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Analysis of the Levitation Forces Generated by High-Temperature Superconductors Located within the Magnetic Field of a UAV Catapult System

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Abstract. This paper presents an analysis of the levitation forces applied to the launch truck of an innovative UAV (unmanned aerial vehicle) catapult system with high-temperature superconductors. The levitation force is a result of the Meissner effect that occurs between a YBCO high-temperature superconductor and the magnetic field generated by neodymium magnets. This paper is an elaboration of the experiments conducted to measure the levitation force value as a function of the gap generated by the superconductors.

Keywords: physics, magnetic levitation, high-temperature superconductors, Meissner effect

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1. INTRODUCTION

Levitation (originates from the Latin word “levitas” for “lightness”) is a physical phenomenon by which a body remains stationary without any contact with a material surface. Application of levitation in mechanical systems would eliminate the phenomenon of friction between a body and its substrate, and significantly improve the energy efficiency.

Until now, magnetic levitation has had the greatest impact on rail transport and the magnetic bearing manufacturing sectors. Currently, there are two commercial magnetic suspension (Mag-Lev) solutions in use [1].

The electromagnetic suspension systems (EMS) developed by Transrapid of Germany work on the principle of the force of attraction between the metallic rails and the controlled electromagnets installed within the undercarriage of the train. There have been Mag-Lev application concepts for passenger vehicles as well. In Tel Aviv, a test route for the Sky-Tram system, developed with NASA, will be built. This project assumes that light, two-man pods with overhead suspension will travel on an aerial infrastructure between predetermined stops, or stations.

Fig. 1. Mag-Lev solutions: Transrapid, Japan and Sky-Tram

An enticing alternative solution is to use levitating diamagnetic substances which include high-temperature superconductors.

Superconductivity is a property of many metallic elements, alloys, intermetallic compounds and extrinsic semiconductors that vary in crystallographic structure. The critical temperatures of superconductive materials range from 0.001 K for radium to 165 K for HgBa2Ca2Cu3O8+δ under 20 GPa of pressure. Hence, the adjective ‘high-temperature’ is a rather relative term and refers to superconductors with a critical temperature of over 30 K. The class of high-temperature superconductors includes both copper oxide based ceramic materials and carbon-based fullerenes.

The atomic structure of ceramic superconductors is not unlike the naturally-occurring minerals called ‘perovskites’. For YBCO to enter the superconductive phase, liquid nitrogen may be applied to it, instead of rather hazardous and dangerous liquid helium.

The experiments presented herein form part of an innovative solution that is based on applying the magnetic suspension system, made from high temperature superconductors, in a UAV catapult system [2].

2. MODEL OF THE UAV MAGNETIC CATAPULT SYSTEM

Magnetic catapults, unlike traditional catapults, are capable of achieving much higher launch velocities that enable the fully automatic launching of aircraft. Fig. 2 shows the components of a Meissner effect magnetic catapult built under EU FP7 GABRIEL (*Integrated Ground and on-Board system for Support of Aircraft Safe Take-off and Landing*).

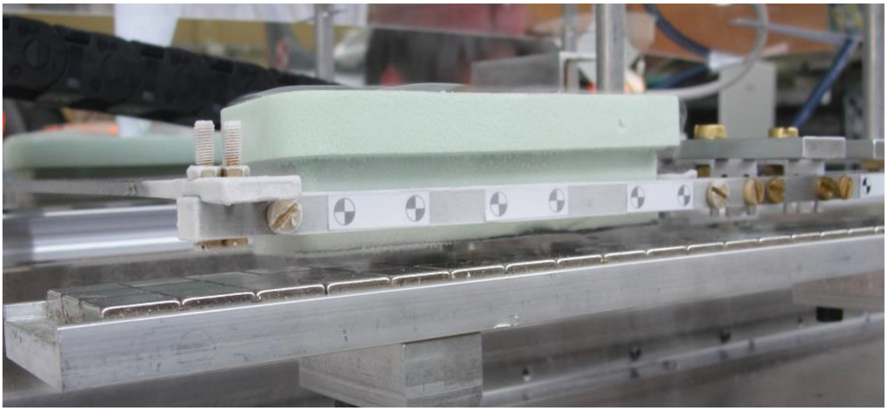

Fig. 2. Components of the prototype UAV magnetic catapult

The UAV to be launched is placed on a launch truck, which is the moving component of the magnetic catapult. The magnetic catapult launch truck comprises a rigid Duralumin frame with four pods (Fig. 2). Each pod houses four YBCO superconductors with a critical temperature of 92 K. Each YBCO superconductor is a cylinder 21 mm in diameter and 8 mm high. The pod cover presses the four YBCO superconductors against the pod bottom to prevent them from shifting. The pod bottom is secured with a carbon fibre material from protection against damage.

