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A NEW CONCEPT OF MODULAR MAGNETIC LEVITATION TRAIN FOR URBAN TRANSPORT

Aim: The aim of our project is to solve all technological and functional problems related to the development of the suspended urban Maglev, while maintaining the requirement of simplicity and low cost of construction, operation and maintenance. Both the infrastructure and the vehicle are designed to be industrially produced and assembled on site.

Methods: Our study is based on the theoretical and experimental results obtained during a project of the Italian National Research Council, concerning the performances of opposing permanent magnets, the design of the linear synchronous motor and the possible solutions for realizing the guidance system. On the basis of these results the study of the suspended system was carried out.

Results: The paper describes the suspended urban Maglev with PM/PM primary suspension (with opposing permanent magnets) and proposes a mechanical guidance system that uses for stabilization the same repulsive forces between permanent magnets. We also propose a new configuration with HTS/PM primary suspension (with high temperature superconductors opposed to permanent magnets), evaluating pros and cons of this solution. Finally we provide design data on the linear synchronous motor suitable for our system.

Conclusion: This paper describes our proposal for a suspended urban Maglev using permanent magnets; our interest focuses on the need to further develop industrially feasible solutions, easy to build and manage, in order to propose a system that is also commercially viable and competitive. The identified advantages justify further studies.

Keywords: Maglev, urban transport, suspended system, modular construction, cost saving.

INTRODUCTION

Despite promising prospects and many decades of research and development, all Maglev systems still face barriers to their success. However, Maglev technology has some very interesting features, especially for urban transport: the lack of contact between the vehicle and the track reduces maintenance costs; other important advantages are the distributed load, the reduced vehicle cross-section, the possibility of overcoming high slopes, the reduction of noise generated by train traffic. Therefore, the development of

Maglev systems must continue, but we need to focus on a new generation, custom-made solution for urban transport, characterized by simple construction, lightweight, low energy consumption, full automation, low cost of construction and operation.

Taking advantage of the improved performance of permanent magnets and building on the studies conducted over the past few years on the optimization of opposing magnets (including those conducted by the Italian National Research Council), an original solution of a suspended urban Maglev (where the vehicle is suspended under a fixed track) has been developed in order to meet these requirements of simplicity and low cost [1, 2, 3]. The first version of this system, already presented at the Maglev 2016 Conference in Berlin [4], adopted vehicle levitation and guidance systems based on repulsive forces between permanent magnets of specific shape and dimensions.

In this paper, we propose some solutions for realizing a reliable suspended Maglev system. We describe a mechanical driving control system for the low speed vehicles stabilization (for urban transport only) which levitate on opposing permanent magnets, and an updated version of the suspended Maglev layout, which adopts a primary suspension composed of high temperature superconductors and permanent magnets. Further technical measures are illustrated for ensuring the industrial feasibility and the competitiveness of this urban transport system.

THE SUSPENDED SYSTEM

Among all possible configurations of the system, we preferred to suspend the vehicle from above (Fig. 1), in order to concentrate the technological part (of the track and the vehicle) in a position that is not easily accessible. This solution allows the intrinsic protection of the magnets against tampering and makes the technological part very compact, also making switches design easier. Moreover, this choice leaves free space on the ground under the vehicle; no equipment is required on the ground along the path. In the case of an underground tunnel itinerary, the floor under the vehicle can be walked on and can be used as an escape route; consequently, free spaces at the sides of the route are not necessary. Vehicle end doors are emergency exits that can be used by passengers for escape.

