# 博士学位论文

中文论文题目：双变量电静液作动器控制特性研究

英文论文题目：**Research on control characteristics of the bivariable electro-hydrostatic actuator**

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# 摘 要


电静液执行器（Electro-hydrostatic actuator，EHA）是一种高度集成电机、液压泵、作动筒、阀块等部件的泵控电液作动系统，具有高能效、高功率密度、即插即用、无管路、易维护等众多优点，在航空领域具有广阔的应用前景。然而，未来飞机的多电/全电化发展对 EHA 的功率密度、控制精度、控制鲁棒性、动态响应和能效均提出了更苛刻的要求。

传统 EHA 采用变转速电机带动定排量液压泵产生液压能来驱动作动筒。在低速重载工况下，电机效率低且发热严重，制约了 EHA 整体能效的提升。为了提高功率密度，EHA 普遍采用非对称单出杆作动筒。但是由于非对称单出杆作动筒的有杆腔与无杆腔的有效工作面积不相等，导致了作动筒的进出油液量不对称，即流量失配，增加了 EHA 的控制难度。针对以上问题，本文提出了一种结合三口泵控非对称作动筒技术和主动负载敏感技术的双变量 EHA 构型，同时开展了双变量 EHA 的高精度、高鲁棒和多目标优化控制方法研究。

<u>本文的主要研究内容总结如下</u>：

1. 双变量 EHA 原理及设计。针对高功率密度需求，本文利用三口柱塞泵驱动非对称单出杆作动筒，能够在不增加控制和制造难度的前提下，提高 EHA 功率密度，又不会带来流量失配问题，从根源上彻底规避目前非对称作动筒引起的流量失配难题。针对高动态与高能效的矛盾问题，本文采用柱塞泵的主动变排量构型，使 EHA 兼具高能效与高动态响应。具体地，主动变排量构型一方面可以提高 EHA 的动态响应，另一方面使电机功率与作动需求匹配，在低速大负载工况下大幅降低电机发热量。本文研制的双变量 EHA 样机功率密度为 0.27kW/kg，最大输出力为 12t，空载最大速度为 115.4mm/s，负载 8t 时的最大速度为 65.2mm/s，频响为 8.3Hz（5%行程）。

2. 高精度控制方法。EHA 是一种多部件强耦合的复杂高阶非线性系统，其非线性因素和电机转速死区的存在严重降低 EHA 的控制精度。针对强非线性问题，本文采用虚拟分解控制方法，将 EHA 虚拟分解为执行、油源和电机三个子系统。对每个子系统分别进行控制器设计，在降低控制器设计难度的同时提升了 EHA 控制精度。针对电机转速死区

问题，在大量试验的基础上总结了 EHA 在全工况下的非线性死区特性。提出了一种基于自适应补偿函数的死区优化控制方法，在实际的 EHA 平台上对该方法进行了验证。仿真和试验结果表明，虚拟分解控制与自适应补偿函数结合后，死区内的位移跟踪误差明显减小。

3. 高鲁棒控制方法。EHA 在实际运行中不可避免地会遇到各种扰动，包括匹配扰动（主要由内部模型不确定性引起，如流量冲击和油液弹性模量变化等）和失配扰动（主要由外部负载不确定性引起，如负载变化等）。复杂扰动会显著降低 EHA 的控制性能。针对上述问题，本文利用扩展状态观测器和非线性扰动观测器分别对匹配扰动和失配扰动进行估计。将所设计的观测器与虚拟分解控制相结合，提出了内外部扰动观测与补偿的 EHA 高鲁棒控制方法，并证明了所提出的控制方法和观测器的稳定性。基于仿真模型和 EHA 试验平台，对所提出控制器进行了系统的验证。所设计的两个观测器能够在 EHA 运行过程中准确估计匹配和失配扰动，通过将设计的观测器与虚拟分解控制方法相结合，可以大大提高 EHA 控制的鲁棒性。

4. 多目标优化控制方法。EHA 高动态和高能效之间相互矛盾，严重影响 EHA 的综合控制性能。基于双变量构型，对 EHA 的能效进行了分析，揭示了不同工况下能效随液压泵排量的变化规律。提出了基于深度确定性策略梯度算法的多目标优化控制方法用于主动变排量控制，实现了主动变排量机构的高动态响应，并有效降低了电机发热。不同测试工况下的仿真和试验结果表明，所研制的双变量 EHA 样机和基于深度确定性策略梯度算法的控制方法能够在保证控制精度和动态响应的前提下，有效降低电机发热。

**关键词：**电静液作动器；控制；虚拟分解；观测器；强化学习。

# ABSTRACT

The electro-hydraulic actuator (EHA) is a pump-controlled electro-hydraulic actuation system that integrates the motor, hydraulic pump, actuator, valve block, and other components. Its advantages include high energy efficiency, high power density, plug-and-play, no pipelines, and easy maintenance. EHA has broad application prospects in the aviation field. However, developing more electric/all-electric aircraft will place more stringent requirements on the power density, control accuracy, control robustness, dynamic response, and energy efficiency of EHA.

