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国产水下插拔光电复合连接器通过深海3000米级百次插拔试验

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摘 要:水下插拔连接器的性能与稳定性,是保障海底工程系统长期可靠运行与安全效能的关键。近年来,国内部分科研单位和企业虽已成功研制出相关原理样机,然而,由于缺乏高效、低成本、覆盖全生命周期的系统试验方法与专用装置,以及完善的海试验证体系,国产产品在市场竞争中仍面临认可度不足的挑战。本文以提升国产水下插拔光电复合连接器的可靠性为出发点,对自主研制的连接器样机开展了系统性测试,并成功研发一套适用于水下压力环境的自动接驳测试装置,实现了连接器的自动循环插拔。海试验证结果表明:自研连接器在2 960米水深条件下顺利完成100次连续插拔操作,其各项性能指标均满足相关国外标准的技术要求,达到国际先进水平。

关键词:水下插拔光电复合连接器;海底观测网;可靠性测试;自动接驳装置;深海试验;插拔寿命试验
中图分类号:P756 **文献标识码**: D **doi**:10.3788/gzxb20265503.0337001

水下插拔连接器是各类海底工程组网项目的关键部件[1]。当前,欧美国家在该领域技术成熟,产品体系完善,能够满足复杂海洋环境下的工程需求。相比之下,中国水下插拔连接器的研发起步较晚、基础薄弱,缺乏充分的环境性能测试及工程应用实践,导致该项技术成为制约我国工业发展的“卡脖子”技术之一[2]。在中国科学院和崂山国家实验室的联合资助下,吴国俊研究团队成功研制了具备4光2电接驳功能的6 000米级水下插拔光电复合连接器。研制过程中,先后突破了水下动密封、光纤低损耗准直耦合、微腔压力平衡及电偶冗余密封等多项核心技术,顺利完成了连接器样机的集成与装配调试。样机各项性能指标:适用水深≥ 6 000 m,光纤插入损耗≤ 0.5 dB @1 550 nm,平均插损≤ 0.35 dB @15 50 nm,光纤回波损耗≤ −30 dB@1 550 nm,电偶绝缘≥ 10 GΩ,接触电阻≤ 5 mΩ等均达到国际先进、国内领先水平。工程样机于2023年11月在南海海底观测网成功实现了国内首套水下插拔光电复合连接器在1 625米深的接驳应用,如图1所示。截至目前已实现连续无故障稳定运行超过两年,充分验证了其在深海环境下运行的长期有效性[3]。

由于深海环境的特殊性,如高压、腐蚀、高导电及生物附着等,对连接器的可靠性和耐久性提出了极高要求。当前,国内水下插拔连接器产品在投入工程应用之前,普遍缺乏系统性的环境模拟试验与充分的工程应用验证,难以实现全面、科学的性能评估与寿命预测。这一现状已成为制约国产水下插拔连接器技术成熟、市场认可度提升及规模化推广应用的关键瓶颈之一。

为了系统地验证水下插拔连接器在复杂环境中的可靠性,研究团队以国际通行的美国石油协会API STD 17F标准[4]以及挪威国家石油公司(Statoil)[5]发布的相关技术规范等为依据,对自主研发的水下插拔光电复合连接器持续开展了一系列涵盖环境适应性、机械力学性能、光学与电学性能的综合性试验。试验项目包括模拟压力环境下的动态循环接驳、高低温冲击、机械振动与冲击、跌落、耐电压测试、局部放电测试,以及充油尾缆拖拽等十余项内容。试验结果表明,连接器在各测试项目中的表现均满足相关标准与规范的要求,进一步验证了其在极端工况下的环境适应性与可靠性。

