



# Characterization Method of the V-shaped High-Temperature Superconducting Maglev Module for Transport System Applications

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## Abstract

It is now recognized that high-temperature superconducting (HTS) technology has a significant potential for future magnetic levitation (Maglev) transit system applications due to the advantages of self-stable levitation, being free of electric power and magnetic drag to the vehicle motion, and system simplicity. This article provides a characterization method of the experimental transport system Maglev levitation module developed at the University of L'Aquila (Italy). More specifically, the lifting and guiding behavior of a single V-shaped Maglev module, which is unique for this type of application, is analyzed and tested. Its working principle is based on the interaction between HTS "skate" onboard of the vehicle and the magnetic field generated by the permanent magnets distributed on the guideway (PMG). A single scaled levitation module was built and tested under quasi-static conditions using dedicated measuring equipment by varying system parameters such as vertical gap, lateral offset, and field cooling height. The latter determines the amount of interacting magnetic field that is trapped in the HTS core during its transition from the resistive to the superconducting state and which, in turn, interacts with the field generated by the PMG to create the suspension phenomenon. The Maglev module's dual behavior due to the double phenomenon of repulsion and attraction has been verified and tested in terms of vertical and lateral forces by varying system parameters. The dual "push and pull" force allows the phenomenon of vehicle driving to be enhanced.

**Keywords** Maglev transport system · High-temperature superconducting maglev · Lifting and guiding forces characterization

## 1 Introduction

Magnetic levitation (Maglev) is a highly advanced technology which finds applications in various fields such as energy, construction, transportation (train and elevator), and military. In Maglev applications, the lack of contact and friction represents the common feature. In the field of transportation, the main advantages of the Maglev-based systems over the conventional wheel-on-rail (WoR) systems are the achievement of higher operating speeds, driving comfort, energy savings, reduction of noise pollution and vibrations, ability to overcome steep track gradients, less need for rail and vehicle maintenance, and reduced risk of derailment [1].

Therefore, various studies on the Maglev technology have been conducted in different parts of world, and a large number of corridors have been studied in applications. The main Maglev-based approaches in transportation can be divided into three categories as follows:

- (a) Electromagnetic suspension (EMS), based on the attractive force between actively servo-controlled electromagnets on the vehicle undercarriage attracted upward to an iron-plate rail. EMS requires highly sophisticated active control systems due to the inherent system instability.
- (b) Electrodynamic suspension (EDS), using cryogenically cooled (4 K) superconducting magnets on the moving vehicle repelled by currents induced in short-circuited coils embedded in the tracks on each side of train. This technology does not allow the vehicle to be suspended at slow speed motion; levitation off of the auxiliary wheels occurs as soon as a low "lift-off" speed is reached.

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- (c) Superconducting magnetic levitation (SML), with high temperature superconducting (HTS) of non-ideal type II superconductor materials on board levitating in the static magnetic field of the track. The flux pinning properties of HTS generate both repulsive and attractive forces whose combination determines stable suspension without the need for any active control.

The development of the EMS and EDS Maglev technologies began in the 1970s and has reached a remarkable level of operational reliability thanks to the significant commercial and experimental applications. EMS-based systems are to date the only passenger transport systems operational with the following applications [2]: (i) extra-urban high-speed version (TR08 in Shanghai, China) and (ii) urban low-speed version (Linimo operating in Nagoya, Japan; Maglev line in Incheon, Korea; Maglev lines in Beijing and in Changsha). 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 where the world record speed of 603 km/h for manned operation was achieved in 2015 [3]. Although the EMS and EDS technologies introduce significant performance improvements over WoR systems, they fail to capture the full potential benefits of magnetic levitation as vehicle suspension requires significant energy consumption and vehicle movement is affected by magnetic resistance.

In fact, the magnetic fields of the moving part induce eddy currents in the conducting materials of the fixed part which, in turn, generate both forces necessary to lift the vehicle off the ground and forces opposing the vehicle's motion. At a low speed  $v$ , the resistance force is proportional to  $v$  while the lift force is proportional to  $v^2$ , and thus, the resistance force dominates [4].

Magnetic resistance to vehicle motion is a clear limitation of the current Maglev technologies, as it implies an increase in tractive effort and consequent energy consumption, as is the case with WoR systems due to rolling resistance.

Depending on the Maglev technology, the magnetic resistance to motion increases, with different trends, as the speed increases, up to a certain speed value, after which it tends to decrease but never disappears, as illustrated in the study of Stephan and Lascher [5].

