Investigation of mechanical properties of a rigid body in magnetic levitation state

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Levitation (from Latin levitas - lightness) is the process in which an object is suspended by a physical force against gravity, in a stable position without solid physical contact. The phenomenon of levitation, caused by magnetic forces is called magnetic levitation. The main advantage of magnetic levitation systems is the elimination of friction, which significantly influences reliability, capability, ecology and safety. The phenomenon of magnetic levitation can be used in Unmanned Aerial Vehicle (UAV) catapult. The article presents the results of experiments performed on the prototype magnetic catapult. Catapult has been designed for small, unmanned aircraft, weighing less than 2 kg. The results show the oscillations of levitating cart of magnetic catapult during simulated and actual take-off and landing procedures.

Key words: magnetic levitation, superconductors, Meissner effect, and UAV catapult

Introduction

The phenomenon of magnetic levitation is closely related to the Earnshaw theorem saying that there is no stationary configuration of permanent magnets witch allows stable levitation [1]. Therefore, the passive suspension using permanent magnets requires additional stabilization achieved by blocking some of the degrees of freedom or by giving levitating object a gyroscopic moment.

Earnshaw theorem does not apply to diamagnetic materials. Meissner effect means that from interior of the material being in superconducting state, all external magnetic fields are pushed off [2]. As a result of this effect, superconducting materials in the superconducting state indicate perfect diamagnetism, and levitate above magnetic materials (fig. 1).

Superconductivity is a thermodynamic state of matter and occurs at very low temperatures. Most of the non-magnetic elements exhibit superconductivity at temperatures of a few Kelvin degrees. A real breakthrough in the research was the discovery of high-temperature superconductors with critical temperatures comparable to the temperature of liquid nitrogen. The most common high-temperature superconductor is YBCO ($YBa_2Cu_3O_7$) with a critical

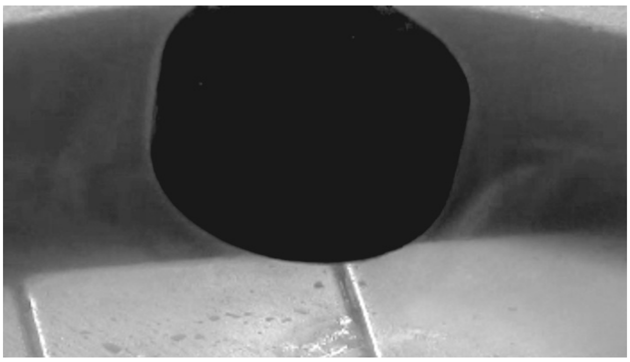

Fig. 1. Meissner effect

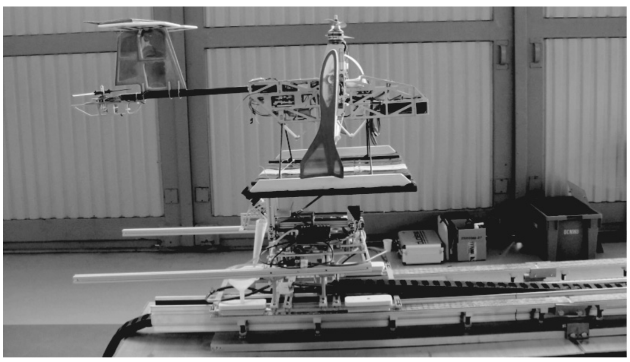

Fig. 2 . Prototype UAV catapult based on Meissner effect

temperature 92K. Laboratories all over the world are working to discover the compounds, which would exhibit superconductivity at higher temperatures. Currently, the highest critical temperature is 135K (HgBa2Ca2Cu3O8) [3].

To date, there have been a small number of research projects considering the use of high-temperature superconductors, magnetic levitation phenomenon in technical issues – mainly in urban transport problems [4,5] – or unmanned aircraft catapults [6] (fig. 2).

Superconductivity arouses a growing curiosity of researchers, mainly because of the promising prospects of technical use. Magnetic catapults, compared with classical solutions enable safe, non-impact service of UAV launches process and allow to expand much bigger final UAV speed. NASA plans using electrodynamics catapults to launch spacecraft and hypersonic planes. It is also planned that Magnetic catapults would replace steam catapults used on aircraft carrier. Nowadays electrodynamics suspensions are used in high-speed trains (Mag-Lev). Magnetic suspensions using Meissner effect are a very attractive alternative to them.

