

分类号:

学校代码:

密 级:

博士学位论文

(学 术 学 位)

测控融合电液比例方向流量阀 性能优化及控制机制

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研究方向: _____

指导教师: _____

论文提交日期: 2025 年 6 月

A Dissertation Submitted to
XXXXXXX University
In partial fulfillment of the requirement
For the degree of Doctor

**Performance Optimization and Control Mechanism of an Electro-
Hydraulic Proportional Directional Flow Valve with Measurement
and Control Integrated Strategy**

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College of Mechanical Engineering

June 2025

摘要

流体传动与控制技术广泛应用于航空航天、海洋工程、冶金、矿山、重型机械、核电站等重要领域。作为流体传动与控制系统的核心元件，电液比例阀通过电信号精确调控输出位移、流量和压力，其性能直接决定装备控制水平。当前我国在系统集成领域已取得显著进展，但在以高性能比例方向阀、伺服比例阀为代表的核心元件领域仍存在明显技术差距，严重制约了我国装备制造业的自主发展。随着工业 4.0 和智能化的深入推进，液压系统面临高效运行与精确控制的双重挑战。为了实现精确的执行器端控制，通常采用系统级闭环控制，这种控制方式严重依赖于大量的位置和速度传感器以及高精度的伺服比例阀，导致成本增加，在工作条件恶劣或预算有限的环境中，这种方法的适用性受到很大限制。而通过精确控制液压系统的流量，可以有效地控制执行器的位置和速度，而不需要位置或速度传感器，不仅降低了系统成本，而且在保持控制精度的同时增强了系统的环境适应性。另外，流量信息在液压系统的故障诊断和预测性维护中发挥着重要作用，为液压系统智能化升级提供关键技术路径。国家充分认识到这一问题的战略意义，《中国制造 2025》以智能化转型和绿色化升级为抓手，全面推进制造强国战略实施，通过工业强基工程夯实智能制造基础，《“十四五”规划纲要》进一步明确将高端化突破作为主攻方向，着力培育涵盖智能装备、绿色制造在内的战略性新兴产业，构建现代化产业体系。基于项目“（ ）和 项目“（ ）的资助，本学位论文聚焦测控融合电液比例方向流量阀的基础理论和技术创新，通过系统研究其性能成因与控制机制，构建具有自主知识产权的高性能比例流量控制元件研发体系，突破高压大流量精准控制与在线感知技术瓶颈，为实现无附加硬件的连续流量检测和控制提供理论支撑，为装备智能化升级和全生命周期管理奠定技术基础。

本学位论文创新提出测控融合电液比例方向流量阀，其创新性架构由集成式控制器、先导驱动单元、流量反馈型主阀及主动调控型流量传感器四个模块构成。在关键技术创新方面，首先设计了主阀上的动阀套反馈槽结构，实现主阀位移对先导阀位移的放大、主阀流量对先导阀流量的放大。其次创新研制了集成电磁铁主动调控单元的节流式流量传感器，突破传统流量检测在动态响应、压力损失与测量精度方面的技术瓶颈，并实现变流量增益调控功能。最终通过将流量传感器嵌入安装在先导阀与主阀之间，构建了具有测控融合功能的电液比例方向流量阀，实现了先导级流量的闭环精确控制与主阀流量的自适应精准放大，无需串联压力补偿阀，也无需附加压损的高成本流量计，仅用控制阀就实现了流量检测和控制的双重功能。

为验证上述理论创新,本研究采用多学科协同的研究方法:在建模分析层面,运用三维建模平台构建了阀体结构的参数化模型,并运用多学科联合仿真软件建立了涵盖机械、电气、液压、测量、控制的多学科联合仿真模型,系统揭示了阀的性能成因与级间耦合规律;在控制策略层面,创新提出了基于最少传感器配置的高精度位移/流量复合控制方法,针对位移开环控制模式设计了液动力、弹簧力补偿算法,针对流量控制模式开发了基于压差位移校正和基于主动调控流量的策略;在试验验证层面,加工试制出原理样阀并在液压阀试验平台上完成测试,系统验证了直动式先导阀、流量反馈型主阀的位移控制动静态特性,以及测控融合电液比例方向流量阀的流量控制特性及抗负载扰动能力。研究表明,设计的阀具有良好的动静态控制特性,在闭环控制下位移滞环为 0.13%,开环控制下位移滞环为 1.47%,具有冗余控制功能。0~100%阶跃响应时间为 28 ms (供油压力 7 MPa)。在流量控制方面,在不增设压力补偿阀的情况下实现了流量的高精度控制,在设计的三种流量控制策略下精度分别为 4%、8%、2%。

