

# 从“制动”到“智动” ——数智化浪潮下列车制动技术创新初探

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数智化(Digital Intelligence)是指通过数字技术和智能算法的结合,实现数据收集、分析和应用,从而提升系统运行效率和智能化水平。数智化不仅是数字化的延伸,更是与智能化的融合。

加速和减速、启动和制动——这对矛盾的统一,构成了列车安全高速运行的复杂动态系统。列车制动的本质是将列车运行的巨大动能在一定时间内转化为其他能量并进行回收或耗散,其核心是实现运行列车的安全、平稳与精准停车。安全是制动的第一要义。

列车制动的科学属性是非结构环境与时变约束条件下的力-能作用,特征是机电/液耦合的复杂分布式控制系统。列车制动技术的演进具有显著的强继承性,这一继承性保证了制动技术的延续与迭代,但在某种意义上也制约了制动技术的革新。当前,数智化技术的发展正在改变甚至颠覆传统工业领域,列车制动技术的创新也应与之相适应。作者结合多年的工作与科研实践,提出制动技术创新所面临的三个转变及其引发的思考,与同行研讨。

首先,制动技术的创新体现在从“列车的制动”转变为“制动的列车”。通常,制动系统的研制先是通过整车对制动进行顶层指标分解,然后是技术路线的选择与方案论证,再是制动系统指标的试验与验证。因此,列车的制动强调的是制动系统对设定条件下整车顶层指标的可达性与维持性,强调的是设定条件下或依据标准的制动技术适应性,关注的是设定条件下指标实现的“安全域”问题,对非预见性工况或条件无法强制要求;而制动的列车需要考虑制动过程中环境变化等各种干扰对预期制动目标实现的影响,关注的是制动过程全部行为与影响的“安全裕”问题,对制动系统提出了更高的要求,比如恶劣条件下的可控性、制动过程的平稳性、干扰影响下的一致性、故障和性能衰退下的能力保持等。因此,从制动的列车角度思考有利于构建更加完善、更具创新意义的制动系统。

其次,制动技术的创新体现在从“公式计算范式”向“数据驱动范式”转变。科学研究旨在探寻客观世界的本质规律,而认识规律的方法与手段称之为科研范式。科研范式大致经历了经验范式、公式范式、计算范式等三个发展阶段。当前,传统基于理论假设和简化模型的研究方法已面临诸多挑战——如解析方程的合理性、公式修正的准确性、计算方法的泛化性以及验证困难等。因此,在能够获取大量数据的条件下,可以转向数据驱动的科学方法,以应对更为复杂的实际问题——如空气制动系统的非线性模型、轮轨黏着模型、防滑控制模型、制动(部件)劣化机理和性能衰退模型、制动故障容错模型等。数据驱动研究方法可以不受限于理论公式的解析与计算,通过获取实际运行的大量数据并进行处理与训练,可以得到实时处理的算法以完成性能预测与系统控制。

第三,制动技术的创新体现在从“实物试验”向“虚拟验证”转变。长期以来,制动技术的开发与创新依赖于大量的实物型式试验。实物试验不仅需要搭建复杂的试验台,还需要投入大量的时间和高昂的成本,而且在某些情况下难以模拟复杂或极端的工况条件。当前,随着仿真计算能力的大幅提升、物理数学模型和数字模型的不断改善,基于仿真的虚拟验证方法应运而生。虚拟验证的优势在于通过构建数字化模型,利用仿真进行系统功能与性能的模拟、测试与验证,进而实现优化。这样做,突破了传统方法的限制,避免了大量重复性实物试验,节省了测试成本,从而实现设计验证由串行向并行、长周期向短周期调整。需要说明的是,虚拟验证并不意味着基于完全的仿真模拟,硬件在环测试在一定程度上可以保证结果的可靠性,对于典型的代表性的工况仍然需要实物试验。因此基于虚拟验证与实物验证的混合式集成验证应是未来发展的主要方向。

综上所述,列车制动技术从功能上可以划分为本源技术和支撑技术,其中,本源技术主要包括制动系统架构技术、黏着利用与非黏技术、摩擦副技术、制动控制技术;支撑技术主要包括设计分析工具技术、试验验证技术、维护检修技术等。

在本源技术方面,随着列车运行速度的提升、高密度运行需求的增加、恶劣环境适应性要求的提高、列车形态的不断演进,以及信号-牵引-制动功能的不断融合、电/液驱动的机械制动(EMB/HMB)方式出现等,制动系统的架构技术将会被重新定义。非黏与多轮轴黏着管理、低排放新型摩擦副、制动智能控制也将匹配发展。在支撑技术方面,基于参数交互的设计工具链和工具集、基于虚拟与实物相结合的验证技术、面向全生命周期的智能运维等是主要的创新发展方向。

