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SUPER ENGINEERING

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Development progress of China's 600 km/h high-speed magnetic levitation train

Keywords 600 km/h high-speed magnetic levitation train, development history, technological innovation

1 Outline

Launched in 2016 with a focus on the key technologies related to high-speed magnetic levitation, China's 600 km/h high-speed maglev train project has provided a number of engineering breakthroughs. Focusing on the development process of China's high-speed maglev system, this paper provides a description of its development history, the innovations achieved, and the capabilities formed throughout the project. The paper commences by introducing the performance and technical innovation of the high-speed maglev system in terms of aerodynamic design, system dynamics, system energy consumption, vibration and noise reduction, and electromagnetic compatibility, among others. The project has necessary conditions needed for the high-speed test demonstration line to carry out the speed test, which has become possible due to China's preparations for setting in place a platform for the research and development (R&D), testing and trial production of the high-speed maglev train, building a localized industry chain for the entire system to form the supporting capability for industrialization, developing an engineering prototype for the entire system, and realizing the low-speed operation of traction and system integrated test.

2 Research background

As one of the important pursuits of social development and technological innovation, transportation speed reflects — to a certain extent — the development level of social economy and technology (Sun et al., 2019). Since its reform and opening up, China's rapid economic growth and social progress, growing passenger flow and cargo flow, and demand for faster commuting have all contributed to creating the possibility for the development of high-speed rail (HSR) transportation. China's railroad mileage has reached 146000 km by the end of 2020 — including 38000 km of HSR tracks — leaping to first place globally, and transforming China from a follower to a leader in terms of HSR trains (Li and Zong, 2013). The increasingly improved rail transportation network has provided a huge boost to the overall development of the country and brought about a demand for high-speed transportation services between economic regions, bringing great convenience to travelers and further stimulating their pursuit of rail transportation modes featuring higher speed, faster travel, and greater safety and comfort as well.

In a continued effort to explore the ways to enhance the speed of the traditional HSR modes of transport, China is currently carrying out R&D for technology reserved to the 400 km/h high-speed train systems. Further speed increasing of HSR trains faces constraints in wheel–rail interaction, pantograph–catenary interaction, and fluid–solid interaction, and train acceleration improving also remains challenging, which is limited by the physical adhesion characteristics of materials used for wheel rail, pantograph, etc.; both of which may lead to longer acceleration braking distances and time, as well as sharply increased traction power demand, and the rotating operation and wear characteristics of bearings will add to the difficulty of HSR trains' daily maintenance. As a result, the maintenance cost of HSR is significantly increased and, thus, industry experts generally believe that the maximum economic operating speed of wheel-track trains is approximately 400 km/h (Wu et al., 2005; Xiong and Deng, 2021).

With the rapid development of China's economy and the demand for medium- and long-distance high-speed

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passenger transportation, people have identified greater requirements for transportation means. Developing high-speed and fast, safe and comfortable, resource-saving, and eco-friendly modes of transport has become the main direction of development for modern transportation. With the advantages of high speed and convenience, high transportation capacity, high safety and reliability, and comfort and punctuality (Fu, 2017), high-speed maglev railways can be adopted for rapid commuting within city clusters so as to enable half-hour commuting. The technology can also be used for integrated transportation between core cities so as to boost the outward development of economic circles, as well as allowing for the creation of strategic economic corridors for the coordination of the economic development of eastern and western China. In filling the speed gap between aviation and high-speed wheel–rail transport modes, high-speed maglev railway plays an indispensable role in improving the transportation speed spectrum and building an integrated modern transportation system (Yan, 2002).

During the “13th Five-Year Plan” period, as a priority project of the National Key Research & Development Program of China, China Railway Rolling Stock Corporation (CRRC) was commissioned to take the lead to create breakthrough engineering results on the key high-speed maglev technology. CRRC gathered advantageous domestic HSR and maglev resources, and set up a team for key research featuring the coordinated efforts of enterprises, universities, and research institutions for the first time, with enterprises as the primary role. Drawing on the mature R&D experience of HSR of “simulation analysis – bench test – line test” cycle iteration optimization, China’s 600 km/h high-speed maglev team strives to set in place a ground testbed and commissioning test lines for system integration, vehicles, traction power supply, operation control communication, and track lines, develop and validate the components and system lines, as well as modify the simulation boundary and optimize the algorithm design (see Fig. 1).

