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INNOVATIONS AND PERFORMANCE OF ITALIAN UAQ4 SUPERCONDUCTING MAGNETIC LEVITATED SYSTEM

Abstract. This article concerned with technological innovations and performance of the UAQ4 Italian maglev train project which aims mainly to reduce energy consumption by eliminating any ordinary resistance to motion (magnetic drag included), except the aerodynamic drag if it operates in atmospheric environment.
The technological feasibility of the UAQ4 suspension and propulsion devices has been patented and successfully laboratory tested.
The train architecture and the work's principles of suspension and propulsion devices are all innovative, with concepts and technologies close to the aeronautical transport system.

Keywords: Superconducting magnetic levitated train, Low energy consumption, High temprature superconductors, Suspension system, Propulsion system.

INTRODUCTION

In the field of the ground passenger transportation systems, maglev system is unanimously considered the most technologically advanced and efficient in terms of speed, comfort and energy requirements.

Maglev trains technology was initially conceived with the aims to realize a vehicle able to float over the guideway using magnetic forces by replacing the mechanical contact between steel wheel/track.

Different levitation methods for practical application have been developed starting from the 70s.

The main current levitation approaches can be classified into the following three categories:

a) Electromagnetic Suspension (EMS), based on the attractive force between actively controlled electromagnets on the vehicle undercarriage and the steel yoke of track.
b) Electrodynamic Suspension (EDS), based on the repulsive force between low temperature superconductive electromagnets on board and short-circuited conductive coils on the track.
c) Superconducting magnetic levitation (SML), with high temperature bulk superconducting (HTS) materials on board levitating in the static magnetic field of the track.

The first two systems (EMS and EDS) have reached a high level of technological maturity and operational reliability.

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The EMS with the German Transrapid TR-07 train is fully operative in China [1].

The EDS with Japanese Yamanashi train were successfully tested for a long time and a top speed of 603 km/h has been reached; it is expected that this system will be ready for commercial applications [2].

Compared with the wheel-on-rail (WoR) train, EMS and EDS systems eliminate mechanical friction but introduce magnetic resistance to the motion that varying with the speed and technology.

The currently operating maglev systems don't achieve the full potential advantages of magnetic levitation, since suspension and propulsion are still affected by magnetic resistance to motion that imply significant power consumption.

When the levitated train travels along a guideway, eddy currents are induced in conductive sheets/coils by the magnetic fields.

The interaction between the magnetic fields produces both a lift/guidance forces and drag force, due to the resistive losses in the conducting sheets/coils.

This is a clear limitation of the use of such type of maglev systems in transport applications: the magnitude of the magnetic resistance plays a fundamental role not only on a technical standpoint but also for economic reasons, since the consumed energy increases substantially the operational costs.

The third levitation approach (SML) started thanks to the emergence, in the late 80s, of new sintered magnetic materials, such as $YBa_2Cu_3O_X$ (YBCO) bulk high temperature superconductors and $Nd_2Fe_{14}B$ (NdFeB) permanent magnets (PMs). This technology potentially allows to overcome the above cited operating limitations of the current maglev systems.

Even if SLM system is in the experimental stage for practical transportation applications yet, it seems to satisfy the expectation for a future generation maglev transportation systems.

Superconductors are the only type of material known today which has a perfect diamagnetic response and zero electrical resistance. The interaction between superconductor and static magnetic field generate a conservative force field.

German [3], Chinese [4], Brazilian [5] and Italian [6] research groups are working on this superconducting maglev technology by developing and testing practical applications in non-conventional guided transportation systems.

This paper illustrates the Italian UAQ4 project SML technology based that is under development at University of L'Aquila (Italy).

ITALIAN HIGH SPEED TRAIN RESEARCH EXPERIENCES

Italian research activities in the field of non-conventional transportation systems started in the early 70s at the University of Palermo, with the prototypal

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construction of the IAP2 (Fig. 1) and IAP3 (Fig. 2) air cushion trains, that were operated on testing ground lines in the Trapani airport area (Sicily).

The IAP2 vehicle was propelled in a “U” shaped concrete guideway by an aeronautical propeller engine. Subsequently the IAP3 prototype was built. For the first time, this vehicle used an alternate current (AC), one-sided, linear induction motor for propulsion and active secondary suspensions [7, 8].

