Status of the Magnetic Levitation Upgrade to Holloman High Speed Test Track

No. 29

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ABSTRACT: Two superconducting magnets, mounted on a sled are propelled by solid fuel rocket motors. During sled motion, the field from the magnets interacts with passive copper rails embedded in a concrete guideway to produce levitation and flight stability. Six flight tests have been successfully conducted to date with the most recent in April 2008 reaching 673 kilometer per hour (418 mph). This will increase to beyond supersonic speed as more guideway is built in the future.

1 INTRODUCTION

The Holloman MagLev program began in the mid-nineties to upgrade the High Speed Test Track at Holloman Air Force Base, New Mexico. A baseline system was defined involving a three-stage sled with superconducting magnets to achieve peak velocities of 3000 m/sec (Mach 9.1). The major Air Force goal is to provide a low vibration environment for payloads on rocket-propelled sleds for speeds from subsonic to over Mach 9. Lower speed applications include testing of electronic systems such as smart fuzes and sensors for Air Force and Navy missile systems as well as demonstrations of launch assist systems for NASA. Mid-range speed applications include testing of sensors and hypersonic air-breathing propulsion systems, such as Scramjets, where low vibration is required to appropriately simulate inlet boundary layer transition. High-speed payloads will include projectiles for missile defense lethality testing for Army, Navy, and Missile Defense Agency programs.

The major system components are sled/magnets and guideway. The magnetic system's primary mission is to provide levitation to the sled throughout a test flight. It also provides magnetic restoring force in both heave and sway directions. The sled weight, magnetic and aerodynamic drags must be sufficiently small for the payload to reach the required velocity for the given thrust of the rocket motors. Various magnet systems had been studied and developed in the earlier phases (Bosmajian et al. 2000). Two superconducting magnets with one pair of split cooper rails on each side were chosen for current deign. Figure 1 shows an artist cut-away view of the configuration. The wing coils and guideway rail designs were optimized using finite element analysis (FEA) software. The fabrication costs were also considered.

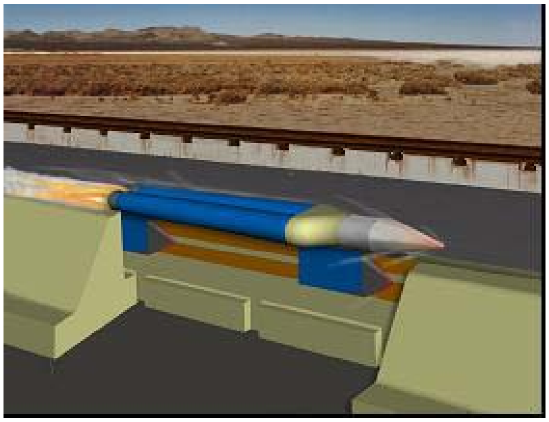

Figure 1. Artist cut-away view of configuration.

2 MODELLING

2.1 *Magnetic Analysis*

As the magnets, propelled by solid rocket motors, proceed down the guideway the moving magnetic field induces eddy currents in the copper rails. These induced currents interact with the magnetic fields from the magnets to produce magnetic forces. These forces are dependent on the sled velocity and distance between the copper rails and magnets. In the down-track direction, this interaction produces magnetic drag. Because of the split rails configuration, this interaction produces restoring forces that act to keep the magnets centered between the rails in both the vertical and cross-track (heave and sway) directions.

Vector Fields' Opera-2d and Opera-3d FEA electromagnetic software and Infolytica's MagNet (Low Frequency Electromagnetic Field Simulation) are used for magnetic analysis. The magnetic drag, restoring forces with various magnet positions are calculated and provided to 1-DoF and 6-DoF flight simulation models. Figure 2 shows magnetic drag force as function velocity for magnet at null (no heave or sway) position. The effects of rail joints between the guideway beam sections on the drag and restoring forces and magnet components are also studied.