The ideal condition for a levitation transport system is to eliminate not only the resistances due to the contact between fixed (track) and moving (vehicle) parts but also the magnetic resistances opposing the motion of the vehicle.

This condition can theoretically be achieved by using superconducting materials, which are the only known materials with a perfect diamagnetic response and zero electrical resistance. The interaction of superconducting bulks and magnetic fields is the basis of the Superconducting Magnetic Levitation (SML) technology.

When the material makes the transition from the normal to superconducting state at the critical temperature  $T_c$ , it actively excludes magnetic fields from its interior (Meissner effect) and the superconductor core cannot be penetrated by an applied magnetic field which must be less than the critical one ( $H_c$ ) [6]. Whether the applied (external) magnetic field becomes bigger than  $H_c$ , the superconductivity breaks down.

The development HTS-based SML methods started with the emergence (in the late 1980s) of  $Nd_2Fe_{14}B$  (NdFeB) permanent magnets (PMs) and  $YBa_2Cu_3O_x$  (YBCO) high temperature superconductors. Although still in the experimental stage, the high temperature SML technology has the potential to overcome the performance limitations of the other Maglev technologies described above.

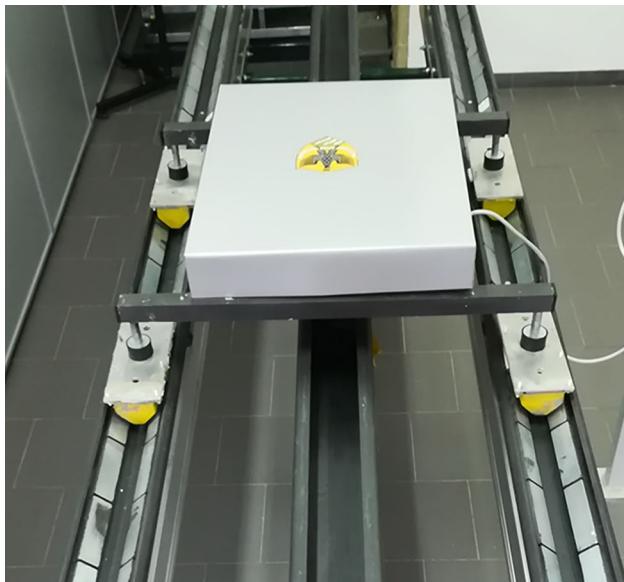
For these reasons, Chinese [7], German [8], Italian [9], Brazilian [10], Japanese [11], and Russian [12] research departments are currently working on HTS Maglev technology in order to develop and test practical applications.

Moreover, the high-temperature superconducting Maglev system has been studied and developed in different suspension configurations including: the vertical one (the conventional mode to which the above references correspond) and the lateral one, which is another typical mode on which extensive research has been conducted [13, 14].

The Italian HTS Maglev experimental system UAQ4 has been developed at the University of L'Aquila; it is based on vertical suspension mode. The dynamic behavior of the prototype was first studied by performing linear analyses and tests in a standstill condition [15, 16]. Moreover, a study addressing the effect of a transition curve on the dynamic behavior of the bogie has been recently performed.

With the present work, our intent is to experimentally analyze and test the self-stabilizing behavior of the Maglev module due to its inherent double phenomenon of repulsion and attraction, as the system parameters such as vertical gap, lateral offset, and field cooling height vary.

This paper is structured as follows. Section 2 describes the experimental UAQ4 Maglev system. Stability analyses, experimental, and results of the Maglev module are presented and discussed in Sect. 3. The concluding remarks are in Sect. 4.



**Fig. 1** UAQ4 Maglev system demonstrator

## 2 Experimental UAQ4 Maglev system

The UAQ4 (University of L'Aquila model 4) Italian Maglev train project started at end 1990s with the first phase of production and marketing of new sintered magnetic materials (YBCO and NeFeB) [17, 18].

UAQ4 project activities made it possible to (i) identify the most suitable technologies for suspension (lifting and guiding) system and propulsion system, (ii) check the system feasibility, and (iii) test the performances.

As a step along the path of the experimental activities, a Maglev linear demonstrator system (Fig. 1) was built and tested and it consists of the following:

1. A track with three parallel iron beam with NdFeB permanent magnets of which the outers are "V" shaped and the central one is "U" shaped.
2. A vehicle with four "V" shaped HTS "skates" and the primary component of a stepper dc linear motor.