本学位论文基本结构如下:

第 1 章,介绍了国内外的比例方向阀研究进展、流量检测方法研究进展与流量控制方法研究进展,归纳总结现有技术存在的不足,提出解决问题的创新思想。

第 2 章,提出测控融合比例方向流量阀,介绍其构型和工作原理,建立数学模型分析其机理和关键参数对性能的影响。

第 3 章,在多学科联合仿真软件中建立“机-电-液-测-控”多学科联合仿真模型,通过仿真进行参数优化,确定阀的关键参数,并分析各参数对阀性能的影响,探究先导阀和主阀的级间耦合规律。

第 4 章,提出无/少传感器高精度位移控制策略,针对位移开环控制模式设计液动力和弹簧力补偿策略,以提高无位移传感器控制的精度,加工试制出原理样阀,在液压阀试验平台上分别对直动式先导阀、流量反馈型主阀的位移控制动静态特性进行验证。

第 5 章,提出无/少传感器高精度流量控制策略,设计基于压差位移校正和基于主动调控型流量传感器的流量控制策略,以提高无流量传感器的控制精度,加工试制出主动调控型流量传感器原理样机,安装在第 4 章的原理样阀上,构成测控融合电液比例方向流量阀,在液压阀试验平台上分别对直动式先导阀、测控融合电液比例方向流量阀的流量控制特性及抗负载扰动能力进行验证。

第 6 章,对本论文的研究工作进行了总结,给出了研究结论,指出了本论文的创新点,并对未来的研究工作进行展望。

关键词: 电液比例控制; 比例方向阀; 流量控制; 流量检测; 测控融合

ABSTRACT

Fluid transmission and control technology is extensively applied in critical domains such as aerospace, ocean engineering, metallurgy, mining, heavy machinery, and nuclear power plants. As the core component of fluid transmission and control systems, electro-hydraulic proportional valves accurately regulate output displacement, flow, and pressure via electrical signals, with their performance directly determining the control precision of equipment. Although China has achieved significant advancements in system integration, a notable technical gap remains in core components, particularly high-performance proportional directional valves and servo proportional valves. This gap severely hinders the independent development of China's equipment manufacturing industry. With the advancement of Industry 4.0 and intelligent technologies, hydraulic systems are confronted with dual challenges: efficient operation and precise control. To achieve accurate actuator control, system-level closed-loop control is frequently employed. However, this approach heavily relies on numerous position and speed sensors, as well as high-precision servo proportional valves, leading to increased costs. Moreover, its applicability is significantly constrained in harsh operating conditions or under limited budgets. By precisely controlling the flow within the hydraulic system, the position and speed of the actuator can be effectively managed without requiring position or speed sensors. This not only reduces system costs but also enhances the system's environmental adaptability while maintaining control accuracy. Additionally, flow information is critical for fault diagnosis and predictive maintenance in hydraulic systems, offering a key technical pathway for the intelligent upgrade of such systems. The government fully recognizes the strategic importance of this issue. With "Made in China 2025," the focus is on intelligent transformation and green upgrading as starting points to comprehensively promote the national strategy of becoming a manufacturing powerhouse. This includes strengthening the industrial base through projects that consolidate the foundation of intelligent manufacturing. Furthermore, the "14th Five-Year Plan" explicitly identifies high-end breakthroughs as the primary direction for advancement, aiming to cultivate strategic emerging industries, including smart equipment and green manufacturing, to construct a modern industrial system. Based on the support of the “ ” () and the “ ” (), this dissertation systematically investigates the fundamental theories and technological innovations of the electro-hydraulic proportional directional flow valve with

measurement and control integrated strategy. Through an in-depth analysis of their performance causes and control mechanisms, it establishes a high-performance proportional flow control component research and development system with independent intellectual property rights. This work overcomes the technical bottlenecks associated with high-pressure and large-flow precision control and online sensing, providing theoretical support for achieving continuous flow measurement and control without additional components. Furthermore, it lays the technical foundation for the upgrade of intelligent equipment and lifecycle management.