Once each pod has been filled with liquid nitrogen, the YBCO superconductors enter the superconductivity state, which triggers the Meissner effect [5], and the YBCO superconductors start to levitate over the tracks (Fig. 2).

The levitation phenomenon ceases when the temperature of the YBCO superconductors rises above the critical point of 92 K; hence, the pods must provide the maximum thermal insulation possible. Each pod was designed to have the largest possible surface area of every superconductor inside covered with liquid nitrogen. In the lid of each pod is a liquid nitrogen fill port and a number of small vents.

The catapult take-off way comprises two parallel tracks, each lined with three rows of permanent magnets. The design has two magnet polarity configurations. In the first configuration, the magnet stacks are polarized in opposite directions: the magnets oriented along the tracks are in monopolar contact, whereas the magnets oriented crosswise to the tracks are in bipolar contact (this is a “gutter” polarity configuration). In the first configuration, the magnetic field gradient along the track is zero; hence there is no force to decelerate the launch truck. Unfortunately, laying, aligning and securing the tracks in this configuration is problematic and requires dedicated engineering solutions because of the strong repulsion of monopolar magnets in successive stack layers. This is concomitant to extreme mechanical stress that may reduce the strength of the tracks.

Another solution (which is called a “checkerboard” polarity configuration) is to orient the polarity of the magnets in such a way that each magnet touches the other magnet with the reverse magnetization vector side to side. The magnetic field gradient along the track line is then different to zero; hence, there is a decelerating force applied to the launch truck. This configuration can be very useful at the track terminus where the launch truck needs to brake to a stop.

3. LEVITATION FORCE

The generation of the levitation force which lifts and keeps the launch truck clear over the magnetic trucks can be explained by the Meissner effect.

The Meissner effect consists in forcing out the magnetic field from within the superconductor (Fig. 3). According to Lenz's law, the inside of a conductor introduced into a magnetic field induces a shielding current that prevents the penetration of the magnetic field flux into the conductor's matter. Since superconductors exhibit zero-resistance currents, the shielding from the magnetic field is complete [5]. The shielding currents flow in a thin layer near the superconductor’s surface. The shielding layer width, or the depth of coherence, is determined by London equations. The shielding currents flowing through the superconductor turn the latter into a magnet with a polarity that opposes the polarity of the external magnetic field.

The magnetization vector of the superconductor is always directed in the opposite direction to the external magnetic field (which is the diamagnetic property), the superconductor remains in a state of stable levitation over the magnets.

The best theory to describe the phenomenon of superconductivity is the Nobel-prize winning theory from John Bardeen, Leon Cooper and Robert Schrieffer, or the BCS theory for short, this theory states that the lossless current flow through a superconductor is caused by the so-called Cooper pairs, and not singular electrons. The current induced in a superconductor by the application of an external magnetic field (and carried by the Cooper pairs) flows without any resistance; there is no energy loss from any interaction between the electrons and the lattice ions. Hence, the shielding from the external magnetic field is complete.

The shielding currents turn the superconductor into a magnet, the magnetisation vector of which always points in the direction opposite to the external magnetic field. These properties are guaranteed by the stability of the superconductor's levitation.

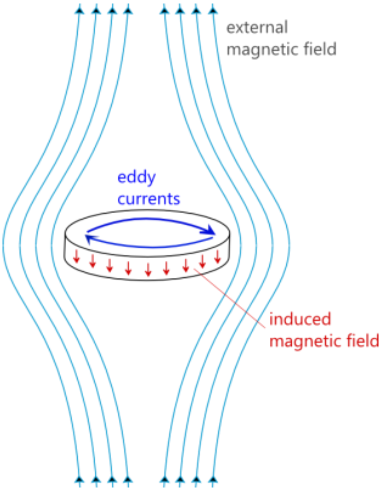

Fig. 3. Meissner effect

4. EXPERIMENTAL MEASUREMENT OF LEVITATION FORCES

The experiments contemplated herein were carried out with a MTS Bionics 793.00 strength testing machine.

The lower fixture jaws of the strength testing machine were fixed and rigidly bound to a 661.18H.01 force sensor with a sensitivity resolution of 1 kN.

The upper fixture jaws of the strength testing machine moved vertically at various velocities. The position of the upper fixture jaws was measured with a laser extensometer.

A section of the magnetic catapult track was mounted in the lower fixture jaws (Fig. 4).

The tested track was built by adhesively bonding three rows of permanent magnets to a metal beam. On one side of the tracks was the checkerboard magnet polarity configuration, with the gutter magnet polarity configuration on the other side. An important stage of these experiments was to compare the levitation forces generated by both magnet polarity configurations.

A chuck was installed in the upper fixture jaws to which the levitating pod of the magnetic catapult launch truck was attached. The levitating pod was made from a good thermal insulator and contained four YBCO high-temperature superconductors.

