

碳纤维地铁列车的商用将开启轨道车辆用材的新时代

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2024年6月26日,中车青岛四方机车车辆股份有限公司(以下简称“中车四方股份公司”)联合青岛地铁集团宣布,为青岛地铁1号线研制的碳纤维地铁列车“CETROVO 1.0 碳星快轨”将于年内在青岛地铁1号线投入运营。这是全球首列用于商业化运营的碳纤维地铁列车,是运载工具应用新材料的里程碑,它将促进轨道交通车辆制造业的升级换代。

车辆技术的代际更替,主要受新能源和新材料的“双轮”驱动。

回顾车辆能源利用的技术进步史:在石器、青铜器与铁器时代,车辆的能源主要来自畜力和人力;在蒸汽时代,车辆的能源主要来自蒸汽机,在铁路上的应用范例就是蒸汽机车;在电力时代,车辆的能源主要来自电动机和内燃机,在铁路上的应用样板就是电力机车和内燃机车。

再看制造车体所用材料的技术进步历程:在古代,车辆主要用木材制作,中国在商代早期已使用木制双轮车,东汉和三国时期出现了木制独轮车;近现代的轨道交通车辆广泛使用金属材料,特别是钢材,利用钢材使车体强度大大提高,钢材强度通常比木材强度高出2~3倍;如今,制造车体所用的材料已从原木材料、金属材料,进入到复合材料的新时代。

复合材料是指利用两种或两种以上物理、化学性能不同的物质组合而成的材料。现代复合材料的典型案例是在第二次世界大战中出现的玻璃钢,它被美国空军用于制造飞机的构件。复合材料主要由基体和增强体两部分组成。基体是起粘合作用的材料,用于粘结增强体并传递载荷到增强体,主要有树脂基、金属基、玻璃基、碳基等。增强体是承受载荷的材料,其形状可以是纤维、颗粒、片状或其他形状。现在主要的增强体都是纤维状的,有玻璃纤维、碳纤维和陶瓷纤维等。

中车四方股份公司研制成功的碳纤维车辆的车体及转向架由新型碳纤维复合材料制作,其强度更高,通常是钢材的5倍以上。与采用传统金属材料相比,碳纤维转向架构架部件具有更强的抗冲击能力,耐疲劳性能更优,车辆更轻,而且其结构使用寿命更长。

载运工具自重减轻是一项重大的技术进展。20年来,我国轨道交通车辆大力推进轻量化,车体主要材料经历了从普通钢、不锈钢、铝合金到碳纤维复合材料的更新。通常铝合金车体比不锈钢车体可减重0.5~1.0 t/辆,而碳纤维车辆则可比铝合金车辆减重3~4 t/辆。铝合金车辆通常只是用铝合金替换车体的不锈钢或普通钢,而碳纤维车辆不仅用碳纤维复合材料替换车体的材料,而且替换了转向架构架等主承载结构的材料。与传统金属材料(钢、铝合金)的地铁车辆相比,碳纤维地铁车辆的车体减重25%,转向架构架减重50%,整车减重约11%,减重后的运行能耗可降低7%。由于该车的牵引系统采用了新型高效节能的碳化硅逆变器和永磁同步牵引电机,与传统地铁车辆相比,整车综合节能15%以上。

此外,由于采用了先进的主动径向技术,这款车型的轮轨磨损和噪声大幅度降低,车辆和轨道的维护量显著减少。加上应用了新型隔声降噪材料和设备,使客室噪声可降低5 dB以上。

从这款车型的制造和运维成本看,中车四方股份公司搭建了全链条研发、制造、验证平台,形成了从碳纤维结构设计研发到成型制造、仿真、试验、质量保障等成套工程化能力,可提供全寿命周期一站式解决方案。通过应用数字孪生技术,打造碳纤维列车SmartCare智能运维平台,实现了整车安全、结构健康及运用性能的自检测与自诊断,提高了运维效率,降低了运维成本。列车全寿命周期检修成本可降低22%。

碳纤维复合材料代表着未来轨道车辆轻量化技术的发展方向。商用碳纤维地铁列车的问世和投入运营,将有力推进地铁车辆主承载结构由钢、铝合金等传统金属材料向碳纤维复合材料转变,这消除了传统金属材料结构减重的瓶颈,实现了我国地铁列车轻量化技术的全新升级,将为推动我国城市轨道交通绿色低碳转型发挥重要作用。

表 1 车地综合感知系统测试结果对比表

Tab.1 Comparison of test results for vehicle-ground integrated sensing system

指标项	纵向检测 范围/m	横向检测 范围/m	有轨电车检 测距离/m	行人检测 距离/m	小障碍物检 测距离/m	响应时间/ s	误(漏)识 别率/%	列车定位 精度	路口行人 检测率/%	V2X 通信 距离/m
预期值	5 ~ 300	3 ~ 5	280	200	100	0.33	<0.1	厘米级	90	300
实际测试值	5 ~ 350	3 ~ 5	350	250	100	0.30	<0.1	厘米级	95	600
团标参考值			280	200	100	0.33	<0.1			

种传感器及 V2X 通信技术,能够实时监测有轨电车内部各部件的运行状态、感知轨道及有轨电车运行环境障碍物、远距离获取地面路口信息,然后通过综合各模块数据执行决策,保障有轨电车安全运行。同时,该系统通过 V2X 通信技术,实现了有轨电车与其他有轨电车以及地面控制系统的实时信息交换,有效提高了线路运营效率。

