

博士学位论文

DOCTORAL DISSERTATION

(学 术 学 位)

论文题目 数字化液压挖掘机单轴运动与多轴协调
控制研究

作者姓名

学科专业 流体传动与控制

指导教师

2025 年 6 月

中图分类号：

UDC：

学校代码：

密级：公开

学术学位博士学位论文

数字化液压挖掘机单轴运动与多轴协调控制 研究

博 士 研 究 生：

导 师：

申 请 学 位：工学博士

学 科 专 业：流体传动与控制

所 属 学 院：机械工程学院

答 辩 日 期：2025 年 5 月

授 予 学 位 单 位：

数字化液压挖掘机单轴运动与多轴协调控制研究

摘要：高精度铲斗齿尖轨迹控制是挖掘机智能化作业的基石。单轴精准运动与多轴高效协调构成了铲斗齿尖精准高效作业的核心要素。液压传动系统作为挖掘机的“骨骼与肌肉”，为执行器提供流量/功率分配，是实现单/多轴运动控制的关键保障。国产现有液压传动系统存在感知能力弱、节流损失大、精准控制难、多轴协调差难题，制约了挖掘机智能化发展。而液压执行器两腔压力/流量可独立调节的数字化电液系统，具有多维状态感知、控制精度高、动态响应快等优势，逐渐受到市场青睐，是挖掘机智能化的必由之路。本文从数字化电液系统中流量/功率分配核心元件多路阀原理设计与结构优化、感知与阀芯控制，电液系统单轴精准运动、多轴高效协调等方面开展理论与实验研究，提升液压挖掘机单/多轴控制精度，为挖掘机智能网联作业奠定基础。

（1）数字液压多路阀构型原理设计与结构优化。自主研发数字液压多路阀，提出全局结构优化方法。首先设计出节能、结构简单、多源状态感知且进出油口独立的新构型电液阀；其次，基于负载功率匹配将先导阀作为动力元件，主阀作为执行元件，通过最大功率输出点处主阀负载轨迹与先导阀输出特性曲线相切确定先导阀基础参数；然后，以匹配性能、线性度和控制灵敏度为优化目标，以不产生自激振荡为约束条件对先导阀结构参量进行自适应寻优；最后基于功率键合图理论建立包含减压阀、溢流阀、系统管路、容腔等结构特征的主阀闭环系统状态空间方程，采用一阶灵敏度方法揭示以上参量对主阀位置动态特性的影响规律并进行试验验证，为后续章节实现多路阀位置控制与电液系统组成奠定硬件基础。

（2）数字液压多路阀阀芯位移精准控制。多路阀常通过阀口匹配实现电液系统中多执行器所需流量/功率分配，阀芯位移精准控制是电液系统实现单/多轴控制的保障。首先将两级数字液压多路阀简化为带弹性负载的阀控对称缸模型并建立状态空间方程；然后，基于线性扩张状态观测器和扰动观测器实现系统中未测量状态与动力学未建模误差及扰动估计；此外，采用连续可微摩擦模型补偿系统中的非线性摩擦，减轻扰动观测器负担。进一步地，将上述获取的信息融入到采用反步法设计的双曲余弦型障碍李雅普诺夫函数控制器中，保证跟踪误差和所有状态误差的瞬态行为在期望范围内，利用李雅普诺夫理论分析闭环系统的稳定性，对比实验验证

所提控制器的优越性。为后续章节电液系统高性能控制奠定软件基础。

(3) 基于数字液压多路阀的电液系统单轴精准运动控制。单轴精准运动是多轴高效协调的基础，单轴精准运动的目标为实现对指令信号的精确跟踪，核心是对机电液耦合系统中的非线性、多关节耦合和未知扰动等进行补偿。首先，将强化学习执行神经网络-评价神经网络架构融入到挖掘机液压机械臂运动控制中，评价神经网络构造性能评价函数用于估计电液系统累计误差，通过最小化累积误差，评估系统控制性能，实时反馈给执行神经网络并激励其策略持续更新，执行神经网络对系统中未建模误差、未知扰动进行估计，提高对指令的跟踪精度；在此架构下，分别设计基于模型驱动与数据驱动的挖掘机液压机械臂单轴精准运动控制策略；进一步地，设计回油压力控制器用于降低系统能耗；最后，根据各执行机构所需流量解算出对应阀口开度，应用本文提出的位置控制策略实现阀口开度高精度跟随，实现电液系统单轴精准控制。