The chucks were made from non-magnetic materials. The chucks were designed and fabricated at the Faculty of Mechatronics. Another difficulty at the concept stage was the need to safely fill the levitating pod with liquid nitrogen.

Fig. 4. Measurement test bed with the MTS Bionics 793.00 strength testing machine

The charts below show a comparison of the levitation forces generated by specific magnet polarity configurations installed on the magnetic catapult tracks. Figure 5 shows the results for the checkerboard polarity configuration. Figure 6 shows the results for the gutter polarity configuration. Each figure shows three charts plotted in MATLAB. The top chart is the levitation force registered by the force sensor of the strength testing machine.

The middle chart shows the movement of the upper fixture jaws, corresponding to the levitation gap between the levitating pod and the magnetic catapult tracks. The bottom chart shows a representation of the levitation force within the gap.

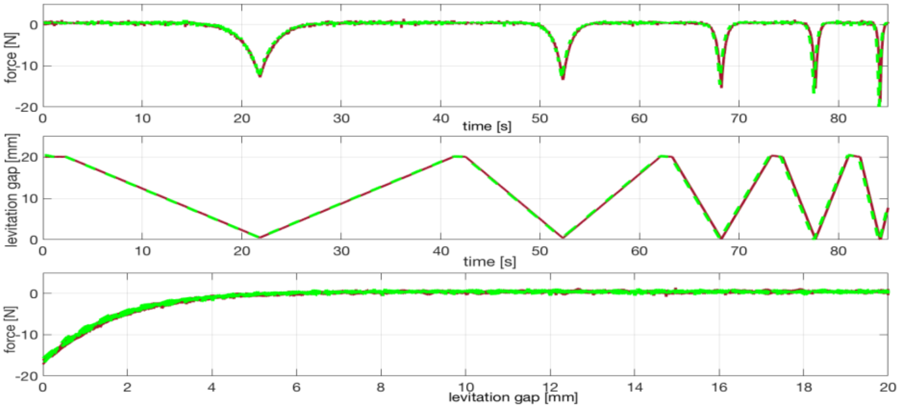

Fig. 5. Effect of the track magnet polarity configuration: the checkerboard

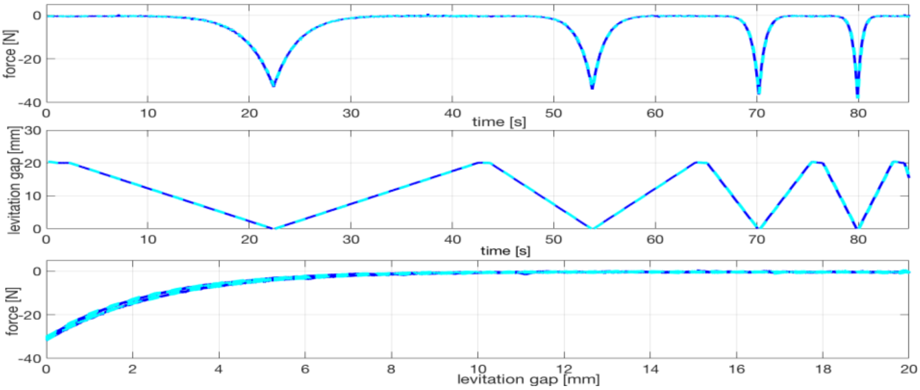

Fig. 6. Effect of the track magnet polarity configuration: the gutter

The results indicate that the checkerboard polarity configuration is approximately three times higher.

The movement rate of the upper fixture jaws has a negligible effect on the force, which is indicative of a negligible attenuation of the tested system

5. CONCLUSION

The test method presented herein is very promising in terms of determining future results. The author plans to repeat the measurements for various numbers and types of superconductors and to experimentally determine the levitation force stiffness ratio. A disadvantage of this method is the inertia of the strength testing machine when it is applied in dynamic measurements, especially when higher motion velocities are present.

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Analiza sił lewitacyjnych generowanych przez wysokotemperaturowe nadprzewodniki umieszczone w polu magnetycznym wyrzutni samolotów bezzałogowych

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Streszczenie. W pracy zaproponowana została analiza sił lewitacyjnych działających na wózek startowy innowacyjnej wyrzutni samolotów bezzałogowych, wykorzystującej wysokotemperaturowe nadprzewodniki. Siła lewitacji jest konsekwencją efektu Meissnera zachodzącego pomiędzy wysokotemperaturowymi nadprzewodnikami YBCO a polem magnetycznym wytwarzanym przez magnesy neodymowe. W pracy opisane zostały eksperymenty przeprowadzone w celu pomiaru wartości siły lewitacyjnej w funkcji szczeliny generowanej przez nadprzewodniki.

Słowa kluczowe: fizyka, lewitacja magnetyczna, wysokotemperaturowe nadprzewodniki, zjawisko Meissnera