数智化浪潮下的列车制动技术正迎来从“制动”到“智动”的变化,其内涵也由“安全域”向“安全裕”拓展。随着数字技术、人工智能等新兴技术的快速推进,列车制动技术的创新将不断涌现与突破,将为轨道交通装备行业的发展提供更强有力的支撑。

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**From 'Classic Train Braking' to 'Intelligent Train Braking'**  
**—An Initial Exploration of Train Braking Technology Innovation**  
**under the Wave of Digital Intelligence**

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Digital intelligence refers to the integration of digital technologies and intelligent algorithms to enable the collection, analysis, and application of data, thereby enhancing system operational efficiency and intelligence level. Digital intelligence is not merely an extension of digitization but a deep fusion with intelligentization.

Acceleration and deceleration, traction and braking—the unity of these opposing forces forms the complex dynamic systems that enable safe and high-speed operation of the trains. The essence of train braking lies in converting the enormous kinetic energy of a moving train into other forms of energy and recycling or dissipating it within certain time. The core objective is to ensure safe, smooth, and precise stopping of the train. Safety is the fundamental principle of braking.

The scientific nature of train braking lies in the force-energy interaction under non-structured environments and time-varying constraints, characterized by a complex distributional control system involving electromechanical and hydraulic coupling. The evolution of train braking technology exhibits strong continuity, which ensures its development and iteration but also, to some extent, limits its own revolutionary possibilities. Today, the development of digital intelligence technology is changing and even re-structuring traditional industries, and the innovation of train braking technology should align with these changes. Drawing on years of work and research experience, the author outlines three key shifts faced by braking technology innovation and the reflections they provoke, for peer discussions.

Firstly, the innovation in braking technology is reflected in the transition from 'train braking' to 'braking-centered train'. Typically, the development of braking systems starts with the top-level decomposition of vehicle braking specifications, followed by the selection of technical routes and the validation of plans, and then testing and verification of system specifications. Therefore, the focus of 'train braking' is on the accessibility and maintenance of top-level specifications under set conditions, emphasizing the adaptability of braking technology under these conditions or according to standards. It concerns the 'safety domain' of meeting specifications under set conditions and does not impose strict requirements for unforeseen operational conditions. In contrast, 'braking-centered train' considers the impact of environmental variations and external disturbances on the delivery of expected braking performance, focusing on the 'safety margin' for the entire braking process and its influences, placing higher demands on the braking system, such as controllability under adverse weather conditions, smoothness throughout braking process, consistency despite external disturbances, capacity retention in faulty mode or performance degradation. As a result, thinking from the 'braking-centered train' perspective is more conducive to constructing comprehensive and innovative braking systems.

Secondly, the innovation in braking technology is reflected in the shift from 'formulaic calculation paradigm' to 'data-driven paradigm'. Scientific research seeks to uncover fundamental laws of the objective world, and the methodologies for recognizing these laws are called research paradigms. Research paradigms have gone through three development stages: empirical, formulaic, and computational paradigms. Currently, traditional research methods based on theoretical hypothesis and simplified models face numerous challenges such as the rationality of analytical equations, the accuracy of formula adjustments, the generalization of computational methods, and difficulties in verification. Therefore, with the ability to access vast amounts of data, research can shift to a data-driven approach to address more complex real-world issues, such as nonlinear models of air braking systems, wheel-rail adhesion models, anti-skid control models, brake (component) deterioration mechanisms and performance degradation models, braking fault-tolerant models. Data-driven approach is not bounded by analysis and calculation of theoretical formulas, but instead utilizes the large amount of actual operational data for processing and training to develop real-time algorithms for performance prediction and system control.

Thirdly, the innovation in braking technology is reflected in the transition from 'physical testing' to 'virtual verification'. For a long time, the development and innovation of braking technology have depended on numerous physical prototype tests. These tests not only require the construction of complex testing setups but also demand significant time investment and high costs. In some cases, it is difficult to replicate extreme or intricate working conditions in simulation. Nowadays, with drastic advancements in simulation computational capabilities and continuously improving accuracy of physical-mathematical and digital models, simulation-based virtual verification method emerges to fulfill the expectations. Virtual verification has advantages in constructing digital models, car-

rying out simulation, testing, and validation of braking system functions and performance for enhancement. This breaks the constraints in conventional methods, avoiding massive amount of repetitive physical tests, saving testing costs, adjusting the verification design from sequential to parallel process and long to short development cycle. It is important to note that virtual verification does not point to a complete simulation. With advancements in hardware-in-the-loop (HIL) testing, hardware can play a crucial role in ensuring result reliability to certain extent. For representative and critical scenarios, physical testing remains essential. The hybrid approach integrating both virtual and physical verification will likely become the main direction for future development.