Despite the validation of several system innovations, air-cushions vehicle development was interrupted due to technological limitations (noise, energy consumption etc.) and other contingent factors of that historical period.

Fig. 1. IAP2 air-cushions vehicle

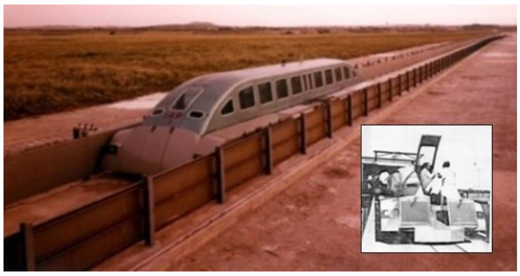

Fig. 2. IAP3 air-cushions vehicle

In the meantime, the research activities were focused on a magnetic levitation suspension with no resistance to motion, by studying an approach based on the interaction between superconducting mirror sheets and magnetic field. In 1990 the method based on the Meissner effect was proposed and patented to levitate, drive, and brake the vehicle by on-board sheets of superconductive material interacting with guideway magnetic fields [9].

Then, with the advent of the new sintered magnetic materials (YBCO and NeFeB), the research was renewed in the end 90s and the UAQ4 (short University of L’Aquila model 4) Italian maglev train project was carried out.

UAQ4 PROJECT AIMS AND ACHIEVEMENTS

The UAQ4 project is the outcome of abovementioned Italian research activities.

The suspension device produce passive, self-balancing interaction between on board superconducting skater devices and PMs distributed along the track. As consequence the train stably floats with a large air gap in all phases of motion, zero speed included, without control devices.

The UAQ4 project was started with the aim to study, define and test environment friendly technological solutions for mass transportation systems, in order to:

a) Eliminate any ordinary resistance to motion (magnetic drag included), except the aerodynamic one.

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b) Realize a levitation system to lift and guide the vehicle in stable conditions in all phases of motion, zero speed included, and with negligible electric power consumption/requirements.
c) Use high efficiency propulsion/braking system, controlled from on board.
d) Realize lightweight vehicle and conceive a system architecture with concepts, technologies and level of comfort close to aeronautical systems.

In order to achieve the project aims, the following four steps were planned:

- identify the most appropriate technologies by analysing their advantages/limitations and by elaborating algorithm a numerical model necessary for the design of main components;
- build laboratory equipment for testing both levitation and propulsion phenomena;
- validate the feasibility by building a fully working laboratory system, with all the components to lift, guide and propel the vehicle;
- design a scaled system (Fig. 3);
- full scale system preliminary design in immersive virtual reality (Fig. 4);
- full scale system detailed design.

The first five steps were carried out while the sixth is under development. As per above, within the possible technological scenarios, the SML method and direct current linear propulsion device were considered the most suitable to meet the design constraints.

Fig. 3. UAQ4 mockup

Fig. 4. Immersive virtual reality deign

TECHNOLOGICAL LABORATORY SYSTEM

The UAQ4 demonstrator system (Fig. 5) was designed and constructed to be quite simple: it consists of two main contact-less parts:

- A track (3.72 m long and 0.81 m wide) with three parallel permanent magnet guideways, of which the outer two are “V” shaped and the central one is “U” shaped. All guideways consist of iron beam with NdFeB permanent magnets arranged in the inner beams surfaces according to a proper polarity configuration.

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- A bogie (0.72 m long, 0.81 m wide), with four “V” shaped superconducting “skaters” (each 0.185 m long) aboard, fixed to both sides of the body, and with the primary of a linear motor in the middle of the frame. The “skates” consists of “V” assembled close arrays of melt textured YBCO bulks cooled at low temperature (77 K at 1 atm.) by liquid nitrogen in a suitable cryogenic vessel.

Fig. 5. UAQ4 laboratory system

The interaction between superconducting “skates” and the magnetic field of the lateral guideways generates stable suspension and guidance of the vehicle.

Fig. 6 illustrates the finite element analysis results of the interaction between guideway magnetic field and superconductors of the “skate”. The resultant of the vertical (F_L) and lateral (F_G) components of the levitation forces (F_S) originates lift and guidance effects of the skate on the guideway.