Interaction between lateral guide-ways topside magnetic flux and the HTS skates generates stable lift and guidance of the vehicle, under both static and dynamic conditions; the DC linear motor in the middle of the track separately provides propulsion or braking.

The suspended vehicle is self-stabilizing since it does not require electromagnets or control circuits to maintain stable levitation; it floats smoothly above the track at standstill and in all phases of motion, zero speed included. Vehicle motion is magnetic drag-free [19].

Performance of the suspension and propulsion components have been successfully laboratory demonstrated and patented.

The whole of the test accomplishments on scaled system and the design activities of a full-scale train through an immersive virtual reality process allowed to demonstrate of (i) realizing a passive (with no control devices) levitation system to lift and guide the vehicle in stable conditions in all phases of motion, zero speed included and (ii) with negligible no power consumption (iii) eliminating any magnetic drag to vehicle motion, (iv) using high efficiency propulsion/braking system, controlled from on board; (v) realizing lightweight vehicle; and (vi) conceiving a system architecture with concepts, technologies, and level of comfort close to aeronautical systems.

## 3 The Maglev module

A single-scaled "V"-shaped Maglev module was constructed in order to perform experimental analysis on vertical and lateral stability.

The selected Maglev module consists of the following:

1. A skate (200-mm long) with assembled close arrays HTS bulks fixed in a cryostat liquid nitrogen (77 K) cooled
2. A guideway stretch (380-mm long, 147-mm large, 60-mm high) composed with iron beam within two parallel arrays of homopolar NdFeB permanent magnets.

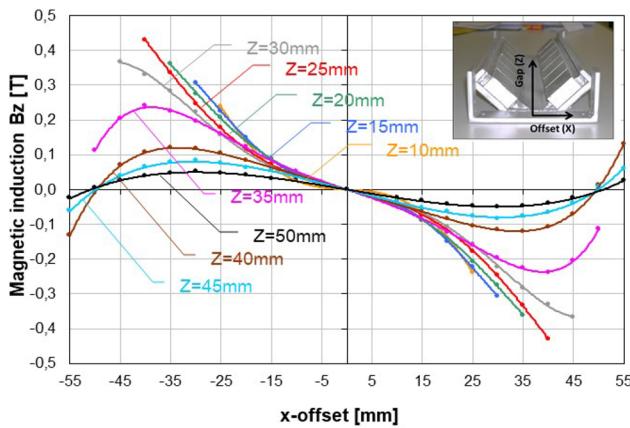
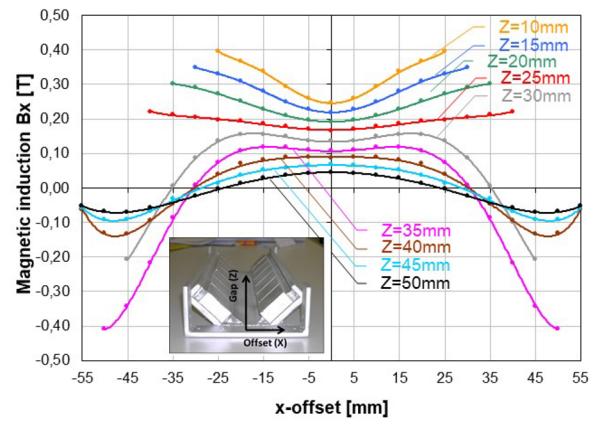
The levitation working principle is based on the interaction of HTS "skat" and the magnetic field generated by PMG.

Figure 2a, b respectively show the induction components  $B_Z$  and  $B_X$  configurations tested in the selected guideway stretch cross section.

The levitation force ( $F_{\text{Lev}}$ ) is influenced by several factors, as [20]:

- The shape and thickness of the HTS bulks
- The field cooling height ( $H_0$ ) that affects the amount of magnetic field trapped within the material when phase transition to superconductivity occurs
- The operating temperature

Moreover, the levitation force 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.

a) Magnetic induction component  $B_Z$ b) Magnetic induction component  $B_x$ Fig. 2 Magnetic induction Vs x-offset for different gap ( $z$ ) values

$$F_{\text{Lev}} = J_c \cdot d \cdot \left( \frac{\partial B}{\partial Z} \right) \quad (1)$$

