IN-DEPTH ANALYSIS AND OPTIMIZATION OF ELECTRONIC CLOSED-LOOP CONTROL FOR PROPORTIONAL ENLARGED VALVES BASED ON SIMULATIONX

by

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This paper conducts an in-depth study on the electronic closed-loop control characteristics of Valvistor valves (a type of proportionally enlarged valve) by leveraging the SimulationX simulation platform. The displacement-area relationship of a 25 mm diameter Valvistor valve was accurately determined through the combination of experimental measurements and theoretical analyses. A highly realistic SIMULATIONX model was constructed based on actual parameters, taking into account oil compression, leakage, viscous friction and other key factors. The proportional-integral-derivative parameters were initially calculated using the genetic algorithm and then refined through a series of fine-tuning operations. The results show that the optimized proportional-integral-derivative control significantly improves the dynamic characteristics of the valve: in the step response of the main valve displacement, the rising response time is reduced by 45 milliseconds, the descending step response time is shortened by 20 milliseconds, and there is almost no overshoot compared with the original valve. Considering the variable pressure differences at the valve port in actual working conditions, the parameters of the feed-forward controller were corrected. Through iterative simulation of different pressure differences and feed-forward gain values within the range of 0.5-2 MPa, a parameter curve of the feed-forward controller was obtained, which ensures the valve's displacement output meets actual operation requirements under different pressure conditions. The research results provide important theoretical support and practical guidance for optimizing the performance of Valvistor valves and improving the control accuracy of hydraulic systems. Meanwhile, the limitations of the research (lack of physical experiment verification and insufficient universality) are pointed out, and future research directions (conducting physical experiments, expanding applications in complex systems, optimizing control algorithms) are clarified.

Key words: *proportionally enlarged valves, electronic closed-loop control, SIMULATIONX, proportional-integral-derivative control, feed-forward control, hydraulic systems*

Introduction

In the field of hydraulic systems, throttle valves [1] play a crucial role in precisely regulating fluid flow and controlling load speed. Proportional throttle valves [2], in particular, have found extensive applications across various industries, from manufacturing equipment to

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construction machinery. However, existing proportional throttle valves often suffer from issues such as low flow control accuracy and poor dynamic response. These problems can lead to inefficiencies in industrial processes, increased energy consumption, and reduced overall system performance.

The Valvistor valve [3], a type of proportional throttle valve, has attracted significant attention due to its potential to overcome some of the limitations of traditional designs. To fully leverage its capabilities and enhance its performance, a comprehensive understanding of its electronic closed-loop control characteristics is essential. This study aims to fill this gap by conducting an in-depth analysis of the Valvistor valve control system.

The SIMULATIONX simulation platform [4, 5] is a powerful tool that enables the accurate modeling of complex physical systems. It allows researchers to simulate the behavior of hydraulic valves under different operating conditions, taking into account factors such as fluid dynamics, mechanical interactions, and electrical control. By using SIMULATIONX, we can avoid the high costs and time-consuming nature of physical experiments at the initial research stages and explore a wide range of control strategies and parameter settings.

The research objectives of this study are two-fold. Firstly, we seek to optimize the control system of the Valvistor valve to improve its dynamic response and control accuracy. This involves fine-tuning the proportional-integral-derivative (PID) controller parameters [6, 7], which are crucial for achieving stable and precise valve operation. Secondly, we aim to explore the effectiveness of different control strategies [8-11], especially the use of a feedforward controller, in adapting to the variable pressure differences that occur in real-world applications. By achieving these objectives, we hope to contribute to the development of more efficient and reliable hydraulic control systems, which are essential for the progress of modern industries relying on hydraulic technology.

Characteristic analysis of electric closed-loop control Valvistor valve

Construction of simulation model

In this study, a 25 mm diameter Valvistor valve is selected as the research subject. The 25 mm dimension represents the inner diameter of the main valve body, which is in line with the industry norms for similar hydraulic valves. To accurately understand the valve behavior, determining its displacement-area relationship is a fundamental step. This relationship is obtained through a comprehensive approach that combines experimental measurements and theoretical analyses.

Experimental measurements play a crucial role in obtaining accurate data. We conducted tests on the valve prototype, carefully measuring the flow rate and pressure variations corresponding to different valve displacements. By collecting a large amount of experimental data, we were able to capture the real-world behavior of the valve. Subsequently, based on the principles of fluid mechanics, we performed in-depth theoretical analyses. Through these analyses, we derived the displacement-area relationship, which provides a mathematical description of how the valve displacement affects the flow-related areas within the valve.