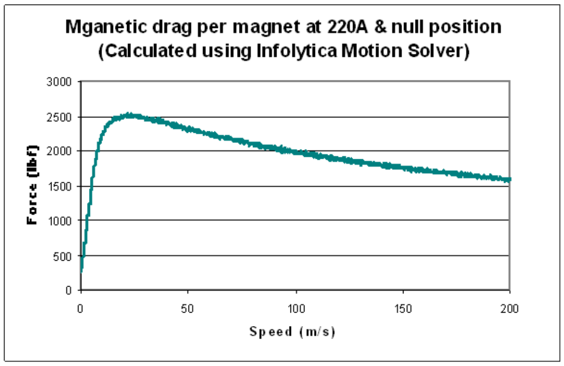

Figure 2. Magnetic drag force versus velocity

2.2 *Flight simulation*

The 1-DoF simulation tool uses Microsoft Excel to calculate system performance. It incorporates look up tables of motor burn profile, magnetic drag and aerodynamic drag as function of velocity. The tables are updated from measured data after each flight test. The effects of sway and heave are not considered. It is used for quick parametric assessment of the sled performance (g levels, velocities, and distance traveled). The spread sheet has the ability to change motors, motor burn profile, power on or power off, weight variation, and magnetic drag variation.

The 6-DoF model is used to determine sled velocity, distance traveled, and sled stability for normal and off-normal conditions for each test.

3 SLED

A low cost single-stage sled for high subsonic to low supersonic flight test was designed by Boeing Company. Three instrument bays, located in the center and forward portions of the sled, contain batteries, signal conditioning, and telemetry electronics. Figure 3 shows the sketch of sled with wing boxes mounted and rocket motors loaded. Sled without magnets and motors weighs about 136kg (300 lbs).

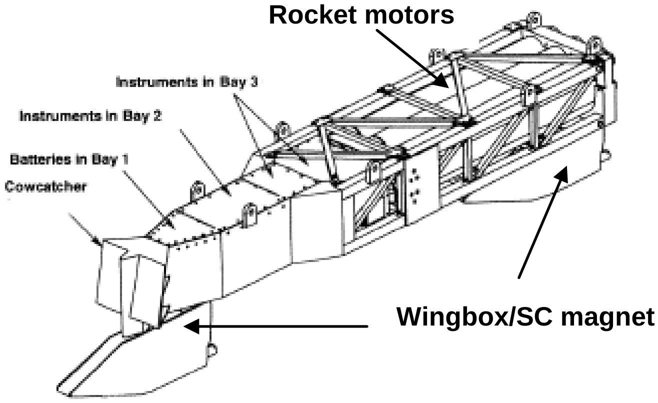

Figure 3. Sled with wingboxes mounted and motors loaded

4 MAGNETS

A minimum of 500 kA-turns is required for the magnet to provide the required levitation and restoring force. Due to the limited space available, coil must have high current density. Therefore a superconducting (SC) coil with high performance conductor was chosen. Also under dynamic (flying) operating conditions, the effect of high acceleration and eddy currents were considered in the magnet design.

The magnet consists of a racetrack coil, helium vessel, thermal shield and vacuum vessel. The coil is wet lay-up wound with rectangular NbTi/Cu wire using glass power filled epoxy. A persistent switch is installed in the magnet bore to maintain the current flow while the power leads are disconnected from the magnet. Figure 4 shows the SC coil with persistent switch (P-switch) installed in half of the helium vessel.

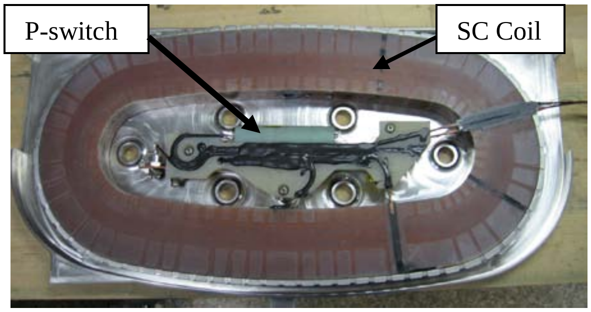

Figure 4. SC coil installed in half of the helium vessel

The helium vessel is made of stainless steel. Its sidewalls are plated with copper. The thermal shield is made of aluminum 6061-T6 and 1100 brazed together. Al 6061 provides the mechanical stiffness for the thermal shield and minimum shield vibration during the flight Copper plating and the aluminum 1100 act as eddy current shields to prevent the induced current heating in the SC coil during flight due to the AC magnetic field from the rail joints. Boil-off helium gas cools thermal shield and current leads.

