to test the accuracy of the system response to varying aspects in the characteristics of the frequency domain namely, step, sinusoidal, and random mixed sequences. The experiment was conducted at 40 degrees Celsius to remove the effect of change in viscosities of the oil on the experiment. Any sensor signal was anti-aliased and secondarily calibrated to make sure that the values sampled were equal to the real measurements. The main techniques are shown in Table 1.

TABLE 1. Main Technical Parameters of Experimental and Simulation Platform

Module Name	Equipment Model	Measuring range	Resolution	Sampling frequency (Hz)	Control Interface
Proportional valve actuator	Bosch-4WE6E6X	21 MPa	0.1 MPa	2000	Analog input
Pressure sensor	HYDAC HDA4744	0–25 MPa	0.01 MPa	2000	CAN bus
Displacement sensor	MicroE 2000-5L	0–10 mm	1 μ m	2000	Analog input
Current driver	Kepco BOP36-6M	0–5 A	1 mA	2000	RS485
Data acquisition system	dSPACE DS1104	± 10 V	0.005 V	2000	PCI bus
Temperature sensor	PT100	0–100 $^{\circ}$ C	0.1 $^{\circ}$ C	50	Analog input

The time-domain matching of experimental signals and control responses was performed based on the parameters listed in Table 1 to ensure that modeling verification and control algorithm testing were conducted under high-fidelity conditions.

IV. RESULTS AND DISCUSSION

A. DYNAMIC CHARACTERISTIC TEST RESULTS

The step response comparative analysis aims to verify the performance of the control strategy under different dynamic conditions. Before the experiment, the sensors and acquisition system were calibrated, the hydraulic source output pressure was set to 16 MPa, and the flow rate was kept constant. A standard step signal was input to the controller to drive the solenoid coil to generate electromagnetic force to move the valve core. Valve core displacement, current feedback, and hydraulic pressure change signals were acquired. The system was tested sequentially with PID, sliding mode, and adaptive sliding mode control algorithms under the same signal and environmental parameters to ensure comparability. The valve core was initially kept at a stable zero position, and the input signal was abruptly applied at 0.1 s, recording the response curve throughout the process. The sampling frequency was fixed at 2 kHz, and changes in various physical quantities were monitored in real time using a high-speed data acquisition system. Electromagnetic hysteresis compensation and signal delay correction programs were implemented to ensure that the three control methods operated under consistent conditions. Each experiment was repeated three times, and the average result was used for subsequent time-domain analysis to ensure data representativeness and repeatability.

B. COMPARISON OF CONTROL PERFORMANCE

The control performance comparison results are derived from multiple sets of repeated experiments under uniform hydraulic conditions and the same input step signal. Valve core displacement and feedback pressure data are recorded through a high-speed sampling system. After signal filtering and time-domain feature extraction, rise time, overshoot, steady-state error and energy consumption index are calculated. The results are obtained by averaging three experiments and are shown in Table 2.

TABLE 2. Comparison Results of Control Performance

Control methods	Rise time (ms)	Overshoot (%)	Steady-state error (%)	Average input current (A)
PID control	28	9.3	1.6	1.42
Sliding mode control	21	4.7	0.9	1.31
Adaptive sliding mode control	16	2.1	0.3	1.22
Theoretical model simulation results	15	2.0	0.3	1.20
Experimental mean deviation	±0.4	±0.3	±0.1	±0.02

Table 2 illustrates the quantitative superiority of the ASMC. The significant reduction in rise time (42.9%) and overshoot (77.4%) is primarily attributed to the adaptive law's ability to provide high gain during the initial transient phase while smoothing the approach to the sliding surface. Unlike the constant-gain PID, the ASMC dynamically dampens the energy of the valve core as it nears the target position, directly resulting in the observed 81.3% improvement in steady-state accuracy. This control strategy improves the system's dynamic tracking capability through self-adjusting gain, reducing energy consumption while ac-

celerating response. The time error between model simulation and experiment is less than 3%, indicating that the control algorithm matches the model with high accuracy, the system response is stable and there is no obvious chattering phenomenon, and it is superior to traditional methods in terms of both accuracy and energy efficiency.

C. EFFECTIVENESS OF MODEL AND CONTROL STRATEGY

The model and control strategy effectiveness was determined as a result of simulation validation and comparison of real measurements. In the experiment, several groups of input signals were chosen such as step, sinusoidal, and random disturbance signals. Under varying loads pressures and temperature, the system was run to observe the dynamic trends of the valve core displacement, electromagnetic current and pressure response. Once all the data were obtained, the results obtained were compared with the model output curves in order to determine the degree to which they were synchronized in response, the magnitude of errors, and stability indicators. The consistency of the model prediction outcomes across different points in time and the stability of the outcome of the model control system were thoroughly tested by measuring the percentage of error and the correlation coefficient to check the accuracy of the model and the strength of the employed control system.

TABLE 3. Comparison of the effectiveness of the model and the control strategy

Test signal type	Mean square error (%)	Peak deviation (%)	Correlation coefficient R	Response synchronization rate (%)
Step input	2.8	3.1	0.995	98.4
Sine input	3.2	3.5	0.992	97.8
Random input	3.7	4.0	0.987	96.9
Average value	3.2	3.5	0.991	97.7

Table 3 shows that the model output and the measured response maintain high consistency under various signal types, with an average correlation coefficient of 0.991 and a mean square error of less than 3.5%. The maximum peak deviation does not exceed 4%, and the dynamic synchronization rate exceeds 97%. These results indicate that the established model can accurately reflect the nonlinear characteristics of the system, and the control strategy has good adaptability and robustness, maintaining stable tracking performance and high dynamic consistency under different operating conditions.

V. CONCLUSION

The mechanism and data fusion based on dynamic response modeling effectively incorporates the dynamic behavior of electro-hydraulic proportional valves under time-varying nonlinear coupling conditions within high-precision manufacturing systems. This integrated approach ensures the mechanical excellence and structural consistency of morphology by synchronizing hydraulic fluctuations with the complex spatial distribution of industrial material. The system together with higher adaptive sliding mode control shows

considerable enhancements in response speed as well as steady-state performance. The control law is very stable and robust in the suppression of the electromagnetic hysteresis and fluid disturbances. The model and control strategy has a stable dynamic behavior in the presence of various operating conditions which proves the engineering viability and broad generalizability of the approach. Nevertheless, the study remains limited by the fact that while valve core friction is realistically modeled, other complex stochastic perturbations such as transient oil temperature fluctuations and cavitation effects have not been fully quantified. Additionally, there is not enough analysis of multi-valve cooperative control. The development of smart updating for the adaptive law and real-time algorithm optimization offers a robust path for further research into the precision control of high-speed textile manufacturing equipment. This advancement will ensure the mechanical excellence and structural consistency of fiber morphology by enabling the control system to dynamically respond to the complex nonlinear couplings inherent in industrial yarn distribution.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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