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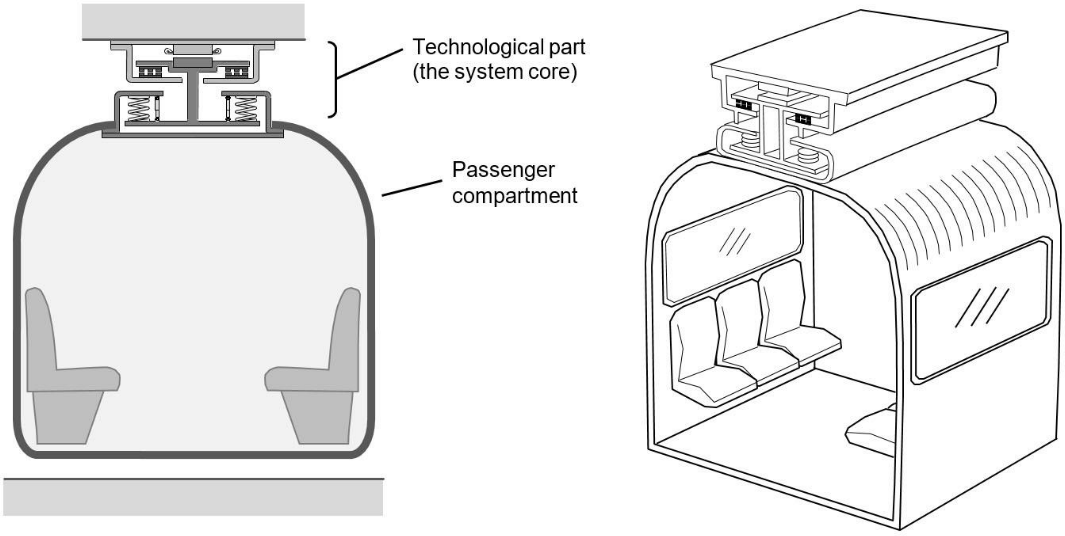

Fig. 1. The suspended Maglev configuration

Fig. 2 shows the solution chosen for the track (red) and the upper part of the vehicle: bogie (green), suspension and body frame (blue).

The track (red) consists of a metal box containing two beds of magnets laid on steel plates and the winding of the linear synchronous motor (LSM) for propulsion and braking. Outside the box, two iron guides ensure the reaction of the electromagnets (for stabilization) and the accidental contact of the anti-derailment skids. Track technology is very simple and feasible as an industrial product, divided into modules of lengths that best fit to production, transport and assembly on site.

The bogie (green) is an aluminum double-T beam (length 0.7 m). Each bogie rests on the track magnet beds through two opposing magnet plates (PM/PM primary suspension), fastened inside the upper wings of the double-T. The stabilization control device and the anti-derailment skids are placed on the vertical band of the double-T beam; they act on the track iron guide. The magnets of the LSM inductor are placed over the double-T. The elastic elements of the suspension, the bogie/vehicle connecting pin, two dampers and a torsion bar are fixed on the lower wings of the double-T beam.

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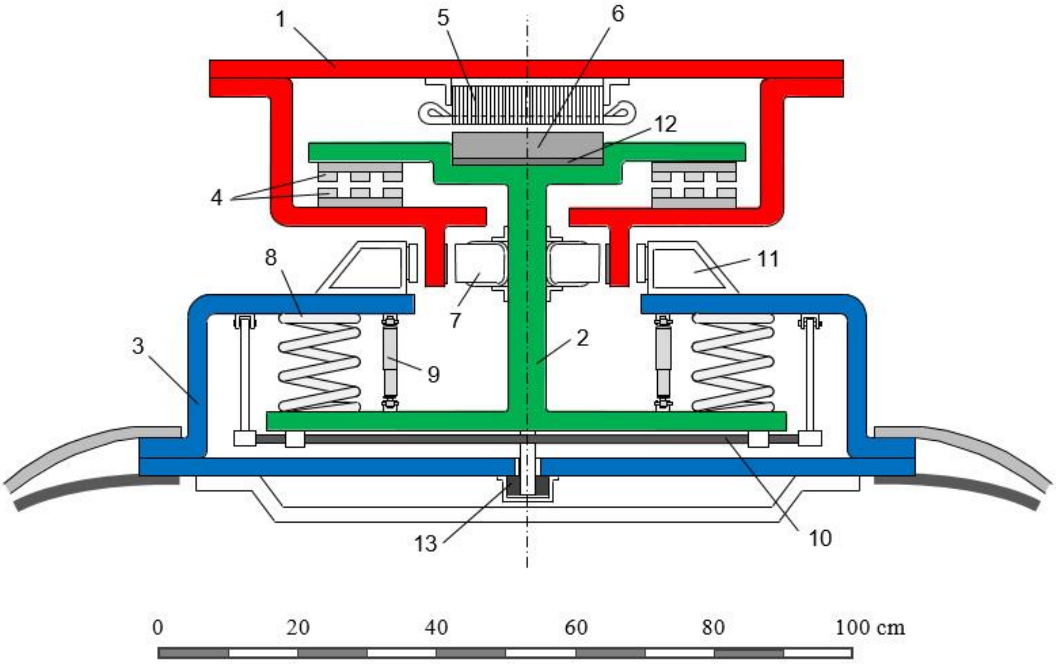