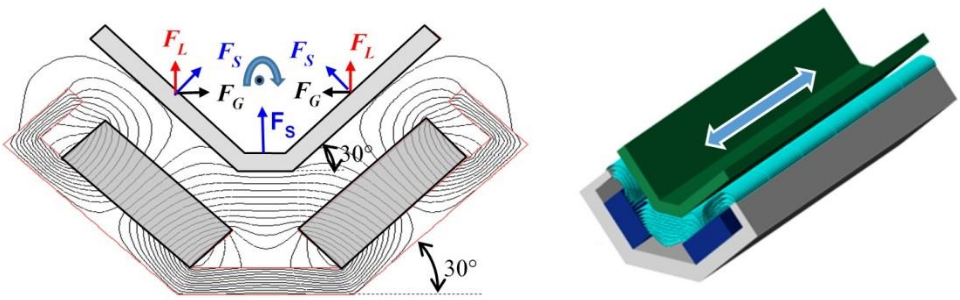

Fig. 6. Magnetic interaction schemes

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Several tests have been performed to fully verify that the suspension modules of the bogie operate in a self-balanced condition [10–13] without magnetic resistance to the motion [14].

High values of guidance effect is obtained by summing the pin effect force to the lateral repulsive forces.

Suspension device doesn't require power consumption for levitation, except the negligible power needed for cooling the bulk superconductors. So, at ordinary motion condition, the traction energy depends only from aerodynamic resistance entity; and at constant and low speed it is almost zero.

Propulsion and braking are provided by an innovative direct current linear stepper motor, safely operating along the whole speed range [15–16]. The secondary of the linear motor that is installed in the middle of the vehicle frame separately provides propulsion by interacting with fixed primary component ("U" shaped central magnetic beam).

Suspension and propulsion devises have been patented [17–18] and laboratory successfully tested.

MAGNETIC RESISTANCE CONSIDERATIONS

The propulsion power $P(t)$ of a maglev train can be calculated, besides the running in tunnels and in curve whenever it is the case, as

$$P(t)=\sum R\cdot v(t) = [R_{ae}(v) \pm R_{gr} + R_{in}(\dot{v}) + R_{mag}(v)]\cdot v(t) \tag{1}$$

where $R_{ae}(v)$ is the aerodynamic resistance, R_{gr} is the gradient resistance, $R_{in}(\dot{v})$ is the inertial resistance and $R_{mag}(v)$ is the magnetic resistance that depends on technology, as well as better detailed below.

The motion resistances are evaluated by using the following relations:

$$R_{aero} = \frac{1}{2}\cdot\rho\cdot S\cdot v^2\cdot(c_{af} + \frac{S}{S'}c_{at}) \tag{2}$$

$$R_{grad} = m\cdot g\cdot sen\alpha \tag{3}$$

$$R_{iner} = m\cdot\frac{dv}{dt} \tag{4}$$

where m is the gross mass of the train, v is the train speed, g is the gravity acceleration, α is the angle of the guideway slope, ρ is the air density, c_{af} and c_{at} are the frontal and tangential aerodynamic coefficients, S and S' are the vehicle

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frontal area and the train tangential area (depending on the number of cars in the train).

Considering regenerative electrical braking, the electric power $P_e(t)$ for propulsion is:

$$P_e(t) = \frac{P(t)}{\mu} \quad @ \ P(t) > 0$$
$$P_e(t) = \mu \cdot P(t) \quad @ \ P(t) < 0 \tag{5}$$

where μ is the efficiency of the propulsion system.
The integration in the time variable of $P_e(t)$ multiplied by the speed allows to obtain the train propulsion energy.

$$E_e(t) = \int P_e(t) \cdot dt \tag{6}$$

Compared with WoR system, EDS and EMS maglev technologies allow to avoid any mechanical contact between train and guideway and to eliminate rolling friction but, at same time, they generate an additional magnetic resistance that do not exist in WoR system.

Additional magnetic resistance (R_{mag}) depends on the kind of maglev technology: it is almost zero for UAQ4 technology while this takes on different values for the EMS and EDS technologies.