With the displacement-area relationship in hand, we proceeded to construct a system model in the SIMULATIONX platform. The model, as presented in fig. 1, consists of two main components: the Valvistor valve and an electronic control unit. A constant pressure source is used as the oil source to ensure a stable supply of hydraulic fluid, and a loading overflow valve is incorporated to simulate the load conditions the valve will encounter in practical applications. The key parameters set in the SIMULATIONX model are shown in tab. 1.

During the model construction, we took into account several important factors that can influence the valve performance. The compression of the oil, which occurs under pressure changes, can affect the overall behavior of the hydraulic system. Leakage, both internal and external, can lead to inefficiencies and inaccurate control. Viscous friction between the moving parts of the valve and the oil also plays a role in determining the valve response. Additionally, we incorporated the actual displacement-area relationship curve of the main valve port into the model. This comprehensive consideration of various factors makes the model highly realistic, enabling us to simulate and analyze the valve performance with a high degree of accuracy.

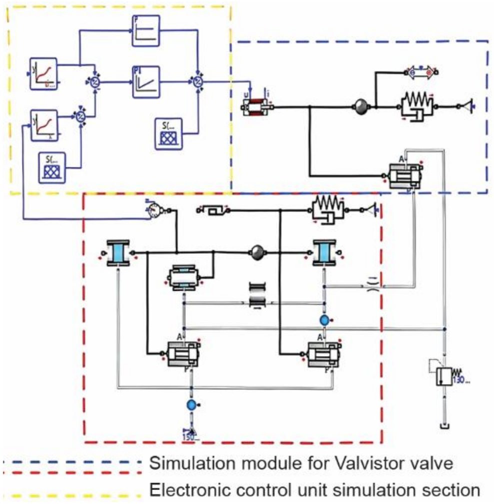

Figure 1. Whole simulation model of Valvistor valve

The selection of each parameter in the model is based on careful consideration. The main valve size of 25 mm was determined according to the specific requirements of the hydraulic system under study. This size is commonly used in relevant applications, ensuring the research practical significance. The feedback throat area gradient of 1.18 mm was derived through a series of experimental measurements and simulations. We tested different prototypes with varying area gradients and analyzed their effects on the valve performance. After a comprehensive evaluation of factors such as dynamic response and stability, we chose 1.18 mm as the optimal value. This value was further verified through additional simulations to ensure its suitability for the Valvistor valve in different operating conditions.

Table 1. Simulation parameter

Parameter name	Numerical value
Main valve size	25 mm
Main valve mass	0.6 kg
Pilot valve rated flow	25 Lpm
Main valve feedback throat area gradient	1.18 mm
Pre-opening amount of main valve	0.4 mm
Diameter of pressure compensator spool	27 mm
Pressure compensator mass	0.6 kg
Valve core stroke of pressure compensator	6 mm

Characteristic analysis of electric closed-loop control valve

It is important to note that all the analysis and results presented in this section are obtained through simulations in the SIMULATIONX environment. Although the description of the process may seem similar to an experimental set-up for clarity, no physical experiments have been conducted at this stage.

The performance of the Valvistor valve is significantly influenced by the parameters of the PID controller. To optimize these parameters, we first used the genetic algorithm to calculate the initial PID values. The genetic algorithm is a powerful optimization tool that can search for the optimal solution in a complex parameter space. After obtaining the initial values, we carried out a series of fine-tuning operations. Through a meticulous optimization and calibration process, we finally determined the optimal PID parameters as k_p = 1.759, k_i = 7.8391, and k_d = 0.0098.

In the simulation, when a rising step signal is applied to the proportional electromagnet, we maintained a constant pressure difference of 1.3 MPa between the two ends of the main valve port. Under these specific conditions, we obtained the displacement response curve of the main valve, as shown in fig. 2. This curve provides valuable insights into the dynamic behavior of the main valve under the influence of the optimized PID parameters and the specified pressure difference.