1. Track box
2. Slipping bogie frame
3. Vehicle body frame
4. Primary suspension (permanent magnets)
5. LSM armature
6. LSM inductor
7. Stability control electromagnets
8. Secondary suspension springs
9. Shock absorbers
10. Torsion bar
11. Emergency brake and lateral end stop
12. Gap adjustment system
13. Bogie/vehicle connection

Fig. 2. The suspended Maglev system core - Solution A with PM/PM primary suspension

The body frame (blue) is an aluminum structure (length 1.6 m) that rests on two bogies by means of four springs (secondary suspensions). The body frames of the adjacent vehicle modules are coupled. Each body frame supports a traveler compartment (shell). The continuous support on the track facilitates not only the vehicle design (the bogie becomes almost continuous, each vehicle is a simple shell of very reduced length), but also that of the track supporting structures, because there is no concentrated load on them.

The passenger compartment. Each body frame supports a passenger compartment (shell). The shell dimensions are: length 1.6 m, width 2.2 m, height 2.2 m. The same 1.6 m long body frame can support three different shell types: the vehicle end module (with the escape doors), the module with access doors (door width 1.4 m) and the module with seats for passengers. Using these types of modules, different compositions of the convoy are possible.

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The resulting train is similar to a flexible tube formed by the union of many modules. Fig. 3 shows a train suitable for low-capacity lines: total length of 26.4 m, composed of 15 modules (10 modules with seats + 5 modules with access doors). If the train can accommodate up to 4 travelers per square meter, the places offered are in total 205, of which 145 standing and 60 seated.

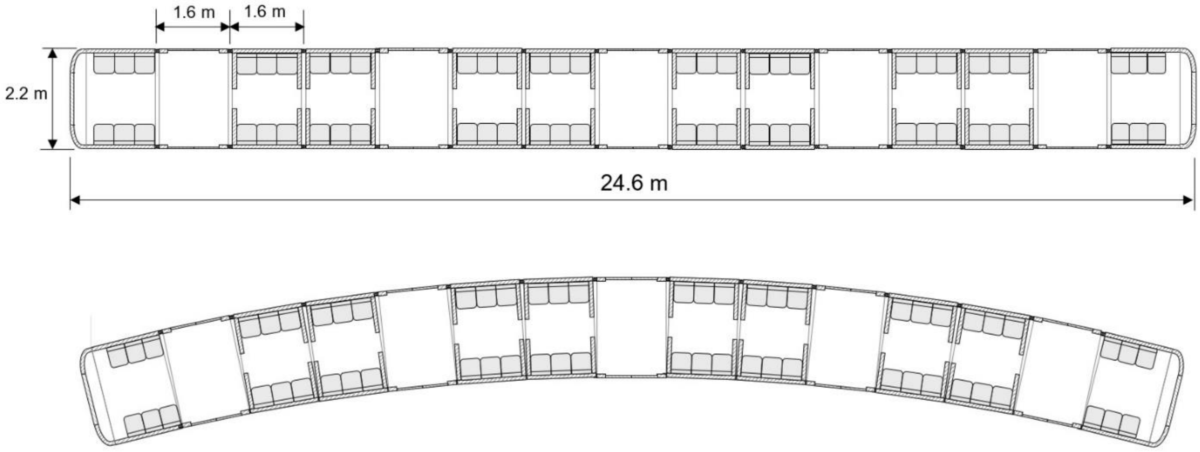

Fig. 3. Modular vehicle layout

With such short modules, even the relative displacements between the ends of the adjacent modules are very small; this facilitates the realization of the deformable coating to be applied along the entire perimeter of the shell. By adopting a minimum radius of 200 meters, the displacements between the ends of the adjacent shells are about 20 mm.

Compared to conventional systems, the vehicle has considerably lower weight and dimensions, as the load is distributed along its entire length. Therefore the vehicle does not have the great longitudinal bending moments operating on vehicles carried by bogies. Consequently, constructive simplification and a reduction in weight of both the infrastructure and the vehicle can be achieved.

In order to minimize maintenance costs and to guarantee the operating continuity, where possible, functions traditionally placed on board (such as the door opening/closing mechanism, the positioning braking system, etc.) can be installed on the ground. Therefore, the active technological part of the vehicle is restricted to the guidance systems, the emergency stop and the communication with the control center, besides lighting and speakers in the shell.