Stephan and Lascher [19] proposed a theoretical calculation method to determinate the additional magnetic resistances of the high speed EMS (Transrapid) and EDS (MLX01) systems. As reported by the Authors, the additional magnetic resistances depend on the considerations and parameters synthetically reported below.

EMS train’s additional magnetic resistance (R_{mag}^{EMS}) is a function of two parameters as indicated by the relation (7):

$$R_{mag}^{EMS} = f(R_{LG}; R_{LM}) \tag{7}$$

where: R_{LG} is the linear generator resistance that is zero for speed up to 100 km/h and R_{LM} is eddy-current resistance (due to the eddy-currents in the guideway) [19].

EDS train’s additional magnetic resistance (R_{mag}^{EDS}) is a function of four parameters as indicated by the following relation (8)

$$R_{mag}^{EDS} = f(K'_{coil}; K_{coil}; n; v_c) \tag{8}$$

where: K'_{coil} is specific coil coefficient that takes into account interference

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among the solenoids consecutively set in a super-conducting magnet of the train; K_{coil} is the coil coefficient, n number of cars in the train and v_c is a specific speed coefficient [19].

According to Stephan and Lascher analysis results, Fig. 7 illustrates the additional magnetic resistance of EMS, EDS calculated for a fixed train configuration (five cars) at constant speed motion condition. In the same Fig. 7 we also report, for the same work conditions, the UAQ4 magnetic resistance graph. The different performances of the three selected systems in terms of magnetic resistance to motion are effectively highlighted in the same figure.

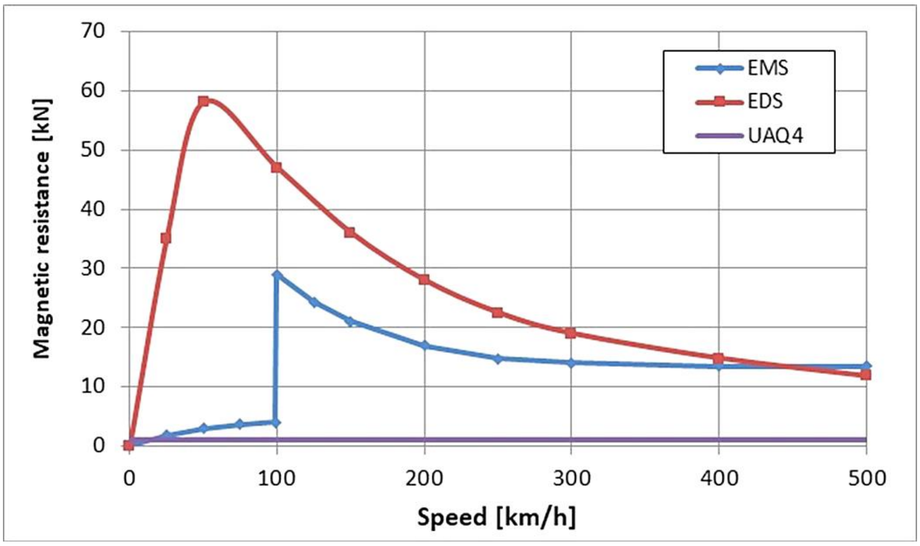

Fig. 7. Additional magnetic resistance for EMS, EDS and UAQ4

Moreover, a numerical comparison between the magnetic resistances of the three maglev systems (EMS, EDS and SML) and rolling resistance of a high speed wheel-on-rail system (WoR) has been performed.

Rolling resistance for WoR high speed train can be calculated by the following relation:

$$R_W = \left[0.7 + \frac{130}{m_{ax} \cdot g} + 0.009 \cdot v\right] \cdot m \cdot g \cdot \cos\alpha \qquad (9)$$

where m_{ax} is the mass on axle, m is the train gross mass and α is the angle of the guideway slope. As relation (9) is empirical formulation, speed is in km/h, mass in ton and resistance in Newton.

Italian high speed WoR train (ETR500) [20] was taken into consideration.

Table 1 lists the convoy configurations and the carrying capacity of the different systems that were taken into account for resistance comparison analysis.

