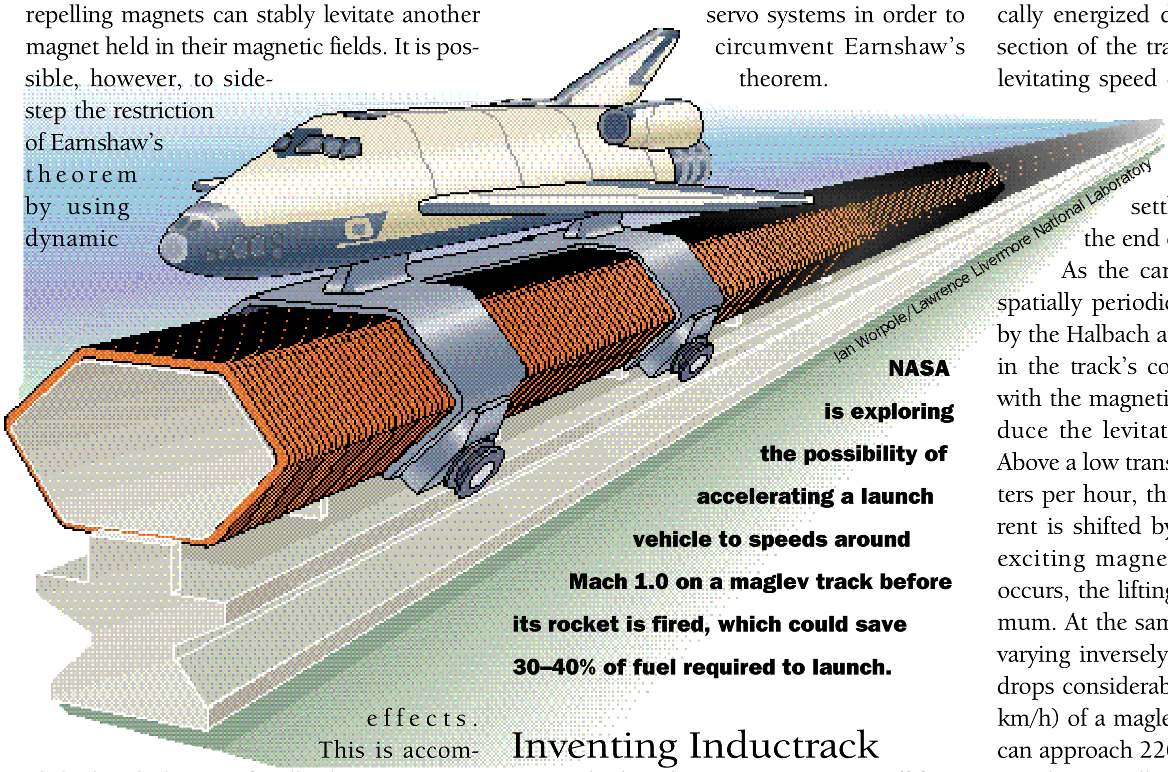
Halbach Arrays Enter the Maglev Race

Magnetic levitation, or maglev, is fascinating because of its potential for almost frictionless motion. One commercial application of magnetic levitation today is the noncontacting magnetic bearings used in machines such as turbo-vacuum pumps, which rotate at high speeds. But here, magnetic levitation is achieved at a penalty: sensors and servo systems are required to stabilize the levitated bearing elements.

Earnshaw's theorem, published in 1839, proves that no combination of attracting or repelling magnets can stably levitate another magnet held in their magnetic fields. It is possible, however, to sidestep the restriction of Earnshaw's theorem by using dynamic effects. This is accomplished with the use of Halbach arrays, a special arrangement of permanent magnets, together with an array of passive coils (see *The Industrial Physicist*, 9/98, pp. 34-36).

The array concept was developed by Klaus Halbach of the Lawrence Berkeley National Laboratory in the 1980s for use in particle accelerators. Arrays consist of permanent magnet bars arranged in such a way that the magnetic field, which varies periodically in space along the array, is concentrated on one face of the array and almost canceled on the opposite face.

Physicist Richard F. Post at the Lawrence Livermore National Laboratory (LLNL) has been using the Halbach array for things other than particle accelerators. In the mid-1990s, he designed an electromechanical battery that combines Halbach arrays with a fiber-composite flywheel rotor. Rotating at up to 50,000 rpm, the Halbach array represents an efficient, high-power electrical generator. In a parallel development at LLNL, Halbach arrays coupled to an array of passive coils are used as "stabilizers" for passive magnetic bearings, which do not require electronic servo systems in order to circumvent Earnshaw's theorem.



NASA is exploring the possibility of accelerating a launch vehicle to speeds around Mach 1.0 on a maglev track before its rocket is fired, which could save 30–40% of fuel required to launch.

Inventing Inductrack

For the last three years, as a spin-off from the passive magnetic bearing applications, Post and LLNL project engineer J. Ray Smith have been developing a maglev system that also takes advantage of the unusual properties of Halbach arrays. "It seemed that a linear version of the Halbach array would be ideal for trains and other vehicles," says Post. "So we built a working model that employs only passive elements: permanent magnets in Halbach arrays on the moving car and a close-packed array of short-circuited coils embedded in the track to provide levitation." A patent for the maglev system, called the Inductrack, has been issued to Post.