Lacking any contact between the vehicle and the track, vehicle braking must be guaranteed even in the event of a power failure. When the train is stopped at the station, the linear motor is not powered, but the train can be kept stationary by the automatic coupling between the train doors and the corresponding station fixed gates, thus avoiding longitudinal movements of the

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train during entry and exit of travelers. Only an emergency brake remains boarded (the operating brake is the same synchronous machine). The remote control system actuates the emergency brake in case of speed excess, abnormal stopping in line, vehicle running back, etc.

As a whole, the proposed solution was strongly based on the simplicity and compactness of the primary suspension composed of permanent magnets in opposition. Two compositions of NdFeB permanent magnets on an iron plate, each 130 mm wide (with 54 m^3 of magnetic material per linear meter), guarantee the levitation of a mass vehicle equal to 1,600 kg per linear meter, with a vertical gap of 12 mm (Fig. 4). That's all! Experimental tests confirmed these values.

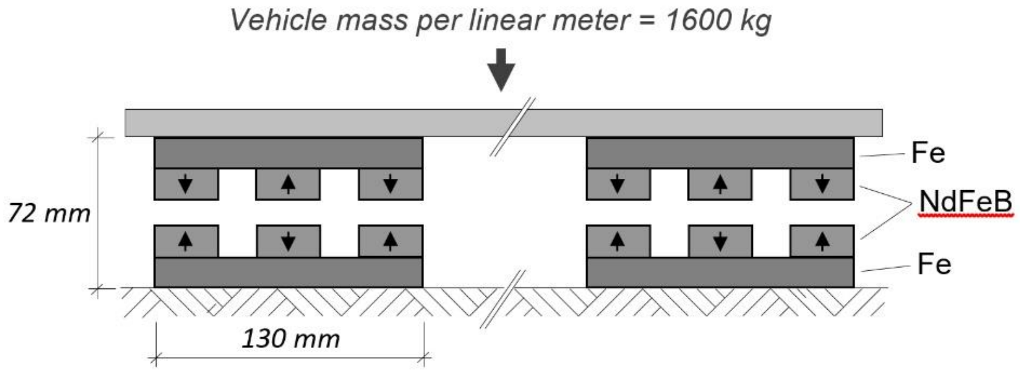

Fig. 4. Magnets' configuration to levitate a 1600 kg/m vehicle

The entire study presented in Berlin in 2016 was aimed at reducing operating costs by simplifying and, if possible, eliminating the active elements on the passenger compartment. The need for maintenance on the mobile part of the system had been reduced to the essential.

THE PRIMARY SUSPENSION

Many Maglev systems do not seem to be ready for commercial transport services, given the difficulties of industrializing systems with cheap, simple and reliable primary suspensions.

The primary suspension of our proposed system aims at these objectives, making use of the incalculable value of simplicity. The result (mass and volume occupied) is so substantial for the design of innovative urban transport systems, that we considered justified any effort aimed at perfecting an appropriate guidance device, capable of controlling the lateral instability inherent in the proposed system (magnets in opposition).

In a system with permanent magnets in opposition, in fact, a lateral displacement y of the upper magnets generates a horizontal force F_y directed in

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the same direction as the displacement y. The moving part moves sideways (instability condition) until it stops on an obstacle (for example a fixed guide parallel to the path).

The load generated on the fixed guide depends on the lateral displacement performed. Fig. 5 shows the value of the horizontal force F_y as a function of the displacement y (experimental results referred to the system of Fig. 4 with 3 + 3 pairs of magnets). In order to keep the F_y force low, it is therefore necessary to limit the y offset as much as possible.