Fig. 8 illustrates the theoretical comparison between the specific

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additional magnetic resistances (kN/passenger) for the three EMS, EDS and SML maglev systems (continuous lines) compared with the specific rolling resistance (kN/passenger) for WoR system (dotted line).

It can be noted that the specific magnetic resistance of UAQ system is almost zero. Moreover, EMS and EDS specific magnetic resistances are higher than the WoR specific rolling resistance up to a speed of around 180 km/h and 240 km/h, respectively. So, in term of motion resistance, WoR system is most efficiently than EMS and EDS at low/average speed values. On the contrary, for high speed motion EDM and EMS systems are more efficient.

Table 1. Guided systems carrying capacities

Technology	Train	N. of cars	Front car		Meaddle car		Train carrying capacity
			N.	*Pass./car*	*N.*	*Pass./car*	*Pass./train*
EDS	MLX1	5	2	24	3	70	258
EMS	Transrapid		2	62	3	84	376
SML	UAQ4		2	72	3	88	408
WOR	ETR 500		1	0	4	68	272

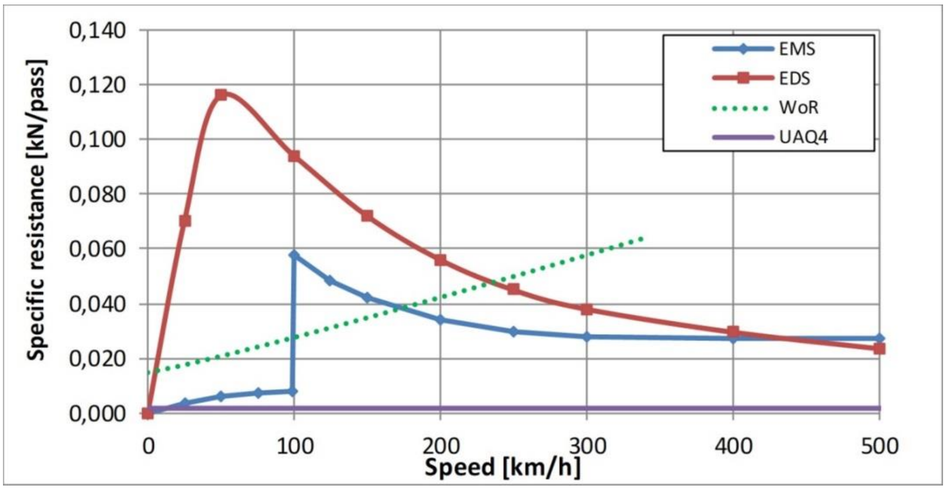

Fig. 8. Specific resistance for EMS, EDS, UAQ4 and WoR systems

INNOVATION AND ADVANTAGES

Compared with the international state of the art of maglev technologies, the UAQ4 system introduces the following significant innovations:

– three axes self-balancing magnetic suspension with large operative air gap;
– self-balancing and high guidance effect;
– no magnetic resistance to motion;
– high-efficiency propulsion system (direct current linear motor with a large air gap);
– near-zero energy consumption at low and constant speed;

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– light-weight vehicle architecture close to aeronautical standard (light materials, big size, and high comfort level).

Even if the work criteria are valid for both low-speed and high-speed transportation applications, the UAQ4 system is particularly suitable for urban environment that involves short distances between stops, the ability to overcome longitudinal gradients, large accelerations, and low operating speed. In this context, the UAQ4 operates with negligible power consumption since the ordinary resistance to the motion is almost zero.

REMARKS AND OUTLOOK

The UAQ4 superconducting magnetically levitated system features were illustrated in this paper.

Compared to other magnetic levitation methods, UAQ4 system eliminates any magnetic resistance to the motion and its suspension device doesn't require power consumption for levitation, except the negligible power needed for cooling the bulk superconductors. Moreover, at ordinary motion condition, the UAQ4 traction energy depends only from aerodynamic resistance entity; at constant and low speed it is almost zero.

The basic research activities for defining and testing the UAQ4 superconducting magnetically levitated system technologies are mostly concluded. The system architecture has been defined and the full scale vehicle is under design.

The implementation outline asks for a consortium of interested industrial partners operating in the aeronautical and the traditional railway industries. The objective is to develop a full scale urban version system prototype with vehicles mainly powered by solar energy.

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