Prototype Magnetic UAV catapult

Our paper deals with innovative solution, based on magnetic levitation phenomena of high-temperature superconducting materials and new design of UAV catapult. In (fig. 3) the prototype of magnetic UAV catapult has been shown.

Magnetic catapult prototype consists of magnetic suspension system and the linear drive [7]. The components of the system are mounted on stable plates, each having a length of 960 mm; so two people can transport the catapult. UAV is taking-off and landing on levitating cart, being a movable part of catapult. Levitating cart is constructed of rigid aluminium frame, magnetic suspension components and a linear electric motor.

To disperse a cart the linear motor HIWIN LMCA Company has been used. The linear motor, powered by a single-phase inverter, consists of a frame mover mounted on the levitating cart and stators 320 mm long combined into a single ruler. It should be noted that the above construction is not the optimal solution - the motor parts should be reversed, so a small team of magnets should be connected to cart and the windings should be attached to the plate.

Fig. 3. Prototype catapult based on Meissner effect, built as part of 7 PR UE GABRIEL

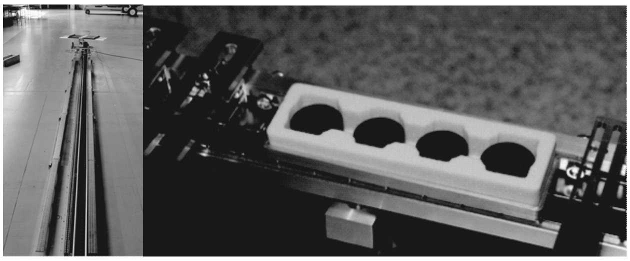

Fig. 4. Magnetic rails six meters longand box for YBCO

However, because of financial limitations, the installation has been limited to commercially available solutions.

Magnetic suspension system consists of magnetic rails and levitating cart. Passive suspension using the Meissner effect consists of a set of magnets and superconductors flooded with liquid nitrogen and placed in a container that is a good thermal insulator. Very low thermal conductivity of the container ensures that the superconductor will remain longer in the critical temperature, which is necessary for the above magnets to levitate. The container is shaped in a way that enables the flowing of the liquid nitrogen over the largest possible surface area of superconductors. The cover of the container is designed to restrict the upward movement of the superconductors (passive suspension response). The lid of the container has a hole for filling with liquid nitrogen and a small vent holes. The container has place for four YBCO superconductors with a critical temperature of 93 K. Superconductors have the shape of cylinders with a diameter of 21mm and a height of 8mm, YBCO are pressed to the base of the container by a cover, the containers are protected against mechanical damage by a carbon fiber mat.

Another element of magnetic suspension is a track built of three rows of magnets polarized in opposite directions. With this arrangement of magnets, a magnetic field above the track takes the form of „gutter". Along the railway line magnetic field gradient is zero, so that the movement of the superconductor is lossless, while the non-zero field gradient across the track pushes a superconductor to the centre track, which improves the stability of the system.

Laboratory and actual tests

Magnetic catapult cart is equipped with XSENSE MTi-300 HRS sensor which contains motion processing core for multiple sensor inputs and data sources, high-performance XEE, beyond traditional Kalman Filtering, tuned for performance under vibrations and magnetic distortions, comprehensive SDK and straightforward integration system, tracking sensitivity -161 dbM, velocity accuracy 0.1 m/s (fig. 6).

The MT Software Suite allows users to configure and easily integrate the MT Wireless Motion Trackers in their own applications. The suite contains a specially developed and easy-to-use graphical user interface, as well as drivers for various operating systems and many other useful tools, exemplary source code and documentation.

Two kinds of experiments had been performed in laboratory conditions. Simulation of vertical landing and simulation of vertical take-off, both with cart velocity that equals zero. Cart response has been recorded by XSENSE sensor. During all of those experiments sampling frequency