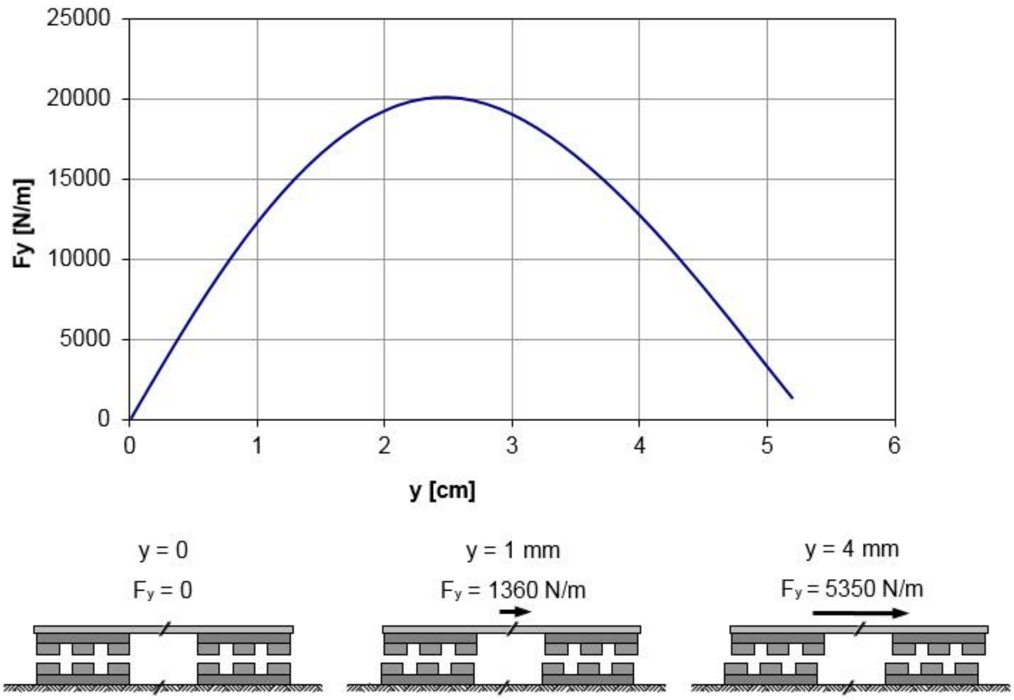

Fig. 5. Lateral force F_y as a function of displacement y, for magnets' composition of Fig. 3

At a lateral displacement y of a few millimeters there corresponds (for any number of pairs of magnets) an increase in force proportional to y and equal to about 8 % of the vertical load for each mm of displacement.

Therefore, in the case of small lateral displacements, a misalignment y corresponds to a horizontal force: $F_y \approx 0.08 \cdot Py$, where P is the vertical load (vehicle's own weight + transported load).

For example, with a vertical load equal to P = 16000 N per linear meter, a lateral force of about F_y = 2050 N acts on a 1.6 m long sliding frame, for each mm of lateral displacement.

To the lateral force $F_y \approx 0.08 \cdot Py$ (which is produced between fixed and movable magnets in the presence of a misalignment), an additional lateral force $P \cdot a/g$ is added, due to an uncompensated acceleration a [m/s^2] (positive or

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negative). The total lateral force F_g that each sliding frame transmits to the fixed guide is therefore given by the sum (1):

$$F_g = 0.08 \cdot Py + P\frac{a}{g} \tag{1}$$

The principle on which the guidance system is based uses the same unstable force F_g. In fact, the lateral equilibrium is assured by an assisted regulation that moves the frame of the upper magnets in the opposite direction to that of the lateral load, until the latter is exactly balanced by the lateral repulsion force F_g acting between the upper magnets and the lower magnets.

Guidance devices (electromagnetic and/or mechanical), able to control the displacement y, have already been tested with encouraging results, even if their total reliability is not yet guaranteed (static tests carried out on prototype at the Polytechnic University of Turin [4, 5] have given satisfactory results, but these must be confirmed in dynamic conditions).

For urban Maglevs, which normally operate at a speed within 25 m/s, a simplified mechanical guidance system has been proposed, capable of keeping the force F_g on the fixed guide within very tight limits (no more than 1÷3% of the vehicle weight P).

A mechanical spacer adjusts the distance between the suspended material and the fixed guide parallel to the path (the spacer rests on the guide with a controlled F_g load). In this way it ensures that the load on the guide is contained within the tight limits indicated.

In case of a train with a weight of P = 16,000 N per linear meter and consisting of a succession of 1.6 long sliding frames, two spacers can be used for each sliding frame. For each spacer, the load F_g on the guide must always be between 130 and 390 N.

In this all-mechanical solution, the useful length of the spacer can be regulated by an electric motor (step-by-step type), that reduces the distance when the load (measured by a load cell inserted in the spacer itself) reaches an upper limit, and increases the distance when the load falls below a lower limit.

Other solutions (partly already tested) are certainly possible, both to overcome the all-mechanical servomechanism and to eliminate the mechanical contact on the fixed side guide.

AN ALTERNATIVE SOLUTION FOR THE PRIMARY SUSPENSION

The solution A in Fig. 2 shows a primary suspension consisting of opposing permanent magnets (PM/PM primary suspension) and guidance control by means of electromagnets.

As an alternative to this solution and partly giving up simplicity, our urban system can also use high critical temperature superconductors (HTS) in

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cryogens, kept at a temperature of about 77 K (liquid nitrogen). Fig. 6 shows the new arrangement (solution B) with primary suspension made by high temperature superconductors on the vehicle and permanent magnets on the track (HTS/PM primary suspension). This arrangement guarantees a stable levitation.

