Proceedings of the Sixth International Conference on
Railway Technology: Research, Development and Maintenance
Edited by: J. Pombo
Civil-Comp Conferences, Volume 7, Paper 16.6
Civil-Comp Press, Edinburgh, United Kingdom, 2024
ISSN: 2753-3239, doi: 10.4203/ccc.7.16.6

V-Shaped High-Temperature Superconducting Suspension System for Maglev Train

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Abstract

Magnetic levitation (maglev) represents the most innovative technology in advanced rail transportation. Several maglev technologies provide the basis for the operation of both experimental and operational systems internationally. In this paper, the high-temperature superconducting maglev technology, based on the interaction between permanent magnets and high-temperature bulk superconductors, is considered and analyzed. Even though superconducting maglev technology is the newest and has a lower level of maturity than the others, it has significant potential for future applications of maglev rail systems because of the advantages of passive and self-stabilizing levitation, the almost complete absence of magnetic resistance to movement, and the extreme simplicity of system configuration. This paper specifically describes the performance characteristics of the V-shaped maglev suspension module, based on superconducting maglev technology, developed at the University of L'Aquila (Italy).

Keywords: magnetic levitation train, high-temperature superconducting maglev technology, V-shaped maglev module, magnetic guideway.

1 Introduction

Magnetic levitation (maglev) is a highly advanced technology applied in various fields such as civil, energy, transport, and military.
Thanks to its innovative content and high performance, maglev trains are widely regarded as the most advanced systems currently available to the railway industry.

Compared with conventional wheel-on-rail (WoR) trains, maglev trains feature the following advantages: no physical contact between vehicle and track, higher speeds, energy savings, reduced vibration and noise pollution, higher comfort levels, overcoming steep longitudinal slopes, reduced maintenance requirements and reduced risk of derailment [1].

The socio-economic needs related to the transportation of people and goods in the most advanced countries have driven and still drive to increase the operating speeds and efficiency of the railway sector. Figure 1 shows the evolutionary trend of railway train speed over time, starting from the early industrial era.

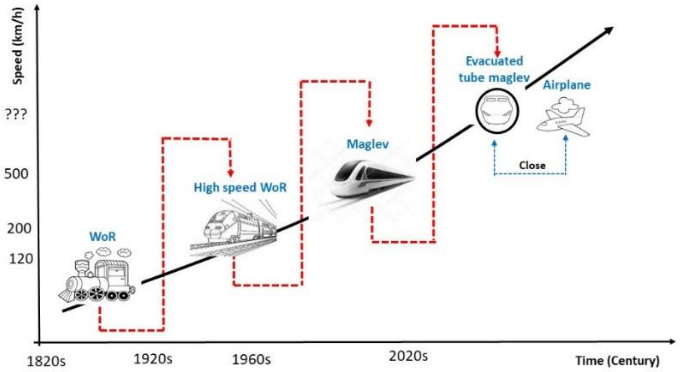

Figure 1: Evolutionary trend of the speed of the railway industry over time

In this evolving scenario, one wonders what speed limits can be achieved in the short and medium term.

Indications for this can be drawn from an in-depth analysis of technological development and innovations in the field of guided transportation systems.

In any case, the speeds of future transport systems used to move goods and passengers are expected to increase significantly. As an extreme limit, new research and development trends are focusing on the study of intubated and evacuated transport (ETT) systems, based on maglev technology, for ultra-high-speed applications [2].

Regarding the development of advanced rail transport in the atmospheric environment, maglev technology has been developed simultaneously in different international contexts and has found commercial applications in both low and high speeds.

The main magnetic levitation systems for transportation applications can be classified according to the technology adopted, as follows: [3,4,5]:

a) Electromagnetic suspension (EMS) which uses forces of attraction generated by the interaction of electromagnets placed on the vehicle and the ferromagnetic parts of the rail. The vehicle is suspended even at zero speeds. This technology requires very sophisticated active control systems due to the inherent instability of the system. EMS-based systems are to date the only operative passenger transport systems;

b) Electrodynamic suspension (EDS), which uses repulsion forces generated by the interaction between low-temperature superconducting magnets placed on the vehicle and the short-circuited electrical windings incorporated in the side parts of the guideway. At low speeds the vehicle travels on wheels; the vehicle's levitation occurs only above critical speed values. EDS is still at an experimental stage but has reached a high level of technological maturity thanks to decades of experience gained at the Yamanashi Maglev test line in Japan;

c) High-temperature superconducting magnetic levitation (SML) based on the interaction between non-ideal type II high-temperature superconductors (HTS) placed on board the vehicle and magnetic field generated by permanent magnets distributed along the rail. The system generates both repulsive and attractive forces, the combination of which results in a stable suspension without the need for any active control. This technology is still in the research, development, and demonstration phase.

Although EMS and EDS technologies introduce significant performance improvements over WoR systems, they still have some disadvantages related to energy consumption, due to the suspension devices and the propulsive power required to overcome magnetic resistance to motion, respectively.