This dissertation innovatively introduces the electro-hydraulic proportional directional flow valve with measurement and control integrated strategy. Its novel architecture comprises four key modules: an integrated controller, a pilot drive unit, a main valve with flow feedback, and a flow sensor with active regulation. In terms of technological innovation, the feedback slot structure of the movable valve sleeve in the main valve is designed to achieve displacement amplification and flow amplification from the main valve to the pilot valve. Furthermore, an active control throttling flow sensor with integrated electromagnet has been developed. This advancement overcomes the technical limitations of traditional flow measurement in dynamic response, pressure loss, and measurement accuracy, enabling variable flow gain control functionality. Finally, by embedding the flow sensor between the pilot valve and the main valve, an electro-hydraulic proportional directional flow valve with measurement and control integrated strategy is constructed. This design enables closed-loop precise control of pilot flow and adaptive accurate amplification of main valve flow without requiring series pressure compensation valves or high-cost flowmeters that incur pressure losses. Thus, the dual functions of flow measurement and control are achieved using only the control valve.

In order to validate the aforementioned theoretical innovations, this study employs a multidisciplinary collaborative research approach. At the modeling and analysis stage, a parametric model of the valve structure was developed using the 3D modeling platform. Additionally, a multidisciplinary co-simulation model encompassing mechanical, electrical, hydraulic, measurement, and control systems was established through the multi-disciplinary co-simulation software. This approach systematically elucidates the factors influencing valve performance and the coupling mechanisms between stages. At the control strategy level, an innovative high-precision displacement/flow composite control method based on minimal sensor configuration was devised. For displacement open-loop control mode, compensation algorithms for flow force and spring force were designed. For flow control mode, pressure difference displacement correction and active flow control strategies were also developed. Finally, at the test validation stage, the prototype valve was fabricated and tested on a hydraulic

valve testing platform. The static and dynamic characteristics of displacement control for the direct-acting pilot valve and flow feedback main valve were comprehensively evaluated. Furthermore, the flow control characteristics and anti-load disturbance capabilities of the electro-hydraulic proportional directional flow valve with measurement and control integrated strategy were also validated. The results demonstrate that the designed valve exhibits excellent dynamic and static control characteristics. Under closed-loop control, the displacement hysteresis is 0.13%, while under open-loop control, it is 1.47%. Additionally, the valve possesses a redundant control function. The 0-100% step response time is 28 ms (with an oil supply pressure of 7 MPa). Regarding flow control, high-precision control is achieved without the need for an additional pressure compensation valve. The accuracy of the three designed flow control strategies is 4%, 8%, and 2%, respectively.

The basic structure of this dissertation is as follows:

Chapter 1 provides an overview of the research progress on proportional directional valves both domestically and internationally, reviews advancements in flow measurement and control methods, identifies the limitations of existing technologies, and proposes innovative solutions to address these challenges.

Chapter 2 introduces the concept of the proportional directional flow valve with measurement and control integrated strategy, detailing its configuration and working principle. A mathematical model is established to analyze its mechanism and the influence of key parameters on its performance.

Chapter 3 establishes a multidisciplinary joint simulation model of “mechanical, electrical, hydraulic, measurement, and control” using the multi-disciplinary co-simulation software. Through simulations, the critical parameters of the valve are optimized, the effects of each parameter on valve performance are analyzed, and the coupling law between the pilot valve and the main valve stages is explored.

Chapter 4 proposes a high-precision displacement control strategy with reduced-sensor or sensorless. A flow force and spring force compensation strategy is designed for the displacement open-loop control mode to enhance the precision of sensorless displacement control. The prototype valve is processed and trial-manufactured, and the dynamic and static characteristics of displacement control for the direct-acting pilot valve and the flow feedback main valve are validated on a hydraulic valve test platform.

Chapter 5 proposes a high-precision flow control strategy with reduced-sensor or sensorless. A flow control strategy based on pressure difference displacement correction and flow sensor with active regulation is designed to improve the accuracy of non-flow sensor

control. The prototype of the flow sensor with active regulation is processed and trial-manufactured, installed on the prototype valve from Chapter 4, forming an electro-hydraulic proportional directional flow valve with measurement and control integrated strategy. The flow control characteristics and anti-load disturbance capabilities of the direct-acting pilot valve and the electro-hydraulic proportional directional flow valve with measurement and control integrated strategy are validated on a hydraulic valve test platform.

Chapter 6 summarizes the research work conducted in this thesis, outlines the conclusions, highlights the innovations achieved, and discusses potential directions for future research.

Keywords: electro-hydraulic proportional control; proportional direction valve; flow control; flow measurement; integrated of measurement and control