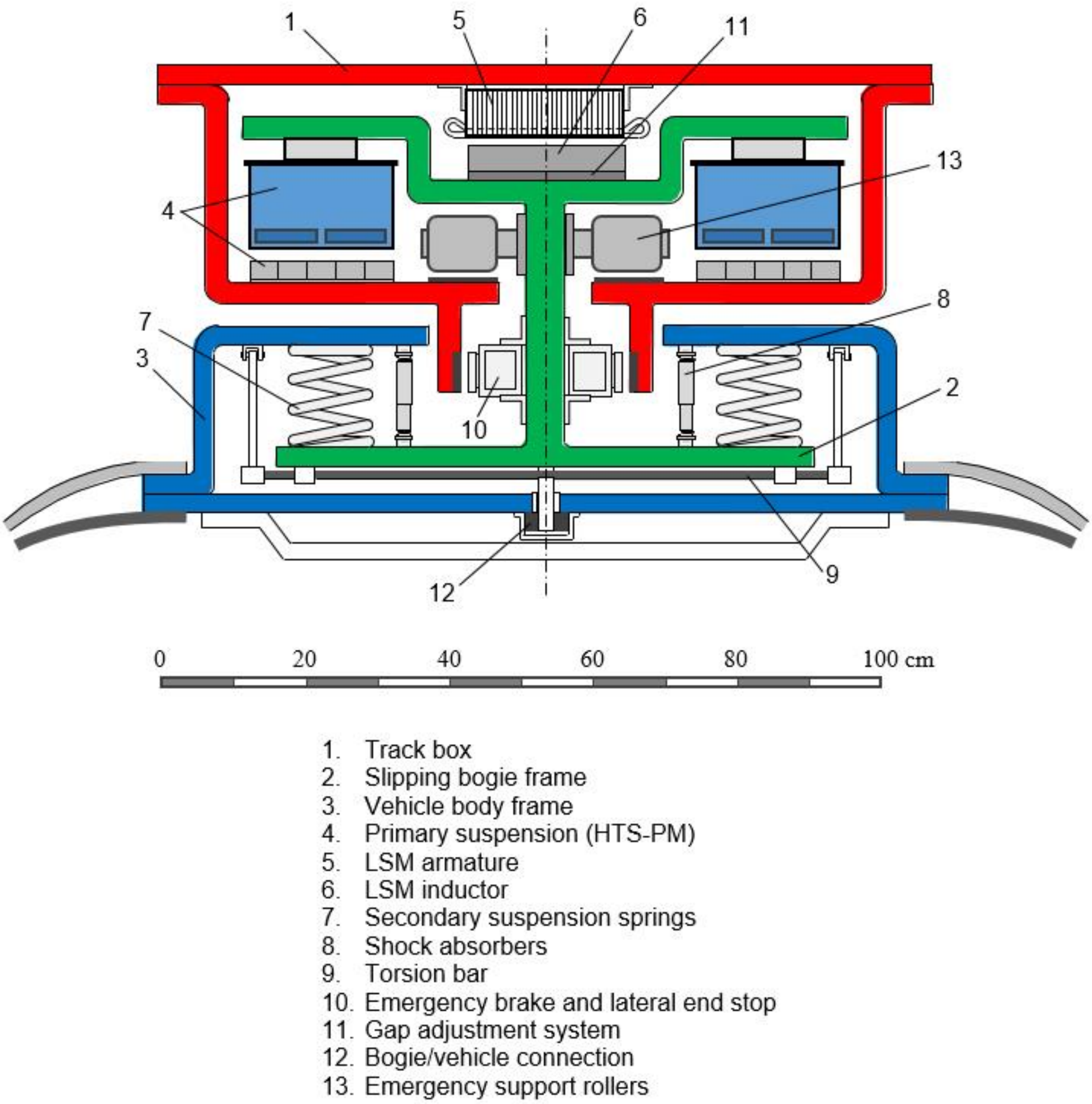

Fig. 6. The suspended Maglev system core – Solution B with HTS/PM primary suspension

This solution presents some unresolved problems:

– the high cost of YBCO superconductors;
– the operational cost for maintaining levitation capability (frequent recharge of the liquid nitrogen and restoration of superconducting conditions in the presence of a magnetic field – these activities require a dedicated plant);

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– the risk of stopping the levitation due to the deterioration of the superconducting conditions, which obliges the provision of a safety support system on the vehicle (wheels or rollers).