2 High-temperature superconducting maglev technology

The ideal condition for a maglev transportation system is to reduce the energy consumption associated with the operation of (i) the vehicle suspension and guidance apparatus to counteract the forces of gravity and (ii) the propulsion apparatus to counteract the resistances to motion including magnetic ones.

This ideal condition can theoretically be achieved by using superconducting materials, which are the only known materials with perfect diamagnetic response and zero electrical resistance.

As such, SML technology has the inherent potential to achieve the performance goals mentioned above. The development of SML maglev technology in the transport field started with the emergence (in the late 80's) of $Nd_2Fe_{14}B$ (NdFeB) permanent magnets (PMs) and $YBa_2Cu_3O_X$ (YBCO) high-temperature superconductors.

Compared with other magnetic levitation technologies, SLM one has significant potential for future applications of maglev transport systems due to the following aspects: i) passive and self-stabilizing levitation; ii) no electrical power; iii) very low power consumption related only to the cooling of superconductors; iv) almost zero magnetic resistance to vehicle motion; and v) simplicity of system design.

For these reasons, Chinese [6], German [7], Italian [8], Brazilian [9], Japanese [10], and Russian [11] research departments are currently working on SML maglev technology to develop and test practical applications.

3 V-shaped high-temperature superconducting maglev system

The Italian SML-based experimental system (UAQ4 named) has been developed at the University of L’Aquila (Italy). The Italian maglev train project started at the end of the '90s with the starting of production and marketing of new sintered magnetic materials (YBCO and NeFeB).

To verify the technological feasibility of the full system and test the performance of the suspension and propulsion equipment, a linear demonstrator of the system (Figure 2) was constructed as follows:

1) a track with three parallel iron beams with NdFeB permanent magnets of which the outers are “V” shaped and the central one is “U” shaped;
2) a bogie with four V-shaped HTS 'skates' positioned on both sides of the chassis to provide lifting and guidance and the primary component of a centrally positioned DC stepper linear motor to provide propulsion and braking.

As a result, the bogie is self-stabilizing (i.e. it does not require electromagnets and control circuits to maintain stable levitation), it levitates above the track even when stationary. Furthermore, the motion of the vehicle is essentially free of magnetic resistance [12].

The dynamic behavior of the prototype was first studied by performing analyses and tests in a standstill condition [13-15].

Figure 3 illustrates the UAQ4 maglev train scaled model.

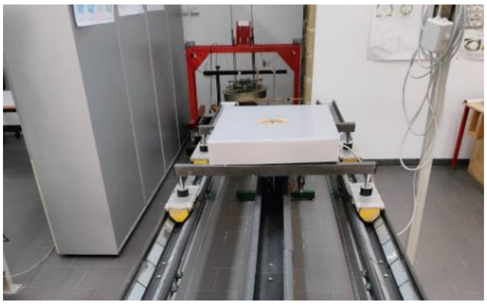
Figure 2: UAQ4 maglev demonstrator


Figure 3: UAQ4 maglev train scaled model

2 Analyses and tests results

The UAQ4 maglev suspension device is based on a V-shaped HTS skate that allows the magnetic suspension force to be broken down into a vertical component F_Z (lift force) and a horizontal component F_X (guidance force), as illustrated in Figure 4 obtained by finite element analysis.

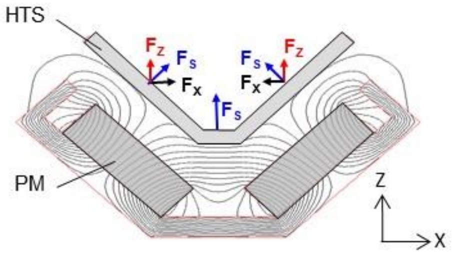

Figure 4: Scheme of the suspension module for lifting and guiding

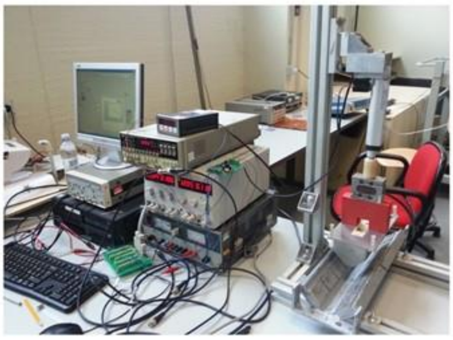
Figure 5: Equipment for levitation force measurements

This suspension device simultaneously provides the vehicle's lift and guide with centering force values suitable for traveling along curved tracks [16,17].