3 Technology innovation

In response to the technical challenge of raising the operating speed of high-speed maglev trains from 430 to 600 km/h, and given actual engineering needs, an advanced top-level index system, covering technical indexes in terms of application environment, comprehensive performance, and featuring requirements of safety and reliability, comfort, and environmental protection, is formed for the purpose of enabling long-distance multi-zone and multi-vehicle automatic tracking, river and mountain crossing, and parking at any point, as well as for rescue and escape convenience.

(1) Large-scale system coupling model: As high-speed magnetic levitation system is a complex tightly-coupled fluid–solid–electromagnetic–electromechanical system (Yu et al., 2020), with the interaction between gap change and control response, the traditional thinking must be broken to establish a coupling model for dynamics, complex electromagnetic fields, control, and large-scale pneumatic systems so as to clarify the coupling relationship and to develop an optimization scheme (see Fig. 2).

(2) Aerodynamic design: As the fluid around a running vehicle with the speed of 600 km/h is about to be compressed, significant changes will happen to the vehicle–rail air gap and both sides of the throttle–flow field boundary and related characteristics, thus presenting aerodynamic design challenges. Through the establishment of a vehicle–rail–tunnel non-constant model, the research in the correlation between the performance indicators of open lines, intersections, and tunnel working conditions and design boundary, the exploration of line spacing, tunnel area and other limit numbers, and the design of the sections, head type, local flow control and others, a comprehensive aerodynamic scheme for the 600 km/h high-speed magnetic levitation system can be formed, on the basis of preliminary simulation – fine evaluation – wind tunnel test optimization. Some main parameters are as follows: Line spacing = 5.6 m; recommended area of

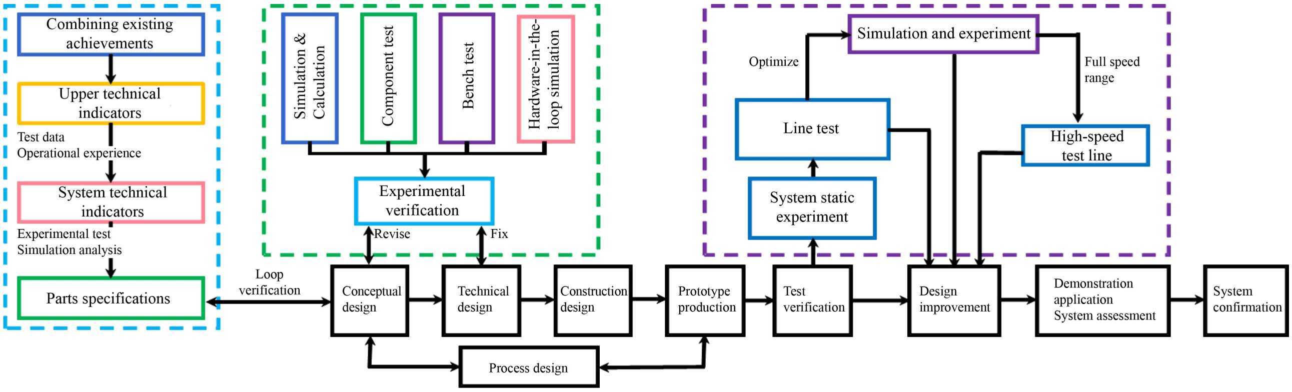


Fig. 1 Development and validation method of 600 km/h high-speed magnetic levitation system in China.