The magnets are cooled through fill bayonets. The charge cables connect to the magnet through MultiLam electrical quick disconnections. These connections are retracted before flight.

The finished wingbox weights about 54.4kg (120 lb). The detailed magnet design was presented in 2008 Applied Superconductivity Conference (Hsu et al 2008)

5 GUIDEWAY

The guideway, shown in Figure 5, consists of 173 sections, each about 4.1 m (13.4’) long.

Figure 5. Guideway beams looking south.

The configuration of the guideway rails is illustrated in Figures 6 and 7. Two pairs of split copper rails are embedded in the guideway, one pair on each side of the SC coil. The copper rail is 140mm (5.5”) wide and 9.5 mm (0.375”) thick with 75mm (3”) gap between the upper and lower rails. The rail gap between the sections is bridged with copper plates.

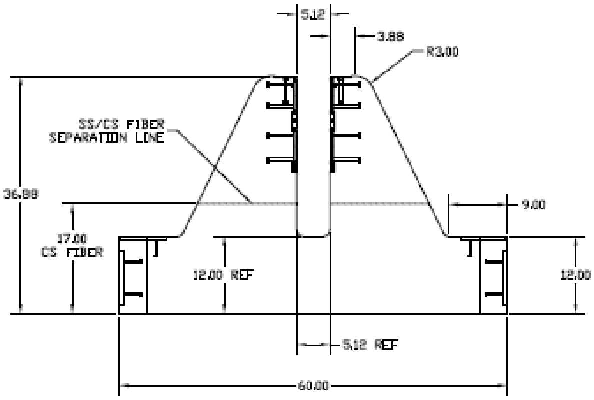

Figure 6. Guideway crossection view (dimension in inch)

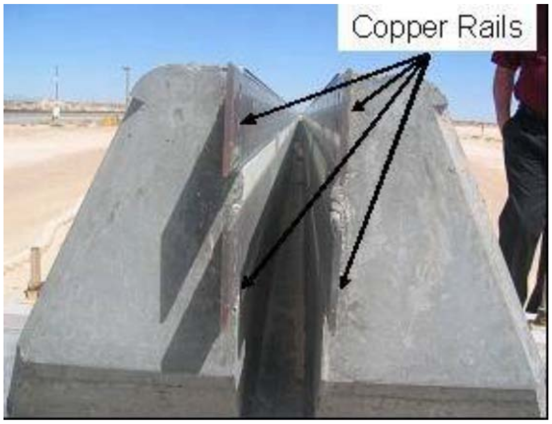

Figure 7. Copper rail embedded in the concrete guideway

The guideway is subject to the dynamic magnetic loads through cooper rails from the moving sled/magnets. The loads, from 2cm sway right and 4 cm heave up are distributed to the 4 copper rails as shown in Figure 8. To prevent cracking caused by induced tensile stresses, the imposed static and dynamic loads, creep and shrinkages, the guideway beams are constructed with steel fiber reinforced concrete (SFRC) (Venkatesh et al., 2006).

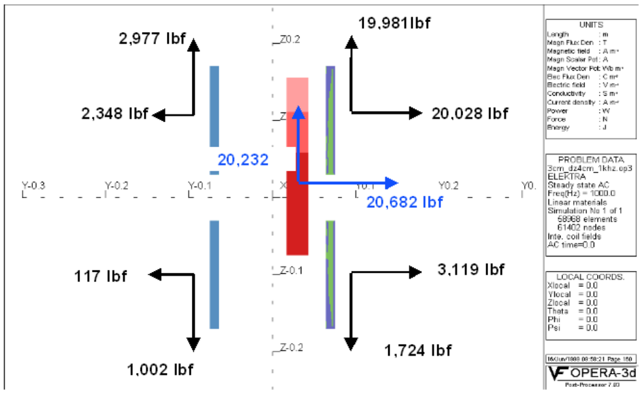

Figure 8. Forces distribution on the guideway rails (2cm sway right, 4 cm heave up)

6 FLIGHT TEST

6.1 Test setup

Flight tests have been conducted at Holloman Air Force base, New Mexico. The sled, shown in Fig. 9, uses two SC magnets mounted fore and aft in a tandem arrangement. The distance between two magnets is about 2.5 m (100”) center to center.