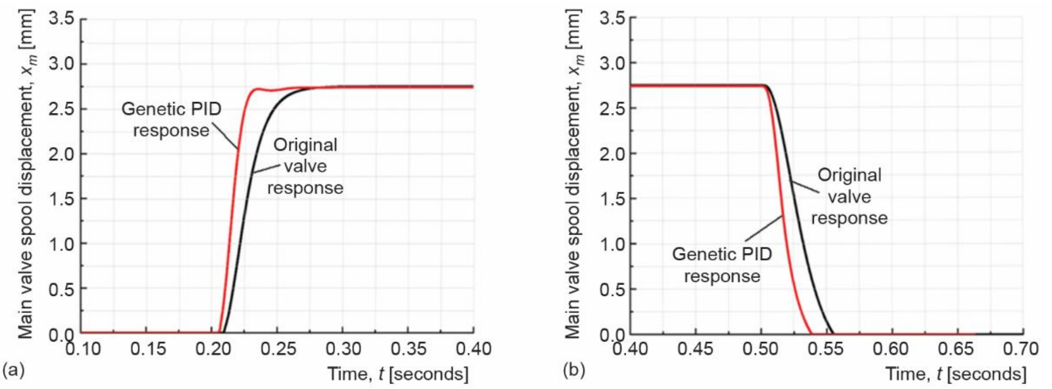

Figure 2. Step response of main valve; (a) step response of main valve displacement rise and (b) step response of main valve displacement drop

Figure 2 shows the step response of the main valve displacement. By comparing the genetic PID response curve with the original valve response, we can clearly observe the improvement in performance achieved by our proposed control method. The genetic PID control leads to a faster response time and reduced overshoot, indicating its effectiveness in enhancing the dynamic characteristics of the Valvistor valve. This improvement is of great significance for the valve application in hydraulic systems, where precise and rapid control is essential for ensuring the system stability and efficiency.

As can be seen from fig. 2(a), when the self-tuning PID control is activated, the response time is approximately 30 ms. This represents a significant improvement compared to the original valve, as the rising response time of the original valve is about 45 ms longer. Moreover, under the genetic PID control, the spool exhibits only a slight overshoot during the rising process, which meets the working requirements. In fig. 2(b), it is evident that under the genetic PID control, the descending step of the spool is relatively rapid, taking about 35 ms. This is approximately 20 ms faster than the response of the original valve, and there is almost no overshoot, demonstrating excellent dynamic characteristics.

The original valve response was obtained when the valve operated under its default control conditions with a traditional proportional control method. The controller gains for the original valve were set according to the manufacturer recommendations or common industry practices for similar valves. In contrast, our proposed method uses a genetic-algorithm-based PID control with MEMS [12-15] integration, which allows for more precise control and better performance optimization.

Correction of feed-forward controller parameters

In the transfer function model initially selected in this study, the pressure difference at the valve port of the main valve was set to 1.3 MPa. However, in actual working scenarios, the pressure difference at the valve port is not constant but varies continuously. Therefore, relying solely on a fixed value of 1.3 MPa cannot meet the actual operating requirements of the valve. Different pressure differences have a significant impact on the valve dynamic characteristics, affecting both the step - up time and the accuracy of the control output.

Under different pressure differences, the response time of the main valve and its output value will change. If these changes are not compensated for under PID control, the final output value will deviate from the desired value, which is not conducive to the proper operation of the flow valve. To address this issue, we decided to correct the final output value by adjusting the parameters of the feed-forward controller.

The determination of the feed-forward gains was achieved through an iterative simulation process. We selected a pressure difference range from 0.5 MPa to 2 MPa at the valve port of the main valve. For each pressure difference value within this range, we simulated the valve system with different feed-forward gain values. By observing the output responses of the valve, specifically the displacement of the main valve and the flow rate, we evaluated the performance of the system. The goal was to find the feed-forward gain values that minimized the error between the desired and actual outputs of the valve under different pressure conditions. Through this iterative process, we obtained a parameter curve of the feed-forward controller, which shows the relationship between the optimal feed-forward gain values and the corresponding pressure differences. This curve can be used to determine the appropriate feed-forward gain values during the actual operation of the valve based on the detected pressure difference at the valve port.

The method for obtaining the parameters of the feed-forward controller involves simulating within a pressure difference range of 0.5 MPa to 2 MPa. Different values of the feed-forward controller parameters are obtained through simulations in this range, resulting in the generation of a parameter curve of the feed-forward controller, as shown in fig. 3.

Figure 3 clearly shows the parameter values of each feed-forward controller. During the simulation process, the pressure difference of the main valve port can be detected in real-time. Based on different detected pressure differences, the controller parameters can be accurately determined. In this state, the step characteristics of the main valve displacement under different pressure differences are depicted in fig. 4. From this figure, it can be clearly seen that the displacement output of the main valve is basically consistent with the output value of the original valve response under PID control. This indicates that the valve performance meets the actual operation requirements of the flow valve.