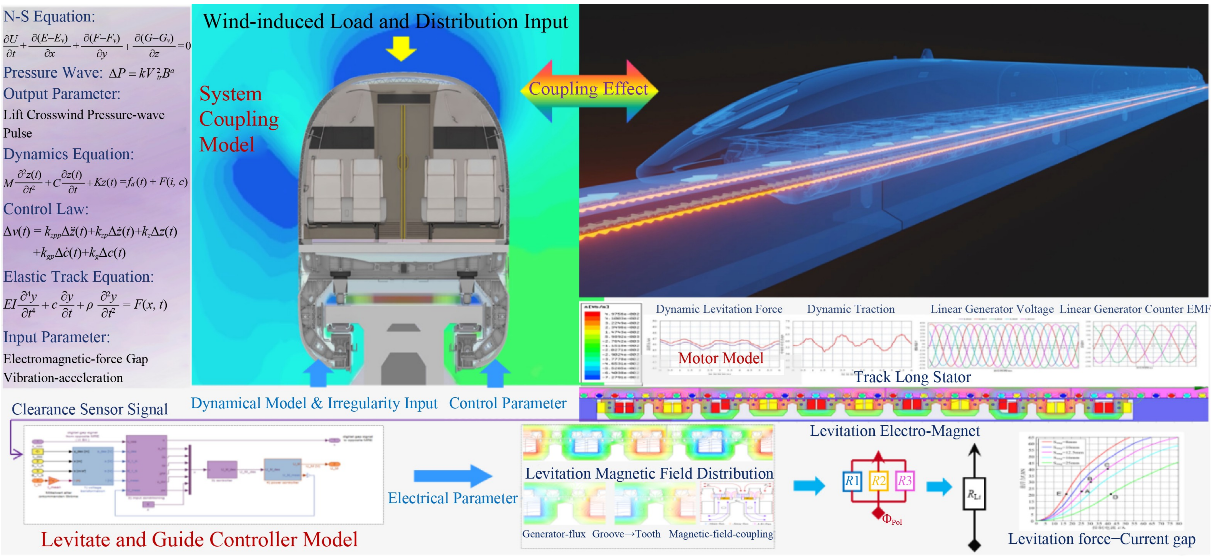


Fig. 2 Coupling model of large-scale high-speed maglev system.

the single/double line tunnel = 70–80 m^2/90–120 m^2; aerodynamic drag reduction = 17%; lift reduction = 21%; aerodynamic noise reduction = 3–5 dB(A); intersecting pressure wave reduction = 5%; and micro-compression wave reduction = 40%.

(3) Vehicle-track coupling: High-speed magnetic levitation system is a strongly-coupled system, where the active control of levitation–guidance forms self-excited vibration, which is affected by external disturbance such as track irregularity, bridge deflection deformation, and faulting of slab ends and junctures, maintaining a stable control gap and ride comfort. The correlation mechanism of speed – levitation – guidance adjustment – motion decoupling – safety and comfort has been studied based upon a large-scale system model; and the vehicle–track coupling issue can be addressed in a coordinated way from the perspective of vehicle suspension, levitation–guidance system, and track system. The new track beam system has been developed with the deflection-to-span ratio for a track beam greater than $L/12500$, where L represents the length of a beam; materials with high magnetic permeability and double-layer winding technology have been adopted to improve the magnet's performance (the levitation/guidance/braking capacity has been improved by 14%/40%/22%, respectively); and the control parameters are optimized to improve system traceability (reducing the 1.2 mm gap fluctuation down to 0.4 mm), and the dynamics performance index meets the design requirements under operating speed of 600 km/h (the vibration acceleration of the vehicle body is approximately 0.29 m/s^2).

(4) High-speed coordination: Adopting the operational mode of vehicle–ground separation and multi-vehicle and multi-partition automatic driving, the high-speed operation of the high-speed magnetic levitation system requires high-precision cooperation of multiple systems covering speed and position detection, vehicle–ground wireless communication, traction power supply, and operational control, so as to achieve signal accuracy, the reduction of transmission time delay and jitter, and the improvement of response and control accuracy of control system. To this end, the detection coil, operating frequency, and processing circuit are all optimized to suppress magnetic field interference; the time division multiplexing and other protocols of heterogeneous network optimization are adopted to enhance the real-time performance; and multi-layer classification technology is used to improve anti-channel fading. Eventually, the wireless transmission delay has been shortened to less than 5.0 ms, jitter has been decreased to less than 1.0 ms, and the traction speed tracking error has been reduced to below 5%, effectively meeting the requirements for dynamic operation system cooperation and high-precision synchronous control.

(5) Noise control: The noise design method of the "Fuxing" bullet trains is emulated in the design of 600 km/h maglev trains in view of such characteristics as large aerodynamic sound source, wide noise bands and significant low-frequency noise (Zhang et al., 2021). With regard to noise in the vehicle, the design principle of frequency division control and equivalent sound power level has been adopted, and the noise source and related propagation characteristics are studied. Based on acoustic energy contribution, the design of the integrated material–structure–function noise reduction scheme has been carried out, enabling a lightweight noise reduction structure. The findings show that the sound insulation performance of the section of a 600 km/h high-speed maglev train is vastly improved, with that of the floor area, side walls, and roof being improved by 7–15 dB. The noise outside the vehicle has been reduced by 4–5 dB(A) through vehicle shape optimization, treatment of track beams, and other methods. Based on the prediction of the validated whole vehicle model, when the vehicle is running at 430 km/h, the in-vehicle noise is 7 dB(A) lower than the measured noise of the Shanghai maglev demonstration line (Zhang et al., 2021). Furthermore, the in-vehicle noise is forecasted to be below 80 dB(A) when the vehicle is running at 600 km/h. With sound barriers, the noise outside the vehicle will meet the requirements as stipulated in the *Emission Standards and Measurement Methods of Railway Noise on the Boundary alongside the Railway Line* (GB12525-90).

