

分类号_____

学校代码_____

学号_____

密级_____

博士学位论文

(学术型☒ 专业型☐)

全海深自适应超高压平衡阀 损伤机理与抑制方法研究

学位申请人：

学科专业：

指导教师：

答辩日期：

**A Dissertation Submitted in Partial Fulfilment of The Requirements
for the Degree of Doctor of Philosophy in Engineering**

**Research on Damage Mechanism and Suppression Methods of
Adaptive Ultra-High-Pressure Balance Valve in Full Ocean
Depth**

Ph.D. Candidate :

Major :

Supervisor :

摘要

海水液压浮力调节系统直接以天然海水作为工作介质，具有结构简单、压力调节范围广、工作深度大等优点，是深海潜水器实现浮力调节、姿态控制的最佳工程方案。平衡阀是设置在海水泵与压载水舱之间的控制元件，通过构筑“压力坝”效应防止海水泵出现马达工况，决定着系统是否能够安全可控注水。然而，在全海深 11000 米环境下，该阀面临极端恶劣工况：阀口工作压差超过 120 MPa，海水流速超过 450 m/s，一旦密封失效，注水流量超 1000 L/min，潜水器会产生沉没的风险。针对上述挑战，本文提出深海压力自适应的平衡阀构型，围绕其阀口高强度碰撞形变、超高流速海水空化、超高硬度悬沙冲蚀三种损伤模式开展了理论和试验研究，并提出面向恶劣工况的损伤抑制和密封自愈方法，研究成果最终成功应用于“奋斗者”号全海深载人潜水器。主要研究内容和成果如下：

1) 全海深压力自适应平衡阀构型。针对全海深潜水器能源约束和超高压差高可靠密封要求，建立基于圆度误差的阀口密封模型，确定极限深度下阀口可靠密封所需最小密封力，为低功耗开启压力的设计提供了理论依据。提出利用海深压力为阀口提供可变密封力的平衡原理及平衡阀构型，实现全海深范围内密封力自适应调节。

2) 平衡阀口碰撞损伤机理和泄漏抑制方法。针对平衡阀口高强度碰撞后密封退化问题，建立平衡阀液固耦合动力学模型和阀口材料动态本构模型，揭示了阀口碰撞引发塑性变形导致密封接触应力下降，从而产生泄漏的退化机理。提出球阀+滑阀二级节流泄漏抑制方法，不增加开启功耗前提下，将密封接触应力提升 17%以上。

3) 随开度异构阀口空化规律及参数调控。针对阀口超高流速工况，分析了球阀+滑阀二级节流结构空化流动规律，该结构的节流效果随开度发生变化：小开度高压差下，滑阀节流产生背压抑制空化；大开度低压差下，滑阀完全开启提升通流能力。研究了滑阀关键节流参数对空化抑制和通流能力的影响，实现了参数与性能匹配。

4) 阀口超高流速含沙海水冲蚀特性及密封自愈方法。建立了冲蚀磨损率模型，揭示了冲蚀率、冲蚀宽度与阀口压差、悬沙浓度、粒径、阀座塑性变形量的定量关

博士学位论文

系。通过模拟真实工况冲蚀试验，发现了阀口损伤状态和密封性在降低阀口压差后可恢复的特征：高压差下工作受损阀口可通过降低压差产生的磨抛作用进行修复，降低泄漏量，基于此，提出不拆解平衡阀仅通过阀口压差调控实现密封自愈的方法。

5) 研制出平衡阀样机，通过陆地试验、全工况环境模拟试验和海试对其工作性能进行全方位测试。自交付至今，浮力调节平衡阀搭载于“奋斗者”号载人潜水器，已下潜 251 次，超过万米下潜 25 次，全程无故障。平衡阀的长服役周期可靠运行充分验证了上述理论成果的有效性。

本文的研究成果满足了国家重大装备的急需，对极端工况下水液压控制阀的研制具有重要的理论指导意义。

关键词：全海深载人潜水器；浮力调节系统；海水平衡阀；损伤机理；密封退化及抑制

Abstract

The seawater hydraulic buoyancy regulation system, using natural seawater as the working medium, offers advantages such as simple structure, wide pressure adjustment range, and deep operational depth, making it the optimal engineering solution for buoyancy control and attitude regulation in deep-sea submersibles. The balance valve is a critical control component installed between the seawater pump and ballast tank, preventing the pump from operating in motor mode by creating a "pressure dam" effect, ensuring safe and controlled water injection. However, under the extreme conditions of 11,000-meter full-ocean depth, the valve faces severe challenges: a pressure difference exceeding 120 MPa at the valve port and seawater velocity exceeding 450 m/s. Once seal failure occurs, the water injection flow rate exceeds 1,000 L/min, posing a risk of submersible sinking. To address these challenges, this paper proposes a deep-sea pressure-adaptive balance valve and conducts theoretical and experimental studies on three damage modes: high-intensity collision deformation, cavitation induced by ultra-high-velocity seawater, and erosion from ultra-hard suspended sand. Damage suppression and seal performance self-healing methods for harsh conditions are developed, with the results successfully applied to the full ocean depth manned submersible "Fendouzhe". The main research contents and results are as follows:

1) Full-Ocean-Depth Pressure-Adaptive Balance Valve Principle. To meet energy constraints and ultra-high-pressure sealing requirements, a seal force model based on roundness error is established to determine the minimum seal force required for reliable sealing performance at extreme depths, providing a theoretical basis for low opening power consumption design. A balance principle and valve structure are proposed, utilizing seawater pressure to adjust seal force dynamically, enabling adaptive seal force across full-ocean depths.

2) Collision Damage Mechanism and Leakage Suppression at Valve Port. For sealing performance degradation caused by high-intensity collisions, a fluid-structure interaction dynamic model and dynamic constitutive model for valve port materials are developed. A mechanism has been revealed that plastic deformation from collisions reduces sealing

contact stress, leading to leakage. A two-stage throttle (ball valve + slide valve) leakage suppression method is proposed, increasing contact stress by over 17% without additional opening power consumption.

3) Cavitation Behavior and Parameter Regulation of Valve Port with Configurational Changes Induced by Opening Degree. For ultra-high-velocity seawater conditions, the cavitation behavior of the two-stage throttle structure is analyzed. The throttling effect varies with valve opening: under small openings and high-pressure differences, the slide valve generates backpressure to suppress cavitation; under large openings and low-pressure differences, the slide valve fully opens to enhance flow capacity. Key slide parameters are optimized to balance cavitation suppression and flow performance.

4) Erosion Characteristics and Sealing Performance Self-Healing of Valve Port in Ultra-High-Velocity Sandy Seawater. An erosion wear rate model is established, quantifying relationships between erosion rate/width and pressure difference, suspended sand concentration, size, and valve seat plastic deformation. The erosion experiment reveals that seal performance can recover after reducing pressure difference due to abrasive polishing effects. A non-disassembled self-healing method is proposed by adjusting the pressure difference.

5) A balance valve prototype is developed and tested through land experiments, environmental simulation experiments, and marine experiments. Since deployment, the balance valve has operated flawlessly in 251 dives of the "Fendouzhe" submersible, including 25 over 10,000 meters. Its long-term reliability validates the effectiveness of the theoretical results.

This research addresses critical needs for major national equipment and provides theoretical guidance for developing water hydraulic control valves under extreme conditions.

Keywords: Full-ocean-depth manned submersible, Buoyancy regulation system, Seawater balance valve, Damage mechanism, Sealing performance degradation and suppression