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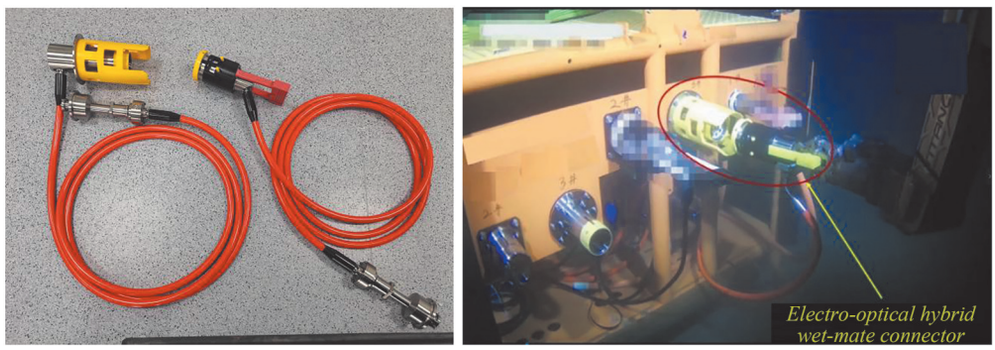


图1 水下插拔光电连接器样机及1 625米深海试

Fig.1 Prototype of an underwater electric-optical hybrid wet-mate connector and a deep-sea test at a depth of 1 625 meters

2025年，研究团队在南海某海域水深2 960余米处，利用自主研制的自动海试接驳装置及接驳盒系统，成功完成了水下插拔光电复合连接器100次循环插拔测试，如图2、3所示。试验过程中，所有光、电耦合功能均稳定正常，负载相机经由连接器供电后拍摄的验证视频，也通过连接器光纤通路实时回传至主控制舱内，如图4所示。此次试验首次实现了国产水下插拔连接器在3 000米级深度的成功接驳，更充分验证了光电复合连接器样机在极端深海环境下的接驳次数与可靠性。

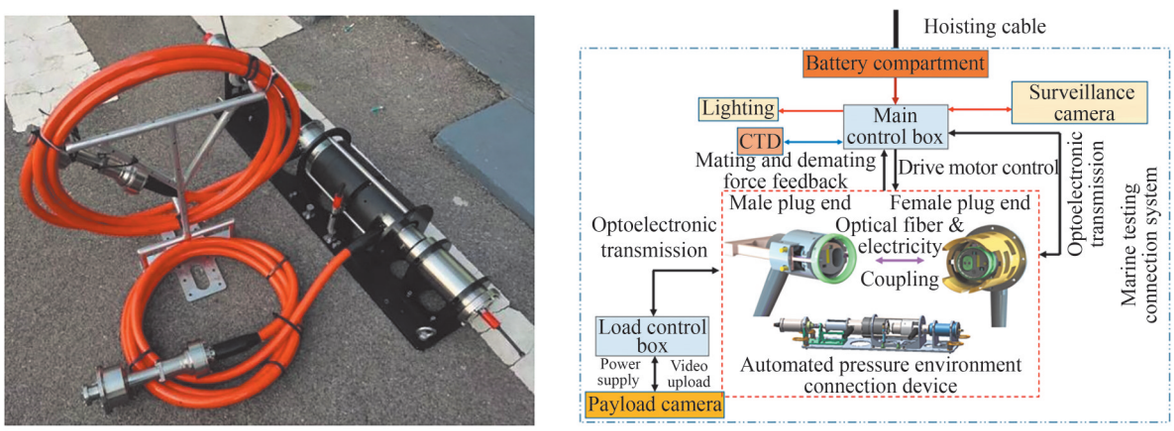


图2 自动接驳装置及海试接驳系统原理图

Fig.2 Schematic diagram of the automatic connection device and the sea-trial connection system



图3 水下插拔光电复合连接器南海接驳试验

Fig.3 Underwater mating and demating test of the electric-optical hybrid wet-mate connector in the South China Sea

海试结果显示，团队自主研发的水下插拔光电复合连接器在适用水深、光电传输性能、接驳寿命及长期运行稳定性等关键指标上，均达到与国际同类先进产品相当的水平，展现出较高的工程可靠性。这标志着我国已具备打破相关领域“卡脖子”技术垄断的技术基础。该连接器的成功研制，将为海底观测网、深海科学实验站以及深水油气资源开发系统等重大工程提供关键基础部件支撑，有望化解该类产品长期严重依赖进口的风险，并在一定程度上降低深海工程建设与运维成本，具有显著的社会经济效益与重要的战略意义。