Vertical force ( $F_z$ ) and lateral force ( $F_x$ ) can be calculated by Eqs. (2) and (3), respectively [21]:

$$F_z = \int J \times B_x dS \quad (2)$$

$$F_x = \int J \times B_z dS \quad (3)$$

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

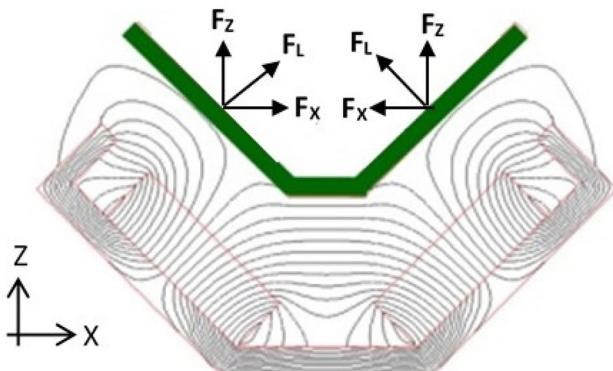


Fig. 3 Cross-section scheme of the magnetic flux line

### 3.1 Experiments

The V-shaped configuration of the levitation module 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 the Fig. 3 obtained by means finite element analysis.

$F_z$  and  $F_x$  were respectively tested, for three different field cooling heights ( $H_0$ ) of 15 mm, 25 mm, and out of field by varying (i) the vertical  $z$ -gap and fixing  $x$ -offset and (ii) by fixing  $z$ -gap and varying  $x$ -offset, according to the symbols illustrated in Fig. 4.

A proper measurement system was designed and constructed to test the static response of the Maglev module estimated from quasi-static cyclic tests in two orthogonal directions, the vertical  $z$  and the lateral  $x$ .

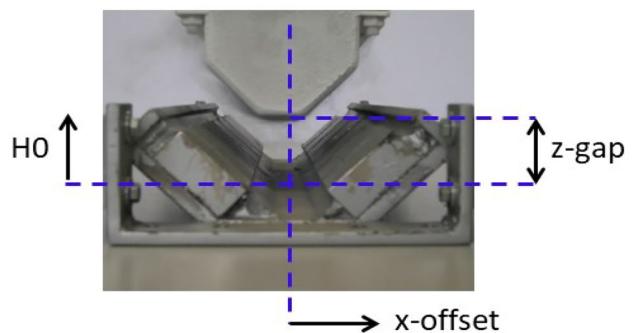
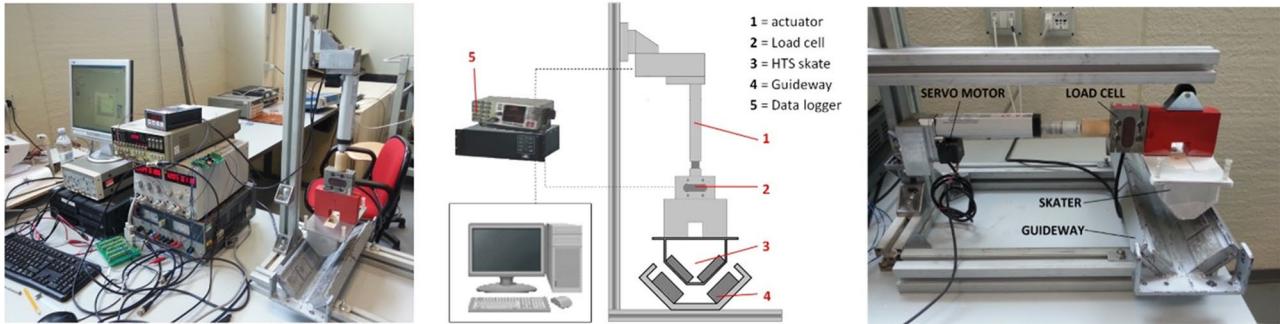


Fig. 4 Scaled Maglev module



**Fig. 5** Equipment for levitation force measurements

The test equipment (Fig. 5) includes a mechanical structure on which an actuator device is connected by means of a load cell to the HTS skate, which moves in one direction with respect to the fixed part (guideway stretch). A computer, control system, and data logger complete the equipment. A load cell measures the force exerted on the HTS skate while the actuator imposes the quasi-static motion (0.47 mm/s of velocity) of the HTS skate in a controlled way. The component forces  $F_Z$  (vertical) and  $F_X$  (lateral) were evaluated separately.

### 3.2 Vertical force

The vertical forces were measured using the following procedure.