Figure 9. Sled/magnet shown being installed in guideway

Two pull-away cables are used. The first provides dc power to the sled electronics prior to launch. The second provides control and monitoring for the cooldown and charging of the magnets.

Umbilicals consisting of MultiLam electrical charge connection and LHe cooldown line connect each magnet to the liquid helium supply and electrical charging system. Warm-air systems are installed to maintain the umbilical area above water’s freezing point. Just prior to flight pneumatic actuators disconnect the umbilicals. A pneumatic valve shuts off the LHe supply after disconnect.

The liquid helium supply Dewars are located on a cryopad adjacent to the launch point. A steel blast shield protects the area. Also located on the cryopad are the power supplies for magnets charging and control system to monitor and control the cooldown and charging process (Figure 10).

An OPTO controller system records pre-flight data. Telemetry recording for in-flight data begins prior to umbilical retraction and continues throughout the flight. The telemetry data has the high resolution at 80µs per point.

The following sensors are used for monitoring the flight performance:

- Laser sensors (6): monitor sled positions
- Pick-up coils (3) each magnet: mounted at helium vessel sidewall, inside and outer surface of thermal shield sidewall
- Accelerometer (3): in three directions
- Hall probe (1) each magnet: on vacuum vessel outer surface

Figure 10. Cryopad setup

Flight tests have been conducted with 1, 2, 3, 4 and 5 HVAR (High Velocity Aircraft Rocket) motors.

6.2 Test Conduct

Both magnets are cooled from room temperature to 4.2K in about 2.5 hours using liquid helium. The magnet is charged to 210A in 6 minutes and placed into persistent mode one at a time. Immediately prior to launch, electrical charging cables and LHe fill umbilicals are retracted. After retraction is confirmed, the rocket motors are fired and the sled accelerates down the track. After rocket motor burnout the sled is decelerated to a stop by magnetic drag. Figures 11 and 12 show the rocket sled with 4 HAVR ready for flight. Figure 13 shows the sled during the flight test.

Figure 11. Sled with 4 HVAR motors installed

Figure 12. Rocket sled with 4 HVAR motors ready for flight test

Figure 13. Sled during the flight test

6.3 *Test results*

The most recent flight test was conducted in April 2008 with 5 HVAR motors, which provided a maximum total thrust of 111,205 Newton (25,000lbf) for about 1.2 seconds. The sled with an initial weight of 495 kg (1093 lb) reached a peak velocity of 673 km/hr (418 mph) and traveled 532m (1745 ft) in 5.5 sec. With the sled at rest, the centers of the magnets were below the center line between the copper. At first the motion, the sled levitated about 1.7 cm (0.67”) in 0.1 second as shown in Figure 14.

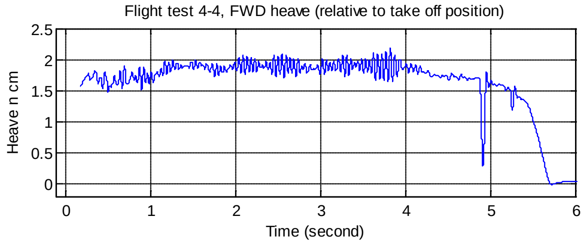

Figure 14. Sled position (relative to take off) versus time

As the sled/magnets pass each joint in the guideway, there is a small disturbance in the magnetic field. This can be seen on the shield outer pickup coil data (upper curve of Fig. 15). . The spacing of the spikes, shown in the lower curve of Fig. 15, is about 4 m apart confirms the spikes are associated with guideway joints. Shield inner pick-up coil data shows these disturbances are well shielded from the SC coil (lower curve of Figure 15).