SOME REMARKS ON PROPULSION SYSTEM DESIGN

The propulsion and braking forces in our system are generated by a Linear Synchronous Motor (LSM). The inductor, made up exclusively of permanent magnets, is carried by the sliding bogies and runs under the armature placed in the middle of the track (see Fig. 2 and Fig. 6). Therefore, the armature is as long as the railway line and the inductor as the vehicle.

A three-phase winding is arranged on the armature (with a pitch corresponding to the length of the excitation poles, Fig. 7), which is fed at a variable frequency by a generator located in the nearest station.

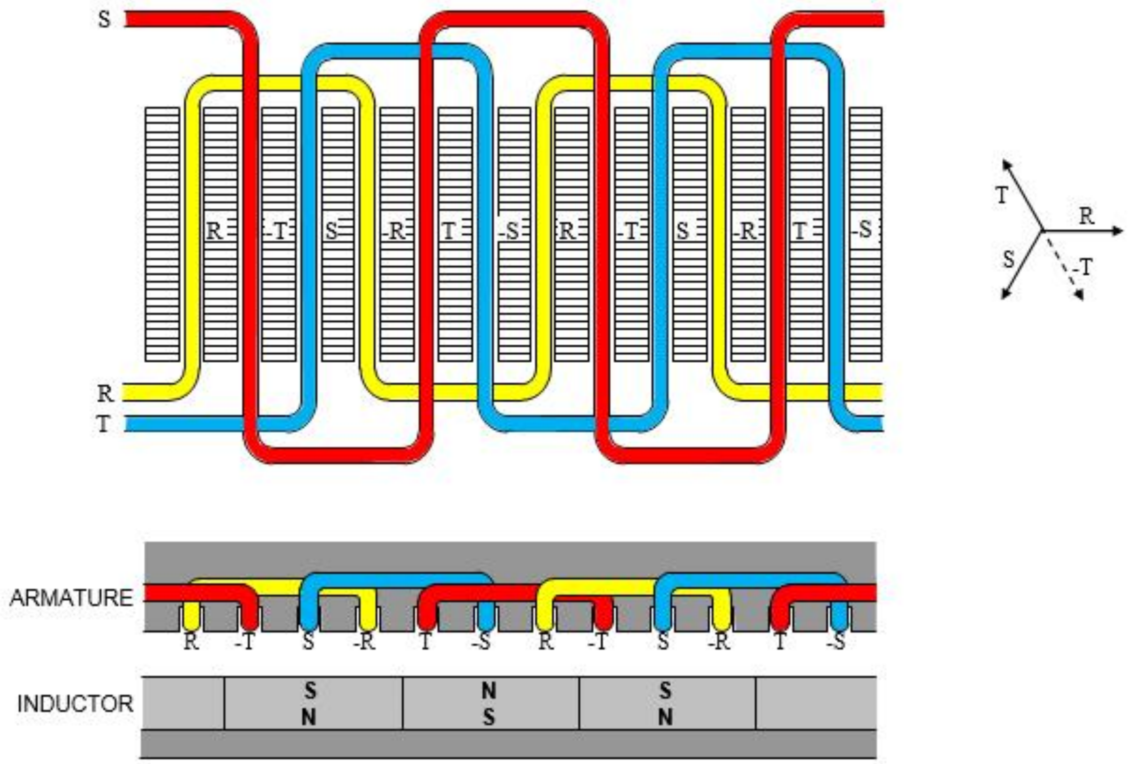

Fig. 7. The Linear Synchronous Motor (LSM)

The inductor poles (height h, semi-step p) are composed of NdFeB permanent magnets and have a sinusoidal profile (Fig. 8). Consequently, also the induction B inside the inductor poles is a sinusoidal function, which reaches the

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maximum value B_m at the vertical median of the pole and is represented, along the axis, by the expression $B_\xi = B_m \sin\frac{\xi}{p}\pi$ (Fig. 9).