Firstly,  $F_Z$  was measured by varying z-gap at x-offset of 0 mm and  $H_0$  of 25 mm, as illustrated in Fig. 6. With reference to the same figure, the cyclic measurement path starts

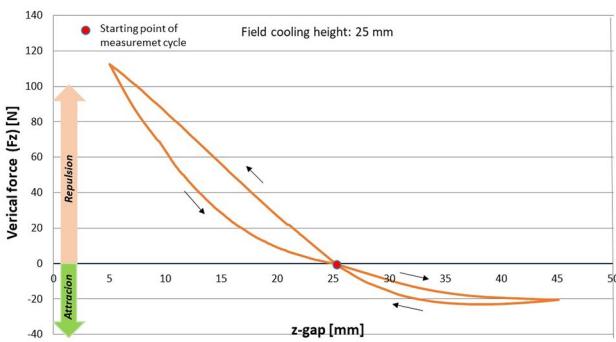
at red dot where the load cell is reset to zero and continues following the arrows. The vertical force curves are hysteretic, both repulsive and attractive with respect to the equilibrium point (red point).

In other words, with respect to the equilibrium point, the double effect is obtained: repulsive forces are generated if the superconductor and the magnets are close to each other and attractive forces if they move away.

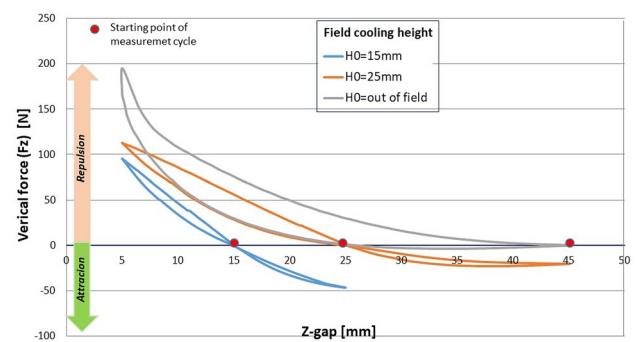
The behavior in the z direction is asymmetric and the repulsion forces being higher than the attractive ones.

This phenomenon is due to the so-called flux pinning effect that is the phenomenon where a superconductor is pinned in space above a magnet.

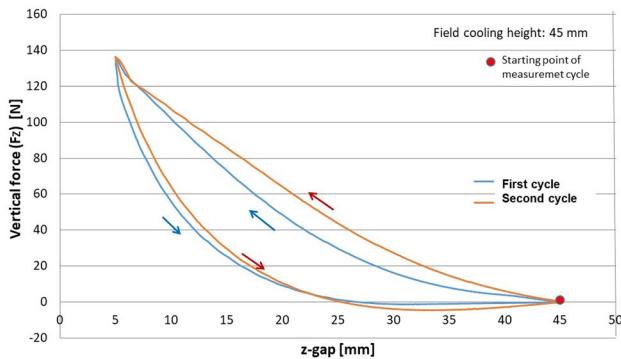
Figure 7 illustrates  $F_Z$  vs z-gap for three different values of  $H_0$  (15 mm, 25 mm, and out of field) at x-offset of 0 mm. It can be noted that the repulsive force increases as  $H_0$  rises.



**Fig. 6** Vertical force ( $F_Z$ ) Vs z-gap at  $x$ -offset = 0 and  $H_0$  = 25 mm



**Fig. 7** Vertical force ( $F_Z$ ) Vs z-gap for three values of  $H_0$



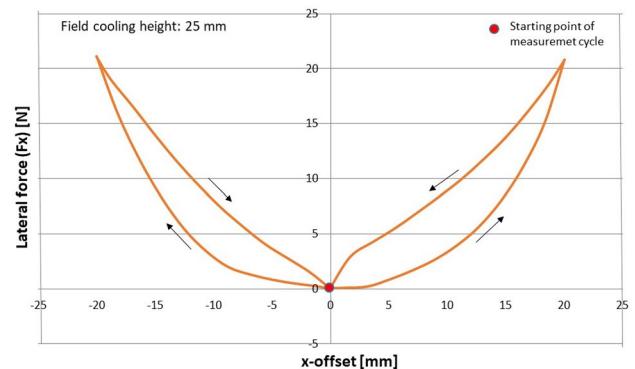
**Fig. 8** Vertical force ( $F_Z$ ) Vs z-gap for two consecutive cycles at x-offset of 0 mm and  $H_0$  of 45 mm

Secondly, the Maglev module was also tested with repetition of cycles and different speeds. Figures 8 and 9 show the vertical force ( $F_Z$ ) vs z-gap, respectively, for (i) two consecutive cycles at x-offset of 0 mm and  $H_0$  of 45 mm and (ii) two different speeds ( $V_z$ ) at x-offset of 0 mm and  $H_0$  of 25 mm.