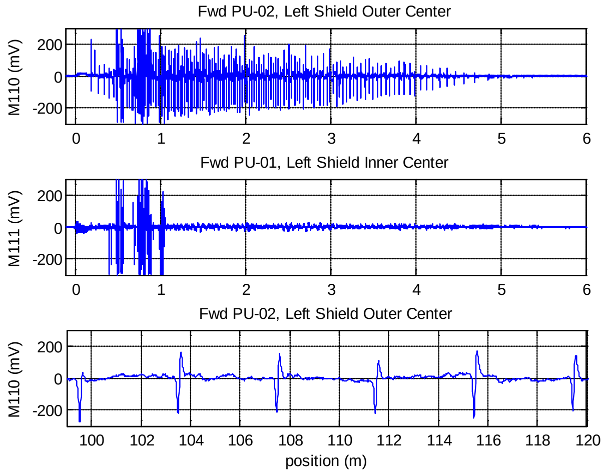

Figure 15. Pick-up coils voltage versus time/position. The lower curve shows AC shielding of thermal shield

Accelerometer data (Figure 16) in travel direction indicates that the magnets experienced an acceleration of 25g during the motor firing and magnet drag of 5g during the coasting to stop.

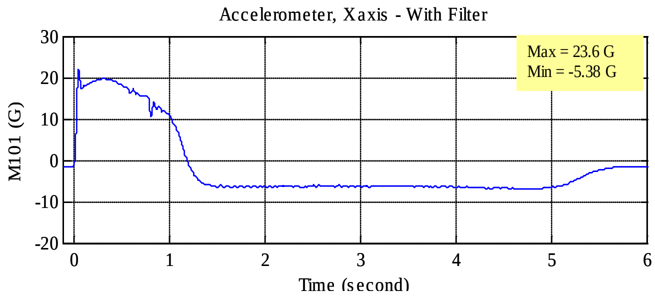

Figure 16. Accelerometer data in travel direction

The plots in Figure 17 shows that the maximum acceleration in sway and heave directions are about

3g. Power spectral density (PSD) was derived from the accelerometer data. The vibrations in heave and sway directions meet Standard Missile Specification of 3.5 g RMS.

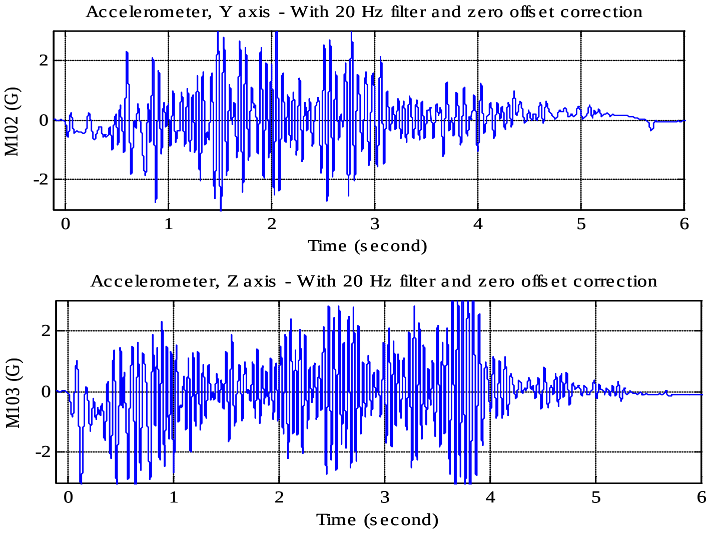

Figure 17. Accelerometer data in heave and sway directions

The magnets quenched in about 23 minutes after the flight due to depletion of liquid helium. The post test weight is 424kg (935 lb).

7 CONCLUSIONS

Successful magnetically levitated flights have been conducted using a rocket propelled sled with superconducting levitating magnets. A speed of 673 km/hr has been reached. The near future plan is to reach a velocity of Mach 1. To reach this goal, the existing guideway will be extended or an augmented braking applied after the sled reaches the peak velocity to reduce the number of guideway beams required.

8 ACKNOWLEDGMENT

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9 REFERENCES

Bosmanjian N., Minto, D. & Holloand, L., “Status of the magnetic levitation upgrade to the Holloman High Speed Test Track,” AIAA Aerodynamic Measurement Technology and Ground Testing Conference, 21st, Denver, CO, June 19-22, 2000. AIAA-2000-2289

Hsu Y., Langhorn A., Ketchen D., Holloland ., Minto D., & Doll D., “Magnetic levitation upgrade to the Holloman High Speed Test Track,” 2008 Applied Superconductivity Conference”, Chicago, Illinois, August 17-22, 2008. To be published.

Venkatesh A., & Jeter P., “Guideway steel Fiber Reinforced Concrete Hybrid Girder Design,” Maglev 2006, Dresden, Germany, September 13-15, 2006. 677