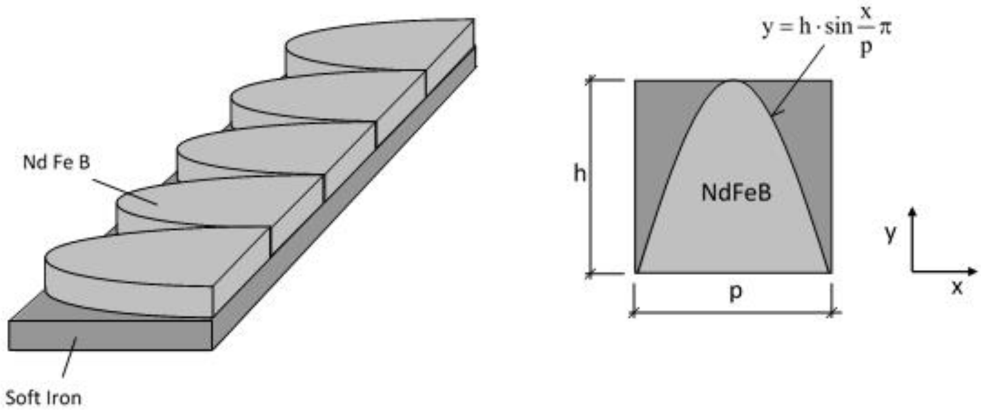

Fig. 8. Inductor shape

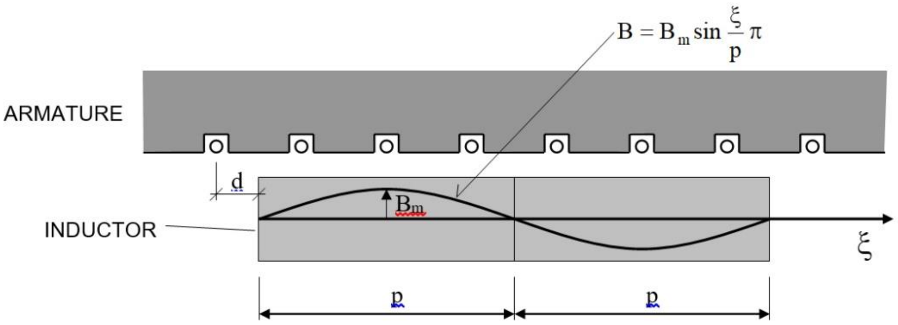

Fig. 9. Sinusoidal trend of induction within the inductor poles

The relationships between electrical, magnetic and mechanical quantities are:

$$E_{\text{eff}} = \frac{1}{\sqrt{2}} B_m \frac{h}{p} vl \tag{2}$$

$$I_{\text{eff}} \cdot \cos\delta = \frac{F_{ml}}{1.5\sqrt{2} B_m \frac{h}{p}} \tag{3}$$

where:

E_{eff}: effective electromotive force along the armature windings (V);
I_{eff}: effective current for each phase of the armature (A);
B_m: maximum induction (T);

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$\delta = \pi d/p$, where d is the phase displacement of the inductor field with respect to the translating field generated by the armature (δ in degrees; d and p in meters)
F_{ml}: propulsion force per linear meter of inductor (N/m);
v: train speed (m/s);
l: train length (m)

Some considerations on formulas (2) and (3):

E_{eff} grows according to the train speed v, the train length l, the maximum induction B_m, the shape ratio h/p, while it is independent of the resistance acting on the train during its movement; the current I_{eff} referred to a phase is independent of the speed and the train length, and it varies inversely to the induction B_m, to the shape ratio h/p and to the cosδ; it grows proportionally to the resistance to motion referred to a linear meter of the train length.

Consequently, for high-speed trains, which run mainly under steady-state conditions with infrequent and not very high accelerations, low values of B_m (0.20÷0.25 T) and h/p ratio (0.4÷0.6) are chosen, not to exceed linked voltages of 2000÷2500 volts in the armature windings, even for trains of 200÷250 m in length.

On the contrary, for urban trains, characterized by very frequent and high accelerations, opposing criteria are adopted in order to limit Joule effect losses due to the high current density in the armature windings: high values of B_m (0.6÷0.8 T), of h/p ratio (1÷1.2) and of cosδ (0.7÷0.9) (the angle δ must be between 0 and $\pi/2$ during propulsion and between 0 and $-\pi/2$ during braking).

CONCLUSIONS

Maglev systems will be competitive in the future against conventional systems only if researchers are able to develop simple solutions with low operational and maintenance costs. There are still important technical issues to be resolved and many different proposals are being developed.

This paper describes our proposal for a suspended urban Maglev. Our interest is focused on the need to find industrially feasible solutions, easy to build and manage, in order to propose a system that is also commercially competitive as an alternative to conventional railway. The benefits identified in the system encourage further studies and experiments.

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