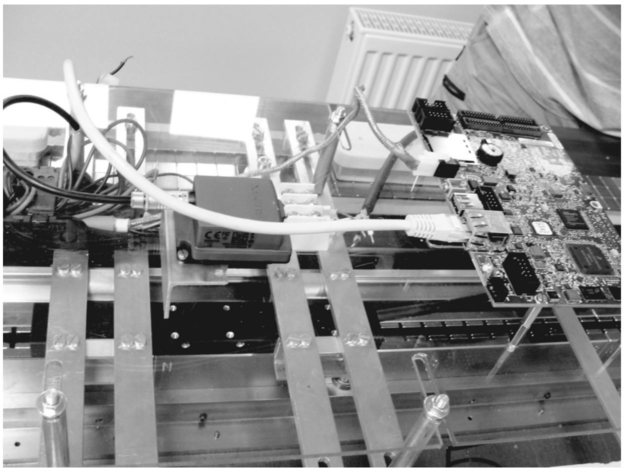

Fig. 6. XSENSE MTi-300 HRS sensor

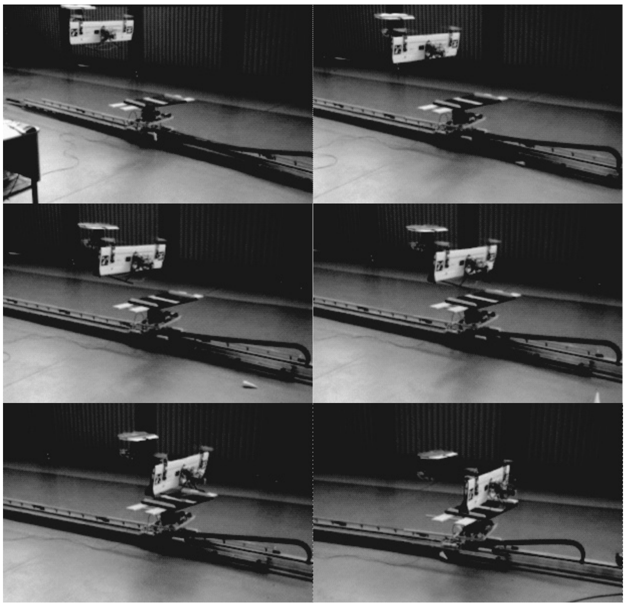

Fig. 7. Frame by frame photos showing a moment of landing on moving cart

Fig. 8. MEMRECAM HX-5 high-speed camera system and camera tags on levitating box

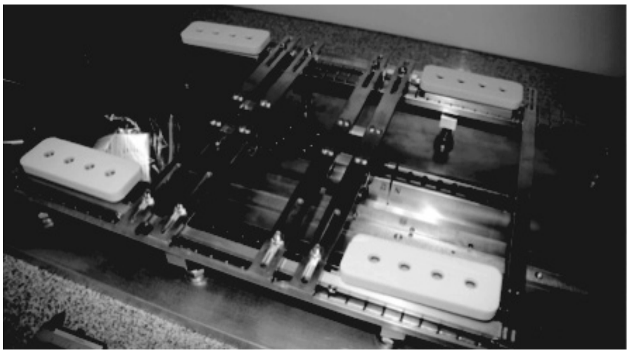

Fig. 5. Levitating cart of magnetic UAV catapult

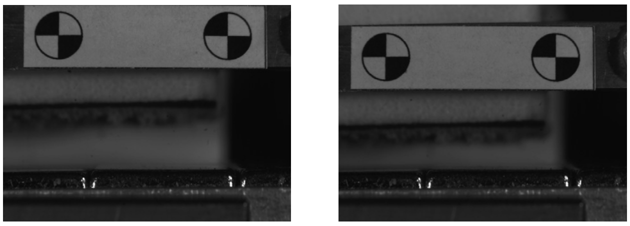

Fig. 9. Photos taken by high-speed camera, showing a levitating gap during a moment of UAV landing

was equalled: f=1000Hz. To filter signals recorded by XSENSE sensor the Butterworth-filter has been used.

We also performed also a series of tests investigating the possibility of a successful take-off and landing with a small-scale validation aircraft, using maglev technology. During planar test a landing aids system was placed on levitating cart. The aid system includes a movable platform that automatically sets the relative angular position of the aircraft. The research team from Aachen University has developed platform and aircraft. Fig. 7 shows frame-by-frame photos of a micro UAV landing on levitating cart.

The test bench measuring system is based on photogrammetry, which requires high-speed camera and dedicated software. It was used MEMRECAM HX-5 high-speed camera system allowed to perform 7030-mega flops video, 1280x760 resolution. Camera system includes dedicated software allowed to measure levitation gap, and vertical velocity of Maglev suspension system fig. 8. fig. 9 shows selected frame photos recorded by MEMRECAM HX-5 high-speed camera system during landing of micro UAV on levitating cart.

Results

Figures below show the results of laboratory tests on linear acceleration of levitating cart during simulated UAV landing and take-off (fig.10-11).

As we can see, the cart oscillations seem to be stabilized before the end of measurement window (3,2 s), so the system appears to be stable. It is worth noting that cart oscillations caused by UAV take-off are bigger and longer than oscillations caused by landing.