(4) 考虑电液系统性能约束的挖掘机多轴高效协调控制。多轴高效协调是实现铲斗齿尖运动的关键。针对挖掘机电液系统复杂工况时出现的恒功率、输出力超限和阀芯位移限制等因素，造成实际输出流量与齿尖规划轨迹需求流量不匹配进而造成多轴协调失衡降低作业效率的问题。首先，基于 5 次 B 样条和 NSGA-II 算法插值构造挖掘机铲斗齿尖用时最短-能耗能少-脉动小的最优轨迹，改善关节脉动对多轴协调的影响；其次，基于最优轨迹以速度场原理为核心设计铲斗齿尖速度矢量场；进一步地，建立液压系统中以功率约束、阀芯位移约束为核心的综合系统约束模型；然后，在铲斗齿尖所规划的速度矢量中加入动态调整权重，通过权重迭代求解出满足综合电液系统约束模型的铲斗齿尖速度，实时分解为不同执行器速度指令，应用本文单轴运动控制算法对速度指令进行精准跟踪，实现多轴高效协调。

(5) 液压挖掘机数字化改造与实验测试。对 1.6 吨挖掘机电液系统进行数字化改造，重新设计动力单元、数采系统、电气单元，多路阀为本文自主设计的数字液压多路阀，液压泵采用力士乐 SYDFE.-2X/71 型电比例泵，基于 dSPACE 控制器采用 MATLAB/SIMULINK 进行控制算法编译。对改造后的数字化电液系统进行挖掘机单轴精准运动与多轴高效协调试验，验证本文所提控制策略的优越性。

关键词：液压挖掘机；数字液压多路阀；电液系统；单轴运动控制；多轴协调控制
分类号：

Research on Single-Axis Motion and Multi-Axis Coordinated Control of Digital Hydraulic Excavators

Abstract: High-precision control of the bucket tooth tip trajectory is the cornerstone of intelligent excavator operations. Precise single-axis motion and efficient multi-axis coordination form the core elements of accurate and efficient bucket tooth tip operations. The hydraulic transmission system, acting as the ‘skeleton and muscles’ of the excavator, provides flow/power distribution for the actuators and is the key guarantee for achieving single-axis and multi-axis motion control. Existing domestic hydraulic transmission systems suffer from weak perception capabilities, significant throttling losses, difficulties in precise control, and poor multi-axis coordination, which restrict the intelligent development of excavators. In contrast, the digital electrohydraulic system with independent regulation of the two-chamber pressure/flow of the hydraulic actuator offers advantages such as multidimensional state perception, high control precision, and fast dynamic response. It is gradually gaining market favor and is the inevitable path for the intelligentization of excavators. This paper conducts theoretical and experimental research on several aspects of the digital electrohydraulic system, including the principle design and structural optimization of the multi-way valve, which is the core element for flow/power distribution, perception and spool control, single-axis precise motion, and multi-axis efficient coordination of the electrohydraulic system. The aim is to improve the control precision of single-axis and multi-axis operations in hydraulic excavators and lay the foundation for intelligent and connected excavator operations.

(1) Design and Structural Optimization of Digital Hydraulic Multiway Valve Configuration. We independently developed a digital hydraulic multiway valve and proposed a global structural optimization method. First, we designed a new type of electro-hydraulic valve that is energy-efficient, structurally simple, capable of multi-source state perception, and has independent inlet and outlet ports. Second, based on load power matching, the pilot valve was used as the power element and the main stage as the actuating element. The basic parameters of the pilot valve were determined by the tangency of the main stage load trajectory and the pilot valve output characteristic curve

at the maximum power output point. Third, with matching performance, linearity, and control sensitivity as optimization objectives, and without self-excited oscillation as a constraint condition, the structural parameters of the pilot valve were adaptively optimized. Finally, based on the power bond graph theory, a state-space equation of the main stage closed-loop system was established, which included structural features such as pressure-reducing valves, relief valves, system piping, and chambers. Using the first-order sensitivity method, the influence of these structural parameters on the dynamic characteristics of the main valve position was revealed and verified experimentally. This work lays the hardware foundation for the position control of the multiway valve and the composition of the electro-hydraulic system in the subsequent chapters.