(6) Electromagnetic compatibility: The integrated grounding, vehicle lightning protection, external radio frequency (RF) radiation suppression and other electromagnetic compatibility designs have been conducted. Combined with the low-speed test data, shielding weaknesses of the vehicle design have been investigated and the external RF disturbance level of the vehicle has been reduced by 3–10 dB. The magnetic flux density tests of the compartments, the station platform under static working conditions, and the maintenance areas have been completed. The results show that the alternating current and direct current (AC&DC) magnetic fluxes under each working condition are significantly lower than the limits outlined in the IEC62597 and EN45502 standards (Wen and Xing, 2021). The simulation model has been corrected based on the test data, and the simulation evaluates that the electromagnetic compatibility under operation speed of 0–600 km/h meets the requirements as stipulated in IEC62597 and EN45502 standards.

4 Research progress

After five years of R&D of high-speed magnetic levitation, China has set in place industrial chain and supply chain around the technology chain, completed the development of the whole-system prototype, and conducted the low-speed test run, with the system meeting expectations for functional performance. China has built R&D, testing, and trial production platforms, developed whole-system engineering prototypes with independent intellectual property rights, and realized low-speed operation of traction and system integrated test.

(1) Building industrial and supply chains around the technology chain and completing the development of whole-system prototype

Relying on the mature industrial chain established around the high-speed railway, and combined with the technical requirements for key components of high-speed maglev railways, technical breakthroughs have been addressed to form a whole-system omni-industrial chain (see Fig. 3), covering materials such as special steel, cables and cords, etc., components such as IGCT (integrated gate commutated thyristors) chips, integrated circuit plates, etc., assembly units such as high-power converters, vital computers, controllers, maglev frames, etc., and equipment such as vehicles, traction power supplies, operation controls, wireless communications, etc. Specifically, the independent development of vehicle bodies, sensors, electromagnets and other key components, as well as the whole vehicle, has been completed. The traction power supply system prototype has been developed, including traction transformer, control, switching station, and long stator linear motor. A complete set of engineering equipment for operation control and communication, with central subsystem, zoning control, maglev-carried vital computer, and vehicle–ground communication, has been finished. New different-structure track beams, turnouts, functional parts, and other line track prototypes have been delivered.

(2) Successful test run of the vehicle prototype and completion of low-speed test verification

Engineering train

High power converter Switch Central operation control system

Fig. 3 Whole system engineering prototype.

Based on the low-speed test line, the track test of the vehicle prototype has been carried out, completing 204 tests in 7 categories: The levitation gap fluctuation < ±guiding gap < ±2 mm, the magnet temperature is maintained below 80°C at the state of levitation, and the precise speed/current closed-loop control achieves a stopping accuracy of ±0.25 m when the vehicle is running at 50 km/h. The safety and stability of the tested prototype have met the design requirements and its overall performance is in line with expectations. The test results show that the overall function of the independently-developed core system is reliable, and that the performance of the prototype meets the design requirements, whose components are developed by the localized whole-system industry chain in accordance with the mature control mode of HSR.

(3) Iterative optimization and high-speed performance simulation evaluation based on test data

Systematic analysis of the low-speed test data, iterative optimization of the simulation model and algorithm, and improvement in the design have been carried out. The iterative optimization of technical solutions and high-speed operation performance evaluation have been conducted in terms of system dynamics, levitation–guidance control, traction control, operation control, wireless communication, noise, and electromagnetic compatibility, among others — the main performance of these optimization tests all meet the design requirements.

(4) Completion of the development of a five-car engineering train and system integrated test to enable the train’s dynamic and stable operation