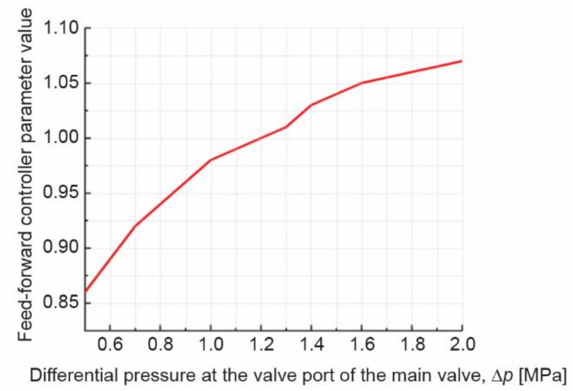

Figure 3. Parameter value curve of feed-forward controller

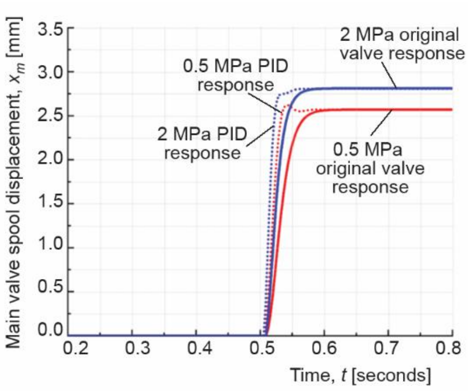

Figure 4. Step response of main valve under different pressure difference after parameter correction

Comparison of PID tuning methods

Tuning principles

Calculated PID gains with fine adjustments. The method of calculating PID gains with subsequent fine-tuning starts with an in-depth understanding of the system underlying principles. Initially, the PID gains are computed using mathematical models that are based on the physical characteristics of the controlled plant. For instance, in the case of the Valvistor valve, factors such as the valve size, mass, and the properties of the hydraulic fluid it operates with are considered. These models are often simplified to make the calculations tractable, but they still capture the essential dynamics of the system.

After obtaining the initial estimates, the real-world performance of the system is closely monitored. By observing the actual system responses to different inputs, such as step changes in the control signal, engineers can identify areas where the control performance can be improved. Fine adjustments are then made to the PID gains. This iterative process of comparing the theoretical and actual responses and making adjustments allows for a more accurate representation of the system behavior. It combines the theoretical rigor of mathematical modeling with the practical insights gained from real-world observations.

Ziegler-Nichols method. The Ziegler-Nichols method [16] offers two distinct approaches for tuning PID controllers. The first approach focuses on the ultimate gain and ultimate period of the system. To implement this, the gain of the proportional controller is gradually increased until the system starts to oscillate with a constant amplitude. The value of this gain is the ultimate gain, and the corresponding period of oscillation is the ultimate period. Empirical formulas are then used to calculate the PID parameters based on these values. This method is based on the assumption that the system behavior near the point of instability can provide valuable information for setting the controller parameters.

The second rule of the Ziegler-Nichols method is applicable when the process reaction curve of the system is known. The process reaction curve describes how the system output responds to a step change in the input. By analyzing the characteristics of this curve, such as the slope at the inflection point and the time delay, the PID parameters can be determined. This approach is useful for systems where the process dynamics can be approximated by a simple model represented by the reaction curve.

Accuracy and precision

Calculated PID gains with fine adjustments. While the initial estimates of the PID gains calculated from mathematical models may not be highly accurate due to the simplifications and assumptions made in the models, the subsequent fine-tuning process offers the potential for high-precision control. When the fine adjustments are based on a detailed analysis of the system performance, including factors like overshoot, settling time, and steady-state error, it is possible to achieve excellent control accuracy. For example, in the control of the Valvistor valve, by carefully observing the valve displacement response to different control signals and making incremental adjustments to the PID gains, the system can be tuned to meet strict performance requirements. This method allows for a high degree of customization based on the specific needs of the system.

Ziegler-Nichols method. The Ziegler-Nichols method provides a quick and convenient way to obtain initial PID settings. However, its reliance on empirical formulas means that the resulting PID gains may not always lead to the most optimal control performance. In complex or non-linear systems, the relationships between the system inputs and outputs are often more intricate than what the empirical formulas can account for. As a result, the control achieved using Ziegler-Nichols-tuned PID controllers may exhibit significant errors, such as larger overshoots or longer settling times. In such cases, additional tuning is usually required to improve the control precision.