As well known, the levitation force (F_{Lev}) depends on the magnet field gradient ($\partial B/\partial Z$), the perimeter of induced shielding current loops (d), and critical current density (J_c), as reported in relation 1.

$$\mathrm{F}_{\mathrm{Lev}} = J_C \cdot d \cdot \left(\frac{\partial B}{\partial Z} \right) \tag{1}$$

Vertical force (F_Z) and lateral force (F_X) can be calculated by Equations (2) and (3), respectively [19]:

$$F_z = \int J \times B_x \mathrm{d}S \tag{2}$$

$$F_x = \int J \times B_z \mathrm{d}S \tag{3}$$

where B_x and B_z refer to the component of magnetic flux density in the horizontal (x) direction and vertical (z) direction, respectively, J is the electric current in superconductors and S is the total area of superconductors.

Moreover, the levitation force is influenced by: i) the shape and thickness of the HTS bulks, ii) the field cooling height (H_0) that affects the amount of magnetic field trapped within the material when phase transition to superconductivity occurs, and iii) the operating temperature [18].

To analyze the magnetic interaction, a scaled V-shaped maglev module was built to reproduce and test the phenomenon in quasi-static conditions according to the vertical z and the lateral x directions.

The test equipment (Figure 5) includes a mechanical structure on which an actuator device is connected via a load cell to the HTS skate, which moves in one direction relative to the fixed part (PM guideway section). A computer, control system, and data recorder complete the equipment. A load cell measures the force exerted on the HTS skate, while the actuator imposes quasi-static movement (speed of 0.47 mm/s) on the skate in a controlled manner. The magnetic force components F_Z (vertical) and F_X (lateral) were evaluated separately [19].

Figures 6 and 7 illustrate F_Z at varying vertical air gap height (z-gap) and the centering forces by varying horizontal offset (x-offset), respectively at a superconductor cooling height (H_0) of 25 mm.

At first, the F_Z values were measured by varying the z-gap without x-offset, as illustrated in Figure 6. The graphs of this figure show that F_Z curves are hysteretic and asymmetrical type; they both repulsive and attractive concerning the equilibrium point and the magnitude of the repulsive forces are greater than the attractive ones. The suspension phenomenon is twofold: repulsive forces are generated if the superconductor and the magnets move closer together and attractive forces if they move apart.

The dual force of "repulsion & attraction" determines the stable phenomenon of the vehicle's lift.

Next, F_X values were measured by varying the x-offset with a z-gap of 25 mm and Ho of 25 mm, as illustrated in Figure 7. In this case, it can be seen that F_X curves are hysteretic and symmetrical concerning the vertical axis passing through the equilibrium point. The dual force of "push & pull" determines the stable phenomenon of the vehicle's guidance

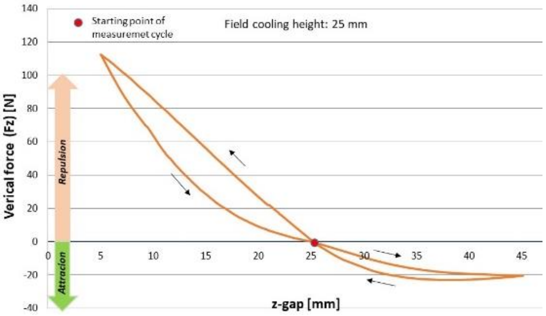

Figure 6: Vertical force (F_Z) Vs z-gap at x-offset=0 and Ho=25 mm

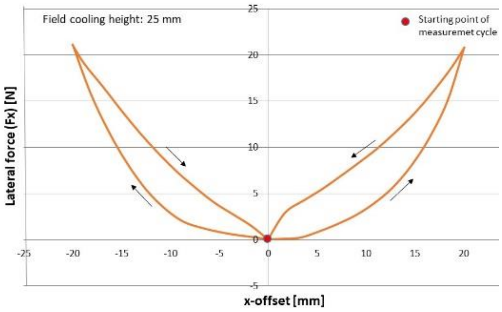

Figure 7: Lateral force (F_X) Vs x-offset at z-gap of 25 mm and Ho of 25 mm

3 Conclusions

In this article, the characteristics of the different maglev technologies adopted in the field of railway transport systems were preliminarily examined. Particular attention was paid to high-temperature superconducting levitation (SML) technology.

Although this technology is the newest and has a lower level of maturity than the others (EMS and EDS), it has significant potential for future applications of maglev rail systems due to the advantages of passive and self-stabilizing levitation, the almost complete absence of magnetic resistance to motion, and the extreme simplicity of system configuration.

In the international context of research on SML maglev transport systems, Italian experiences were illustrated.

In addition, test results were described, in terms of vertical (F_Z) and lateral (F_X) magnetic forces, carried out on a single V-scale levitation module under quasi-static conditions.

The results showed that:

- F_Z curves are both repulsive and attractive concerning the equilibrium point and the magnitude of the repulsive forces is greater than the attractive ones. The dual force of "repulsion & attraction" determines the stable phenomenon of the vehicle's lift;
- F_X curves are symmetrical concerning the vertical axis passing through the equilibrium point. The dual force of "push & pull' determines the stable phenomenon of the vehicle's guidance.

Future research activities focus on the design of a full-scale linear urban system.

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