In summary, train braking technology can be categorized into 'core technologies' and 'supporting technologies' from functional perspective. Core technologies include system architecture, adhesion utilization and non-adhesion, friction pair, and braking control. Supporting technologies encompass design analysis tools, testing and verification techniques, and maintenance strategies.

In terms of core technology, with the increasing train operating speeds, higher requirements on high-density operations, adaptability to harsher environmental conditions, evolution of train forms, deep fusion of signaling-traction-braking functions, and electric/hydraulic-driven mechanical braking systems (EMB/HMB), braking system architecture technologies will be redefined. Non-adhesion and multi-axle adhesion management, low-emission friction pairs, and intelligent braking control will also develop in parallel. In terms of supporting technology, design toolchains and toolsets based on interactive parameters, hybrid virtual-physical verification methodologies, and intelligent operation and maintenance technologies for the entire lifecycle are the main innovative development directions.

The wave of digital intelligence is ushering the transition from 'classic train braking' to 'intelligent train braking' for train braking technology, expanding its connotations from 'safety domain' to 'safety margin'. As emerging technologies such as digital technologies and artificial intelligence continue to advance rapidly, innovative breakthroughs in train braking technology will keep springing, providing strong support for the development of the rail transit equipment industry.

(This article is an abstract of the author's presentation at the 'New Trends in Rail Transit Braking Technology Forum' in Nanjing on January 18, 2025.)

Translated by ZHANG Liman

## 苏州北站综合枢纽开工建设

2025 年 2 月 24 日,国家级综合交通枢纽苏州北站综合枢纽工程在苏州市相城区开工,标志着苏州市建城史上投资最大的交通枢纽项目正式迈入建设阶段。省委常委、苏州市委书记刘小涛宣布开工,副省长夏心旻出席开工仪式并讲话。中国铁路上海局集团有限公司总经理赵丽建,沪杭铁路客运专线公司董事长张利国,省政府副秘书长崔巍,省交通运输厅厅长吴永宏,苏州市委副书记、市长吴庆文,省铁路集团董事长丁建奇等出席。

夏心旻在讲话时表示,苏州北站综合枢纽开工是江苏推动交通强省建设、服务长三角一体化发展的有力举措,标志着苏州建设“全国性综合交通枢纽城市”迈出坚实一步。希望苏州市及全体参建单位以“走在前、做示范”的责任担当,坚持安全为先、质量为本、创新为要,将项目打造成为智慧枢纽新标杆、产城融合新引擎。同时,要把握国家和省里增量政策加力支持的机遇,加快建设北沿江、通苏嘉甬高铁等重大项目,抓紧推进如通苏湖、水乡旅游线等项目前期工作,全力以赴扩大交通建设有效投资,为全省持续巩固和增强经济回升向好态势作出更大贡献。

苏州北站综合枢纽建设涵盖高铁苏州北站铁路站房工程及高铁苏州北站改扩建配套工程两大核心项目。此次扩容提升后的苏州北站总站线规模将达 10 台 24 线,新建站房建筑规模约达 17 万  $\text{m}^2$ ,站场能级与城市门户形象实现“双跃升”。高铁苏州北站改扩建配套工程包括落客快速联络道工程、快速联络道东连接线工程、站房改扩建配套设施工程等 7 个子项,各子项目将分期分批实施,确保建设时序与城市发展需求精准匹配。苏州北站综合枢纽作为国家高铁“八纵八横”大动脉京沪线和通苏嘉甬高铁的十字交汇处,不仅是虹桥国际开放枢纽北向拓展带向外辐射的桥头堡,更是苏州城市发展的新引擎。苏州北站综合枢纽以“国家级综合交通枢纽”为定位,按照“站城融合、产城融合、环境融合、文旅融合”的建设目标,积极打造集高速铁路、城际铁路、市域铁路及城市轨道交通“四网融合”于一体的综合交通枢纽。作为长三角一体化的重要节点,苏州北站综合枢纽被赋予“协同上海虹桥建设国际开放枢纽”的战略使命。苏州北站综合枢纽将依托虹桥国际开放枢纽北向拓展带,推动苏沪两地产业链、创新链深度融合,共同构建服务长三角、助力长三角的交通与经济“双引擎”。

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