### 3.3 Lateral force

A measurement procedure similar to the one described in the previous subsection was adopted to measure the lateral forces ( $F_X$ ) as the system parameters vary.

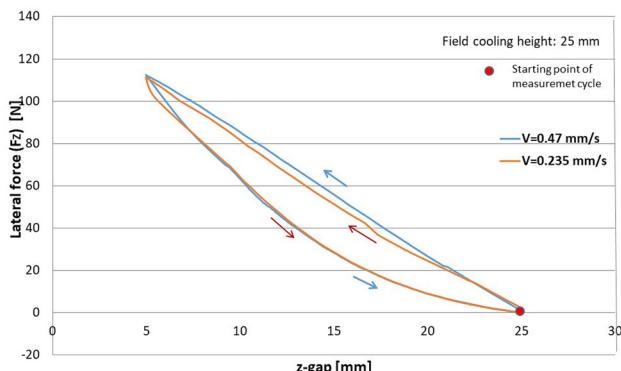
Firstly,  $F_X$  were measured by varying x-offset at z-gap of 25 mm and  $H_0$  of 25 mm, as illustrated in Fig. 10. It can be



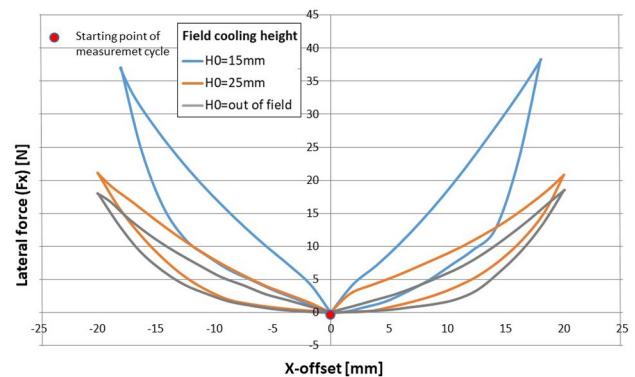
**Fig. 10** Lateral force ( $F_X$ ) Vs x-offset at z-gap of 25 mm and  $H_0$  of 25 mm

noted that the hysteretic curves are symmetric with respect to the vertical axis passing through the red dot.

Secondly,  $F_X$  was tested by varying x-offset for three different values of  $H_0$  at z-gap of 25 mm (Fig. 11). It can be noted that the lateral (guidance) force increases as field cooling height ( $H_0$ ) decreases. The results show that whether the HTS skate moves to the left or right side, the part of the guide closest to the side of the skate produces repulsive force, while the part farthest away produces attractive force. This type of dual “push and pull” force allows the phenomenon of vehicular guidance to be optimized.



**Fig. 9** Vertical force ( $F_Z$ ) Vs z-gap for two speeds at x-offset of 0 mm and  $H_0$  of 25 mm



**Fig. 11** Lateral force ( $F_X$ ) Vs gap for three values of field cooling height

## 4 Conclusions

The magnetic behavior of a single V-shaped module of the UAQ4 Maglev experimental transport system has been analyzed and tested in this study. Its working principle is based on the interaction between HTS “skate” onboard of the vehicle and the magnetic field generated by the permanent magnets distributed on the guideway. A single-scaled levitation module was built and tested under quasi-static conditions using dedicated measurement equipment. The module self-stabilizing behavior due to its inherent double phenomenon of repulsion and attraction has been verified and tested in terms of vertical and lateral forces as the system parameters are varied.

Vertical and lateral forces were respectively tested in a quasi-static condition varying vertical z-gap and x-offset for three different field cooling heights of 15 mm, 25 mm, and out of field. The module was also tested with repetition of cycles and different speeds.

The obtained results indicate as follows:

- The vertical force hysteretic curves are both repulsive and attractive with respect to the equilibrium point; the magnitude of the force increases with increasing field cooling heights
- The lateral force hysteretic curves are symmetrical with respect to the vertical axis passing through the equilibrium point: the magnitude of the force increases with decreasing field cooling heights.

A trade-off between lifting and guiding forces is obtained by using an average value of field cooling heights. The dual “push and pull” force allows the phenomenon of vehicle driving to be enhanced. This research contributes to strengthening the technical feasibility of transport systems based on Maglev HTS technology; the results can provide a useful reference for engineering application.

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