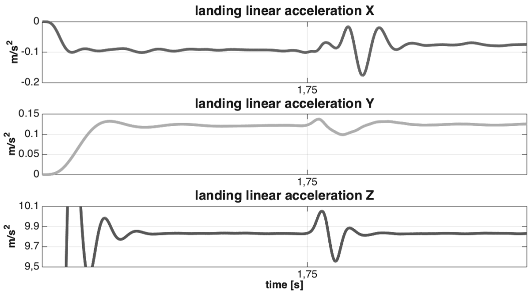

Fig. 10. Linear acceleration of levitating cart during landing simulation

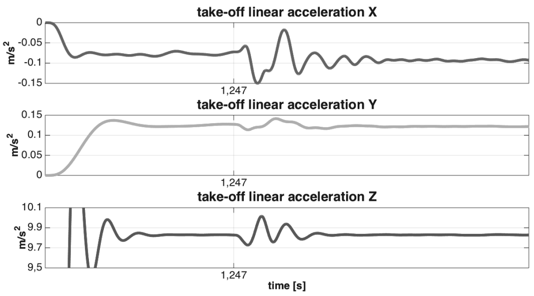

Fig. 11. Linear acceleration of levitating cart during take-off simulation

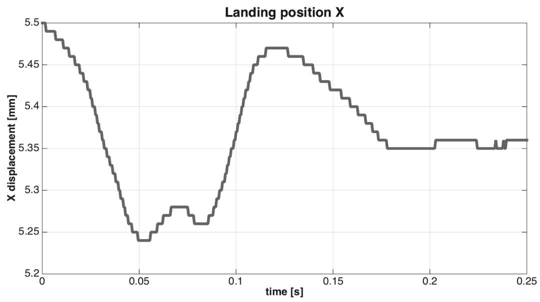

Fig. 12. Levitating cart displacement along vertical axis during UAV landing

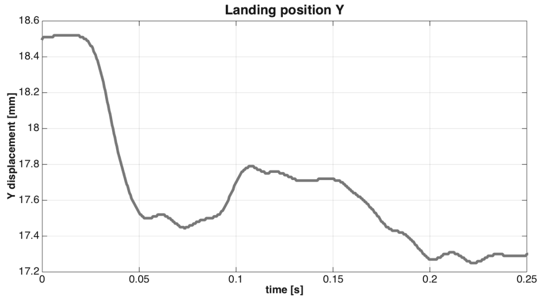

Fig. 13. Levitating cart displacement along horizontal axis during UAV landing

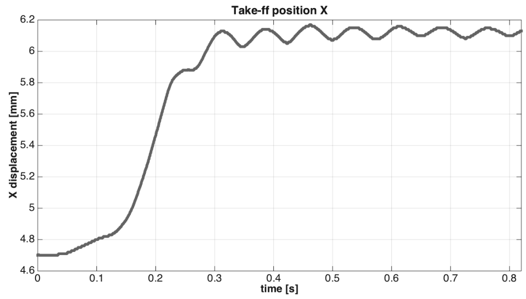

Fig. 14. Levitating cart displacement along vertical axis during UAV take-off

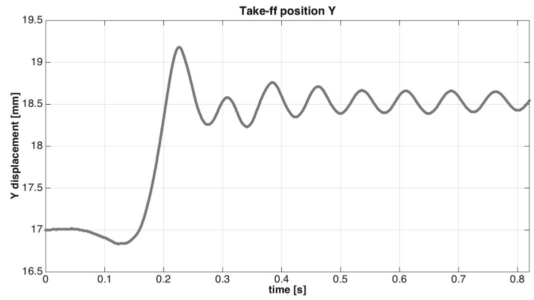

Fig. 15. Levitating cart displacement along horizontal axis during UAV take-off

Cart displacement during UAV landing, recorded by high-speed camera, is shown in fig. 12-13. The cart position is stabilized without vibrations after 0.2 s. During the landing there is a significant loss of kinetic energy due to nonlinear phenomena occurring in type 2 superconductors. This non-linearity can be explained by unequal distribution of lines of magnetic field and by flux pinning effect [8,9]. The loss of kinetic energy during the UAV landing on the launcher is a desirable phenomenon.

At the time of take-off, as shown in fig. 14-15, there are strong cart oscillations, around an equilibrium point. These oscillations are very poorly suppressed, indicating negligible energy loss of the system.

Conclusions

The conclusion driven from the experiments is that the magnetic suspension using the Meissner effect exhibits different properties during take-off and landing. Description of the levitating force acting in magnetic suspension using Meissner effect will be a crucial element of future work.

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