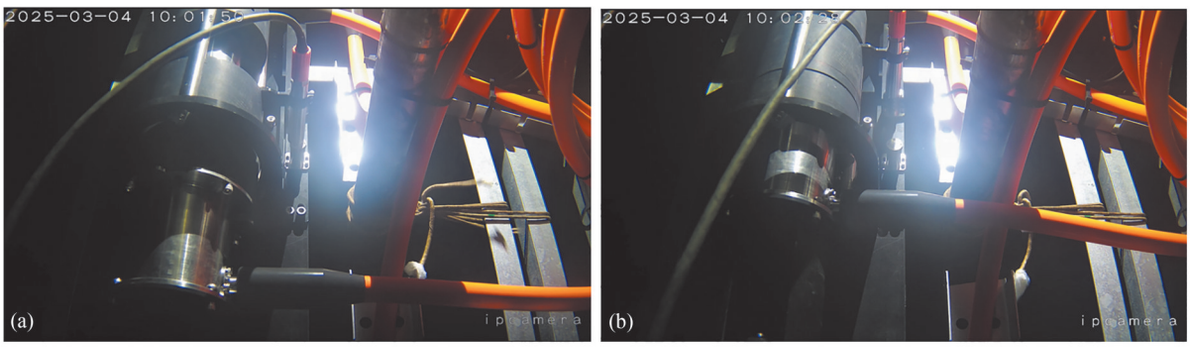


图4 监控相机记录2 960米深海百次接驳试验。(a)分离状态；(b)对接状态

Fig.4 Surveillance cameras documented the 100th docking test conducted at a depth of 2 960 meters in the deep sea. (a) Disconnected state; (b) Mating state

参考文献

[1] HOWE B, DUENNEBIER F, LUKAS R. The ALOHA cabled observatory[M]. SEAFLOOR OBSERVATORIES A new vision of the Earth from the Abyss, Heidelberg: Springer Berlin, 2015.

[2] XU H, LIU H, LI Q, et al. Structural and sealing health monitoring of subsea watertight connectors using embedded fiber Bragg grating sensors[J]. Measurement, 2025: 119367.

[3] ZHAO L, WU G, YAN Z, et al. Current status and trends of wet-mate connectors[J]. Intelligent Marine Technology and Systems, 2025, 3(1):4.

[4] API. Specification for subsea production control systems: API STD 17F [S]. 3rd ed. Washington: API, 2014.

[5] Statoil. Electrical and optical connector specification: TR2390 [S]. Stavanger: Statoil, 2007.

The Domestically Manufactured underwater Electro-optical Hybrid Wet-mate Connector has Successfully Completed the 100-cycle Mating and Demating Test at a Depth of 3,000 Meters in the Deep Sea Class

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Abstract: The performance and stability of underwater wet-mate connectors are of great significance for guaranteeing the long - term reliable operation and safety of subsea engineering systems. In recent years, while some domestic research institutions and enterprises have successfully developed prototype models based on relevant principles, domestic products still face the challenge of insufficient market recognition in the competition. This is due to the lack of efficient, low-cost, and full-life-cycle system testing methods, dedicated equipment, and a comprehensive sea-trial verification system. This paper commences from the perspective of enhancing the reliability of domestically-produced underwater electric-optical hybrid wet-mate connectors. A systematic series of tests were carried out on the self-developed connector prototypes, and a set of automatic connecting test devices suitable for underwater pressure environments was successfully developed, enabling automatic cyclic mating and demating operations of the connectors. The outcomes of sea trials indicate that the self-developed connectors successfully accomplished 100 consecutive mating and demating operations at a water depth of 2 960 meters, and all performance indicators met the technical requirements of relevant foreign standards, attaining an international advanced level.

Key words: Underwater electric-optical hybrid wet-mate connectors; Seafloor observation networks; Reliability testing; Automatic docking devices; Deep-sea trials; Mating and demating life testing

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