试验数据表明,苏州高新有轨电车车地感知综合系统具备良好的性能和系统稳定性。后续还需对复杂光照、恶劣天气环境下的系统性能做进一步的优化研究。

车地综合感知系统在苏州高新有轨电车的应用实践证明,该系统能够提升有轨电车运营的安全性及运营效率。本文的研究也丰富了现代有轨电车车地综合感知系统的设计理念,为进一步实现有轨电车无人驾驶技术提供了重要参考。

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Commercial Use of Carbon Fiber Metro Trains Opening A New Era of Rail Vehicle Materials

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On June 26, 2024, CRRC Qingdao Sifang Co., Ltd. (hereinafter referred to as CRRC Sifang) and Qingdao Metro Group

Co., Ltd. jointly announced that the carbon fiber metro train "CETROVO 1.0 Carbon Star Express Rail" developed for Qingdao Metro Line 1, would be put into operation on Qingdao Metro Line 1 within the year. This is the world's first carbon fiber metro train for commercial operation, marking a milestone in the application of new materials in vehicles, which will promote the upgrading of rail transit vehicle manufacturing industry.

The generational replacement of vehicle technology is mainly driven by the two wheels of new energy and new materials.

In retrospect, the history of technological progress in utilization of vehicle energy is as follows. In the Stone Age, Bronze Age and Iron Age, the vehicle energy mainly came from animal power and manpower. In the Age of Steam, it was from the steam engine, and the steam locomotive was the application example in the railway. In the Age of Electricity, the vehicle energy mainly came from electric motors and internal combustion engines, and electric locomotives and diesel locomotives were the application models in the railway.

As for the technological progress of the materials used in the manufacture of car bodies, in ancient times, vehicles were mainly made of wood. Wooden two-wheelers were already used in China in the early Shang Dynasty, and wooden unicycles appeared in the periods of Eastern Han and Three Kingdoms. Modern rail transit vehicles widely use metal materials, especially steel, which greatly improves the strength of the car body as steel strength is usually 2 to 3 times higher than that of wood. Nowadays, the materials used for car bodies have entered into a new era of composite materials from log and metal materials.

Composite materials refer to the combinations of two or more substances with different physical and chemical properties. A typical example of a modern composite material is GFRP (Glass Fiber Reinforced Plastic), which emerged in World War II and was used by the US Air Force to make components for aircraft. Composite materials are mainly composed of two parts: matrix and reinforcement. Matrix is a bonding material, mainly including resin base, metal base, glass base, carbon base and so on, used to bond the reinforcement and transfer the load to the reinforcement. Reinforcement, maybe in the shape of a fiber, particle, sheet or others, is the material that bears the load. Now the main reinforcement is fibrous, such as glass fiber, carbon fiber and ceramic fiber.

The car body and bogie of the carbon fiber vehicle developed by CRRC Sifang are made of a new type of carbon fiber composite material with higher strength, usually more than five times that of steel. Compared with the traditional metal-material components, the carbon fiber bogie frame components have stronger impact resistance, better fatigue resistance, lighter vehicle and longer structural service life.

The vehicle self-weight reduction is an important technical progress. The past two decades witnessed vigorous promotion of lightweight in China's rail transit vehicles, and the updating of the car body main materials from ordinary steel, stainless steel, aluminum alloy to carbon fiber composite materials. Usually, the aluminum alloy car body can reduce 0.5 to 1.0 ton per vehicle compared to the stainless steel car body, while the carbon fiber vehicle can further reduce 3 to 4 tons per vehicle. In aluminum alloy vehicles, the aluminum alloy usually replaces only the stainless steel or ordinary steel of the car body, while in carbon fiber vehicles, the carbon fiber composite material replaces not only the material of the car body, but also that of the main bearing structures such as the bogie frame. Compared with the traditional metal metro vehicles (steel, aluminum alloy), the carbon fiber metro vehicles are reduced by 25% of car body weight, 50% of bogie frame weight, and about 11% of the whole vehicle weight. The operation energy consumption after the weight reduction can decrease by 7%. As a new type of efficient energy-saving silicon carbide inverter and the permanent magnet synchronous traction motor are used in the traction system of the carbon fiber metro vehicle, the overall energy saving of the vehicle is more than 15% compared with the traditional ones.

In addition, thanks to the use of advanced active radial technology, the wheel-rail wear and noise of the carbon fiber vehicle are significantly reduced, and the workload of the vehicle and track maintenance is greatly decreased. Furthermore, the application of the new sound insulation and noise reduction materials and equipment reduces the noise in the passenger cabin by more than 5 dB.

From the perspective of the manufacturing, operation and maintenance cost of the carbon fiber vehicle, CRRC Sifang has built a full-chain platform for research and development, manufacturing and verification, forming a complete set of engineering capabilities from carbon fiber structure design and development to molding manufacturing, simulation, testing, quality assurance, etc. and providing a one-stop solution for the whole life cycle of the vehicle. Through the use of digital twin technology, the intelligent operation and maintenance SmartCare platform for the carbon fiber train is built, which realizes self-detection and self-diagnosis of vehicle safety, structural health and operation performance, improves operation and maintenance efficiency and reduces operation and maintenance costs. Train life cycle maintenance costs can be reduced by 22%.

Carbon fiber composite materials represent the development direction of lightweight technology for rail vehicles. The advent and operation of commercial carbon fiber metro trains will effectively promote the transformation of the main load-carrying structure of metro vehicles from traditional metal materials such as steel and aluminum alloy to carbon fiber composite materials, which removes the bottleneck of structure weight reduction with traditional metal material, realizes the fully new upgrading of China's metro train lightweight technology, and will play an important role in promoting the green and low-carbon transformation of China's urban rail transit.

(Translated by DAI Xiaoyun)