Built with internal LLNL funding, the scale model of Inductrack is 20 m long, and the track contains 1,000 passive wire coils of rectangular shape. Each coil is a closed circuit, not connected to other coils or to an external power source. The 22-kg test cart has wheels that ride on aluminum rails when the vehicle is not levitated. The lower surface of the cart is fitted fore and aft with Halbach arrays; smaller Halbach arrays on each side provide sideways stability. A series of electrically energized drive coils in the beginning section of the track accelerate the cart to its levitating speed of about 10 m/s. After it is launched, the cart flies down the track, remaining stably levitated until it settles back on its wheels near the end of the track.

As the cart moves over its track, the spatially periodic magnetic fields produced by the Halbach arrays induce strong currents in the track's coils. These currents interact with the magnetic fields of the arrays to produce the levitating and stabilizing forces. Above a low transition speed of a few kilometers per hour, the phase of the induced current is shifted by almost 90° relative to the exciting magnetic field. When this shift occurs, the lifting force approaches its maximum. At the same time, the drag force, now varying inversely with the increasing speed, drops considerably. At the high speeds (500 km/h) of a maglev train, the lift-to-drag ratio can approach 220:1.

When a Halbach array is fabricated from a high-field permanent magnet material, such as neodymium-iron-boron (NdFeB), it can produce a flux density of more than 1 T. If such an array is used in the Inductrack, it can produce a levitation of more than 40 tonne/m^2, which typically corresponds to about 50 times the array's weight.

At operating speeds, the levitation force of an Inductrack train acts like a stiff spring. Increasing the passenger or cargo load will only slightly decrease the clearance between the Halbach arrays and the track. Thus, Inductrack systems can be designed to accommodate changing loads within predetermined limits.

A train operating on an Inductrack would need wheels to support it at rest and while it accelerates to levitation speeds. Some type of propulsion also would be needed to accelerate the train and to overcome aerodynamic drag. A 500 km/h train would require 5 to 10 MW of drive power to overcome drag forces, and only 200 or 300 kW of this power would be dissipated by the coils in the Inductrack. The propelling force needed to overcome drag forces could be provided by interleaving externally powered drive coils with the passive coils of the Inductrack. The powered coils and the magnetic fields of the Halbach arrays would be, in effect, a linear motor. Alternatively, the train could be propelled by an on-board turbofan, which would eliminate the need to electrify the track.

Safety issues

Post points out that the Inductrack is inherently fail-safe. As long as the train is moving above the levitation speed, it remains stably levitated. If it slows down below the lifting speed of a few kilometers per hour, the train simply settles onto its auxiliary wheels.

Inductrack's simplicity and fail-safe feature may give it advantages over maglev train systems being developed in Germany and Japan. Both countries have built full-scale maglev tracks to test their technologies. The German maglev system, called Transrapid, uses powered electromagnets and a track made of iron plates. To maintain stable levitation in the face of Earnshaw's theorem, the German system requires a sophisticated servo control system. Failure of this control system when the train is moving at high speed could result in a disaster. The Japanese use superconducting coils in their system that require cryogenic-cooling and magnet-control systems. Again, quenching the superconducting coils or any major failure in the cryogenic system or its controls during high-speed travel could result in a serious accident.

After several fallow years, the maglev-train effort in the United States may get back on track thanks to new federal funding that allocates $1 billion to the Department of Transportation (DOT) for development and construction of a high-speed maglev-train demonstration facility. The Transportation Equity Act for the 21st century (TEA-21) instructs DOT to solicit and evaluate proposals for the maglev project and gives it contract authority to spend $55 million for preconstruction planning, design, and engineering activities. TEA-21 also provides $5 million for research grants and the development of low-speed superconductivity magnetic-levitation technology related to public transportation in urban areas.

NASA's Maglifter program

The Inductrack may find a use in the U.S. space program. NASA has contracted with LLNL for a version of the Inductrack that will test its potential for launching rockets. NASA's Maglifter program is exploring the possibility of accelerating a launch vehicle to speeds around Mach 1.0 on a maglev track before its rocket is fired. Using a Maglifter, NASA could substantially reduce its launching costs by saving the 30% to 40% of fuel required to launch spacecraft. The Maglifter approach might even make it possible to send craft into orbit using only a single-stage rocket. LLNL is building a model-scale test launcher track that has its passive levitation coils interleaved with powered coils designed to provide 10 g acceleration to a cart with a model rocket body to speeds of about Mach 0.5 (170 m/s).

Another possible maglev application is being explored through preliminary testing at the Holloman Air Force Base in New Mexico. A consortium headed by General Atomics is looking into the possibility of retrofitting the existing high-speed 10-mile Holloman Test Track with a maglev system. Using superconducting wire from the defunct Superconducting Super Collider program, the group has performed tests using a vehicle equipped with superconducting coils interacting with copper-wire coils installed over a short portion of the existing track. High-speed test tracks could become another application of the Inductrack concept.