Traditional EHA uses a variable-speed motor to drive a fixed-displacement hydraulic pump to generate hydraulic energy to drive the actuator. Under low-speed and heavy-load conditions, the traditional EHA motor has low efficiency and severe heat generation, which restricts the energy efficiency improvement. In order to improve power density, EHA generally uses asymmetric single-rod actuators. However, since the practical working areas of the rod chamber and the rodless chamber are not equal, the amount of oil entering and exiting the asymmetric single rod actuator is asymmetric, that is, the flow mismatch, which increases the control difficulty of the EHA. In response to the above problems, this thesis proposes a bivariate EHA configuration that combines three-port pump-controlled non-pair cylinder technology and active load sensitive technology. Furthermore, research on high-precision, highly robust, and multi-objective optimization control methods of bivariable EHA is carried out.

The main research contents of this thesis are as follows:：

1. Principle and design of the bivariate EHA prototype is developed. In response to the demand for high power density, this thesis uses a three-port piston pump to drive an asymmetric single-rod cylinder, which can increase the power density of the EHA without increasing the difficulty of manufacturing and control, and without causing the flow mismatch problem. Using the three-port piston pump can completely solve the flow mismatch problem caused by the asymmetric single-rod cylinder. In response to the conflicting problem of high dynamics and high energy efficiency, this thesis adopts the active variable displacement configuration of the piston pump, so that the EHA has both high energy efficiency and high dynamic response. Specifically, the active variable displacement configuration can improve the dynamic response of the EHA and match the motor power with the actuation demand, significantly reducing the motor heat generation under low-speed and heavy-load conditions. The bivariate EHA prototype developed

in this thesis has a power density of 0.27 kW/kg, a maximum output force of 12 t, a maximum no-load speed of 115.4 mm/s, a maximum speed of 65.2 mm/s with a load of 8 t, and a frequency response of 8.3 Hz (5 % stroke).

2. High-precision control of the bivariable EHA is discussed. EHA is a complex high-order nonlinear system with strong coupling of multiple components. Its nonlinear factors and the existence of motor speed dead zone seriously reduce the control accuracy of EHA. In response to the strong nonlinear problem, this thesis adopts the virtual decomposition control method to virtually decompose the EHA into three subsystems: actuation, oil source, and motor. The controller is designed separately for each subsystem, which reduces the difficulty of controller design and improves the EHA control accuracy. In response to the problem of motor speed dead zone, the nonlinear dead zone characteristics of EHA under all working conditions were summarized based on a large number of experiments. A dead zone optimization control method based on adaptive compensation function is proposed, and the method is verified on the actual EHA platform. Simulation and experimental results show that after the virtual decomposition control is combined with the adaptive compensation function, the displacement tracking error in the dead zone is significantly reduced.

3. High robust control of the bivariable EHA is carried out. EHA will inevitably encounter various disturbances in actual operation, including matching disturbances (mainly caused by internal model parameter uncertainties, such as flow shocks and changes in oil elastic modulus.) and mismatch disturbances (mainly caused by external load uncertainties, such as load changes.). Complex disturbances will significantly reduce the control performance of EHA. In response to the above problems, this thesis uses the extended state observer and nonlinear disturbance observer to estimate the matching and mismatch disturbances, respectively. Combining the designed observers with the virtual decomposition controller, a highly robust EHA control method for internal and external disturbance compensation is proposed, and the stability of the proposed control method and observer is proved. Simulation and experimental test results show that the two designed observers can accurately estimate matching and mismatch disturbances during EHA operation. Combining the designed observer with the virtual decomposition control method can greatly improve the robustness of EHA control.

4. Multi-objective optimization control of the bivariable EHA is discussed. The dynamic response and energy efficiency of EHA are contradictory, which seriously affects the comprehensive control performance of EHA. Based on the bivariate configuration, the energy efficiency of the EHA is analyzed, and the changing pattern of energy efficiency with the pump

displacement under different operating conditions is revealed. A multi-objective optimization control method based on the deep deterministic policy gradient algorithm is proposed for active variable displacement control, which achieves a high dynamic response of the active variable displacement mechanism and effectively reduces motor heating. Simulation and experimental results under different test conditions show that the proposed multi-objective optimization control method can effectively reduce motor heating while ensuring the accuracy and dynamic response of bivariate EHA control.

**Keywords:** Electro-hydrostatic actuator; Control; Virtual decomposition; Observers; Reinforcement learning.

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