Complexity and ease of use

Calculated PID gains with fine adjustments. The process of calculating the initial PID gains and then fine-tuning them is relatively complex. It demands a solid understanding of control theory, system dynamics, and the specific characteristics of the controlled system. For example, in the case of the Valvistor valve, engineers need to be familiar with hydraulic principles, the behavior of the valve under different loads, and the interaction between the valve and the control system. The fine-tuning process often involves a trial-and-error approach or a detailed analysis of system responses, which can be time-consuming. This complexity may limit its use in situations where quick solutions are required or where the expertise in control theory is limited.

Ziegler-Nichols method. In contrast, the Ziegler-Nichols method is relatively easy to use. It does not always require a detailed mathematical model of the system. For example, in some simple industrial processes, operators can use the Ziegler-Nichols rules to quickly obtain initial PID settings without a deep understanding of the system internal dynamics. This makes it accessible to a wide range of users, including those with limited control engineering knowledge. It can serve as a good starting point for getting a system up and running in a relatively stable state, especially in situations where time is of the essence.

Adaptability to different systems

Calculated PID gains with fine adjustments. This approach is highly adaptable to different types of systems. Since the fine-tuning process can be customized based on the specific characteristics of the system, it can effectively handle systems with non-linearities, time-varying parameters, and complex interactions. For example, in a hydraulic system with multiple Valvistor valves operating under varying loads and pressures, the PID gains can be adjusted to account for the unique behavior of each valve and the interactions between them. This flexibility allows for better control performance across a wide range of operating conditions.

Ziegler-Nichols method. The Ziegler-Nichols method is most effective for linear, time-invariant systems. In these systems, the relationships between the inputs and outputs are relatively straightforward, and the empirical formulas used in the method can accurately predict the optimal PID settings. However, for highly non-linear systems, where the behavior of the system changes non-linearly with the input, or time-varying systems, where the parameters of the system change over time, the Ziegler-Nichols method may not perform well. In systems with multiple inputs and outputs, the method also struggles to account for the complex interactions between the different variables, leading to sub-optimal control performance.

Conclusions

This paper conducts an in-depth study on the electronic closed-loop control characteristics of Valvistor valves, a type of proportionally enlarged valve, using the SIMULATIONX simulation platform. Through experimental measurements, theoretical analyses, model construction, parameter optimization, and comparison of multiple PID tuning methods, the following conclusions are drawn.

- The PID parameters are calculated by the genetic algorithm and fine-tuned, and the optimal parameters (k_p = 1.759, k_i = 7.8391, and k_d = 0.0098) for a 25 mm diameter Valvistor valve are determined. Compared with the original valve, the optimized PID control significantly improves the dynamic characteristics of the valve. In the step response of the main valve displacement, the rising response time is reduced by 45 ms, the descending response time is shortened by 20 ms, and there is almost no overshoot, meeting the requirements of precise and rapid control of valves in hydraulic systems.
- Considering the variable pressure differences at the valve port in actual working conditions, the parameters of the feed-forward controller are corrected. Through iterative simulations within the pressure difference range of 0.5-2 MPa, a parameter curve of the feed-forward controller is obtained. This curve can be used to determine appropriate feed-forward gain values based on the detected pressure difference at the valve port, ensuring that the valve displacement output can meet the actual operation requirements under different pressure conditions.
- The method of calculating PID gains with subsequent fine-tuning relies on mathematical models based on physical characteristics in the early stage, and the process is complex. However, after fine-tuning based on system performance, it can achieve high-precision control and has strong adaptability to different types of systems. The Ziegler-Nichols method is convenient for obtaining initial PID settings and is suitable for linear, time - invariant systems. However, for complex or non-linear systems, due to its reliance on empirical formulas, the control accuracy is poor, and additional tuning is often required.
- This research has certain limitations, such as the lack of physical experiment verification and the need to improve the universality of research results. In the future, physical experiments can be carried out to verify the research results, the research can be extended to the application of complex systems, and control algorithms can be further optimized to promote the performance improvement of Valvistor valves and the control accuracy of hydraulic systems.

In summary, this research provides theoretical support and practical guidance for optimizing the performance of Valvistor valves and improving the control accuracy of hydraulic systems. Future research can explore in-depth based on the existing deficiencies to contribute to the development of related fields.

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