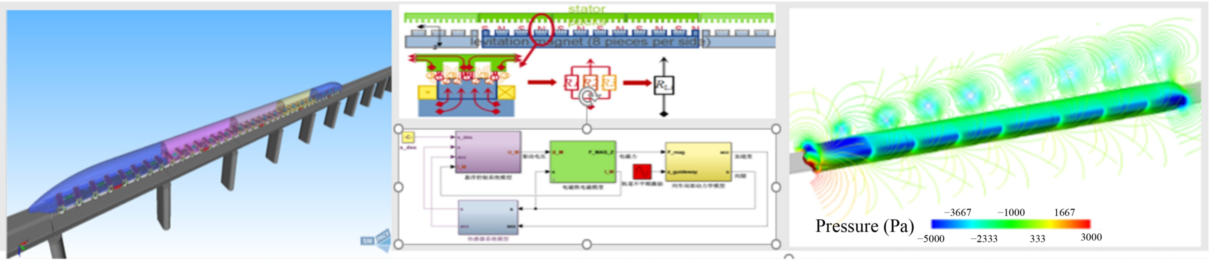
In December 2020, a five-car engineering train was completed. The development of whole-system engineering prototypes of the traction power supply and operation control and communication were also completed in the same timeframe, with a 665 m commissioning line having been subsequently built. At present, the joint tuning of the vehicle, traction power supply, and operation control and communication systems have been completed, enabling the smooth traction operation of the five-car engineering train under speed of 30 km/h: Power factor of the variable current system is higher than 0.99, speed following accuracy is below 5%, stopping accuracy is below 0.5 m, wireless communication time delay is shorter than 5 ms, and the jitter has been shortened to less than 1.0 ms. As such, the functions and performance are all in line with the design requirements. On July 20, 2021, the 600 km/h high-speed maglev transportation system was officially rolled off the production line.

(5) Independently building a whole-system collaborative simulation, test and trial production platform

A system-wide collaborative simulation platform (see Fig. 4) covering dynamics, aerodynamics, noise, electromagnetic, control, linear motor, traction, operation control, communication simulation, etc., has been built to provide comprehensive, systematic and scientific simulation evaluation for the demonstration and optimization of technical solutions. Thanks to the joint planning by the participating units, a system-wide test platform has been built to meet the ground bench test verification needs of components, systems and large-scale system integration. The new high-speed maglev trial production center has been built to develop the system-wide small-batch engineering trial production capability for vehicles, traction power supply, operation control and communication, and track lines.

5 Application demonstration

Vehicle prototypes of the 600 km/h high-speed maglev transportation system (see Fig. 5) — based on the construction and operation of the demonstration line in Shanghai and several rounds of independent innovation — have been developed with the goal to carry out low-speed tests. The indicators such as safety and stability have fulfilled the design requirements, and the overall performance meets the expectations. Based on the previous research and experience, the 600 km/h high-speed maglev transportation system has overcome the shortages of the Shanghai demonstration line such as point-to-point short-distance operation, simple working condition, and without surroundings like rivers and mountains, and achieved the localization of core technologies including levitation–guidance, traction operation control, etc. Considering the practical engineering application of multi-scenario and



Maglev train model Control-Magnet model Aerodynamic safety analysis

Fig. 4 Collaborative simulation platform.

Fig. 5 600 km/h high-speed maglev transportation system.

multi-density tracking network, the 600 km/h high-speed maglev transportation system has improved the aerodynamic performance after speed increases and reduced the aerodynamic lift and running resistance. In light of the large-scale system coupling model, the 600 km/h high-speed maglev system has solved the issues of vehicle–track coupling and system vibrations in terms of track lines, levitation–guidance control and running system, ensuring the safety, comfort and smoothness of vehicles running at 0–600 km/h. When it comes to high-speed synergy, the system has tackled the problems of synchronous traction and precise linkage control of vehicle–ground systems, improving the real-time reliability of wireless communications. In terms of vibration and noise reduction and electromagnetic compatibility, the spectrum characteristics and propagation excitation mechanism have been studied, and engineering scheme design has been subsequently carried out so as to improve the environmental adaptability of the system. The 600 km/h high-speed maglev transportation system meets the needs of long-distance, multi-zone, multi-vehicle automatic tracking operation, river and mountain crossing, arbitrary parking, and convenient rescue and escape. The development of complete engineering solutions and full-set engineering equipment has been completed, covering application environment, comprehensive performance, safety and reliability, and comfort and eco-friendliness. The 600 km/h high-speed maglev transportation system was successfully released in Qingdao in July 2021, marking that China has mastered a complete set of high-speed maglev technology and engineering capability.

Based on the Shanghai demonstration line and studies during the past three Five-Year Plan periods, China has successfully mastered the core technology of high-speed magnetic levitation train, implemented an R&D, testing, and trial production platform, set up a localized system-wide industry chain, developed the supporting industrialization capacity, created the whole-system engineering prototype, and realized the low-speed operation of traction and system integrated test. Consequently, China is well prepared for setting up high-speed testing demonstration line to carry out speed-reaching test.

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