(2) Precise Control of Spool Displacement in Digital Hydraulic Multiway Valves. Multiway valves typically achieve flow/power distribution required by multiple actuators in an electro-hydraulic system through orifice matching. Precise control of spool displacement is essential for realizing single/multi-axis control in electro-hydraulic systems. First, a two-stage digital hydraulic multiway valve is simplified into a valve-controlled symmetric cylinder model with an elastic load, and a state-space equation is established. Then, based on the linear extended state observer and disturbance observer, estimates are made of the unmeasured states and dynamic unmodeled error disturbances in the system. Additionally, a continuously differentiable friction model is employed to compensate for the nonlinear friction present in the system, thereby reducing the burden on the disturbance observer. Furthermore, the information obtained above is integrated into a hyperbolic cosine barrier Lyapunov function controller designed using the backstepping method. This ensures that the transient behavior of the tracking error and all state errors remains within the desired range. The stability of the closed-loop system is analyzed using Lyapunov theory, and comparative experiments are conducted to verify the superiority of the proposed controller. This work lays the software foundation for high-performance control of the electro-hydraulic system in the subsequent chapters.

(3) Single-Axis Precision Motion Control of Electrohydraulic Systems Based on Digital Hydraulic Multi-Way Valves. Single-axis precision motion is the foundation for

efficient multi-axis coordination. The objective of single-axis precision motion is to achieve precise tracking of command signals. The core of this process is to compensate for nonlinearities, multi-joint coupling, and unknown disturbances within the electromechanical-hydraulic coupled system. First, the reinforcement learning-based actor-critic neural network architecture is integrated into the motion control of the excavator's hydraulic manipulator. The critic neural network constructs a performance evaluation function to estimate the cumulative error of the electrohydraulic system. By minimizing the cumulative error, the control performance of the system is assessed, and real-time feedback is provided to the actor neural network to encourage continuous updates of its control strategy. The actor neural network estimates unmodeled errors and unknown disturbances within the system, thereby improving the tracking accuracy of the command signals. Under this architecture, single-axis precision motion control strategies for the excavator's hydraulic manipulator are designed based on both model-driven and data-driven approaches. Furthermore, a return oil pressure controller is designed to reduce system energy consumption. Finally, the corresponding valve orifice opening is calculated based on the flow required by each actuator, and the position control strategy proposed in this paper is applied to achieve high-precision following of the valve orifice opening, thereby realizing single-axis precision control of the electrohydraulic system.

(4) Efficient Multi-Axis Coordinated Control of Excavators Considering the Performance Constraints of Electrohydraulic Systems. Efficient multi-axis coordination is crucial for achieving the desired motion of the bucket tooth tip. When excavators operate under complex working conditions, factors such as constant power output, excessive output force, and spool displacement limitations in the electrohydraulic system can cause mismatches between the actual output flow and the required flow for the planned tooth tip trajectory. This mismatch leads to imbalances in multi-axis coordination and reduces operational efficiency. To address this issue, the following steps are taken: Firstly, based on the 5th-order B-spline and the NSGA-II algorithm, an optimal trajectory for the excavator bucket tooth tip is constructed through interpolation. This trajectory aims to achieve the shortest time, minimum energy consumption, and

minimal pulsation. By doing so, the impact of joint pulsation on multi-axis coordination is mitigated. Secondly, a velocity vector field for the bucket tooth tip is designed based on the optimal trajectory, with the velocity field principle as the core. This helps in better controlling the motion dynamics. Furthermore, a comprehensive system constraint model is established for the hydraulic system, focusing on power constraints and spool displacement constraints. This model ensures that the system operates within the desired performance limits. Then, dynamic adjustment weights are introduced into the planned velocity vector of the bucket tooth tip. Through iterative weight optimization, the velocity of the bucket tooth tip that satisfies the comprehensive electrohydraulic system constraint model is calculated in real time. This velocity is then decomposed into speed commands for different actuators. Finally, the single-axis motion control algorithm proposed in this paper is applied to accurately track these speed commands. This approach enables efficient and coordinated multi-axis control, thereby improving the overall operational efficiency of the excavator.

(5) Digital transformation and experimental test of hydraulic excavator. The 1.6-ton excavator electromechanical hydraulic system is digitally transformed, and the power unit, data collection system and electrical unit are redesigned. The multi-channel valve is the digital hydraulic multi-channel valve designed in this paper. The hydraulic pump adopts Rexroth SYDFE.-2X/71 electric proportional pump, and the control programming is carried out by MATLAB/SIMULINK based on dSPACE controller. The single-axis control and multi-axis coordination tests are carried out to verify the superiority of the control strategy proposed in this paper.

Keywords: Hydraulic excavator; Digital hydraulic multiway valve; Electrohydraulic system; Single axis motion control; Multiaxis coordination control

Classification: