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Magnetically Levitated Vehicles: Suspension, Propulsion and Guidance

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***Abstract*—This paper explains the basis features of a Magnetically Levitated Vehicle, which consider the magnetic suspensions, propulsion and guidance. There are basically two modes of magnetic suspension, utilizing either the repulsive force between vehicle-borne superconductive magnets and induced currents in conductive guideway components i.e. Electrodynamic suspension system (EDS) or the attractive force between iron core electromagnets and ferromagnetic rails i.e. Electromagnetic suspension system (EMS). Propulsion is achieved by linear motors instead of conventional motors. In EMS mode guidance may be provided by magnetic guidance forces generated by interaction of separate set of electromagnets and in EDS system the guidance is provided by the principle of null-flux which is achieved by cross coupling the conducting coil mounted on the guideway.**

Keywords—Magnetıcally Levıtated Vehıcles; Electrodynamic suspension system; Electromagnetic suspension system; Propulsion; Guidance

I. INTRODUCTION

Speed is an important factor for attracting users to public transportation. To improve urban and intercity transportation, several unconventional forms of ground transportation vehicle systems have been considered. Vehicles, which possess improved and innovative suspensions and/or propulsion systems, have been proposed and include:

- Advanced rail-wheeled vehicle systems
- Track levitated vehicle systems

  This is sub classified as
  - Air cushion vehicles

    This is further sub classified as
    (a) Externally pressurized vehicles
    (b) Ram air cushion vehicles
  - Magnetic vehicles

  This is sub classified as
    (a) Electrodynamic vehicles
    (b) Electromagnetic vehicles

The design and development of these transportation systems needs considerations of suspensions, propulsion, power pick up and guideway construction. A typical suspension consists of a primary suspension which contacts the road and a secondary suspension which connects the vehicle body to the primary suspension. Non-contacting guided ground transportation systems offer potential for operational speeds which are limited only by energy consumption consideration, for minimal guideway maintenance, for a high utilization rate of the guideway, and for systems operation without direct reliance on petrochemical fuels. The relatively high power requirement of the tracked air cushion vehicle concept (approx. 30-50 kW to statically support one metric ton) coupled with its requirement for relatively wide close toleranced guideway surfaces and its high exterior noise level lead investigation into alternatively non-contacting magnetic suspension or Maglev concepts. Magnetic suspension concepts require substantially less power, do not generate noise. Most of the non-contact suspension and propulsion technology development for high speed, 400-500 km/h (248-310 mph) applications has taken place in the federal republic of Germany, and in Japan. Significant research has been carried out in other countries including Canada, Romania, Great Britain and the United States. High speed Maglev vehicle has been the area of interest for researchers in the past [1] [2] [3] [4], The author[1] has carried out a broad survey of rail vehicle dynamics [5] and performed ride analysis [6] [7], sensitivity analysis [8] [9], stability and eigenvalue analysis [10] considering 37 DoF coupled vertical-lateral model of Indian railway vehicle

II. MAGNETIC SUSPENSIONS

Two types of magnetic suspensions that have received primary attention are

A. Electrodynamic Suspension (EDS)

In electrodynamic system (Figure 1), a current carrying coil is built into the vehicle. As the vehicle moves, the flux produced by the current flowing in the on-board coil induces currents either in passive coils located in the guidway or in conducting nonmagnetic sheets (typically aluminum) which form the guideway's surface. The induced currents produce a magnetic flux, which opposes that of the coils located on the vehicle and produces lift, which is a function of vehicle velocity. By using superconducting cryogenic coils in the vehicle, very high currents and, therefore, fields can be produced with negligible resistance losses. As a result, the vehicle can be lifted several inches above the guideway. Because of these large clearances, electrodynamic systems feature low sensitivity to guideway roughness. Electrodynamic systems are inherently statically stable and require no feedback control for static stability; however their damping is very low and special provisions must be included to damp vehicle motions (for example, active control). At low speeds, the induced currents are too small to lift the vehicle and typically wheels will be necessary for low speed operations.

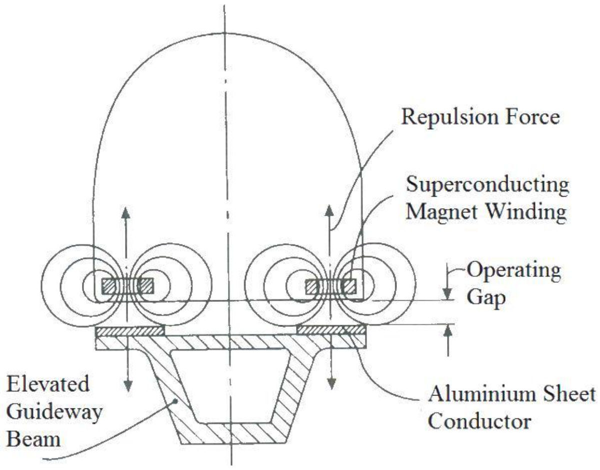

Fig. 1 Electrdynamic Suspension

B. Electromagnetic Suspension (EMS)

In electromagnetic suspension system (Figure 2 and Figure 3), a current-carrying coil excites a magnetic circuit consisting of an iron core in the vehicle and a ferromagnetic rail fixed to the track and the on-board core is attracted to the rail. Lift is provided essentially independently of vehicle velocity. When excited by a current or voltage source, the suspension is statically unstable, and appropriate displacement sensors (gap sensor) and control circuits are required to achieve statically stable and dynamically acceptable suspension characteristics. The brackets, which support the rail, are designed so that the magnet is at a specified distance from the ground. The distance is selected to restrain the vehicle from falling to gaps, which are so large that the vehicle leaves the track. The general configuration will have four magnets, one at each corner of the vehicle. Additional magnets are used for lateral control or it may be possible to obtain lateral guidance with only the lifting magnets. In the EMS system, additional wheels are not necessary because the vehicle can be lifted at low speed or at standstill. For high-speed running, high response performance of the levitation control system is required in order to cope with the guideway roughness. Eddy currents, which cause the drop of energy efficiency of the system, are induced in the rail. The magnets should be distributed along the vehicle length from the reason that the smaller the width of magnet poles, the smaller the drop in efficiency. Summarizing, there are basically two modes of magnetic suspension, utilizing either the repulsive force between vehicle-borne superconductive magnets and induced currents in conductive guideway components or the attractive force between iron core electromagnets and ferro magnetic rails (reaction rail).

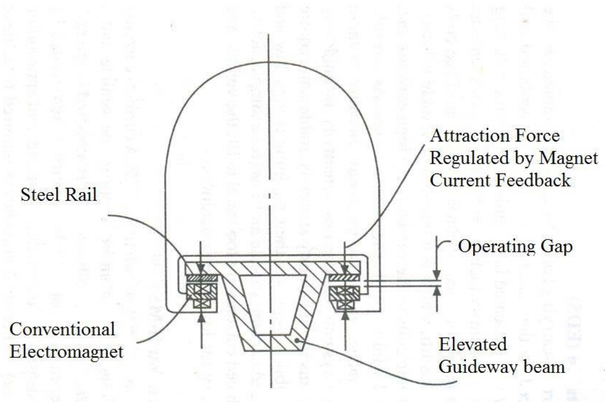

Fig. 2 Electromagnetic Suspension

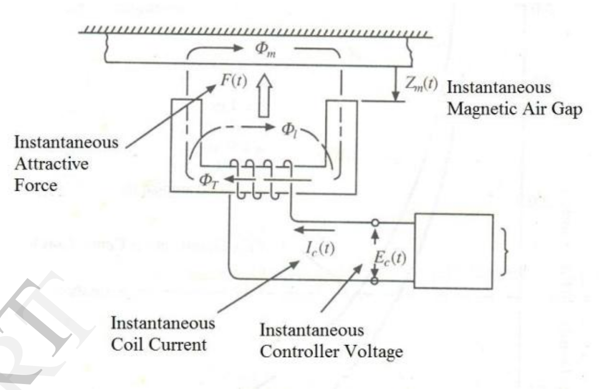

Fig. 3 Schematic Of Electromagnetic Suspension

The former code is referred to as electrodynamic suspension (EDS) and the latter mode is referred to as electromagnetic suspension (EMS). In the EDS system, the vehicle carries powerful superconducting magnets for levitation, guidance and propulsion. The guideway conductors, in which currents are induced by the time-varying flux linkage produced by forward motion of the vehicle, can be continuous strips or discrete short-circuited loops. There are a number of design options for magnet disposition guideway configuration. While the guideway clearance is 100 mm for vertical direction and 150 mm for lateral direction at high speed, the levitation height is speed-dependent; the lift-off speed (from wheels) being approximately 150 km/h). The suspension is dynamically stable but under damped Passive or active damping is a secondary suspension is required to achieve good ride quality. The vehicle requires a propulsion system that is compatible with the large clearance produced by EDS. A linear synchronous motor with three phase armature windings or coils in the guideway and field excitation from an array of on board superconducting magnets provides speed control with a high power factor efficiency product. The vehicle can be guided by cross coupled null-flux coils, which can be integrated with the synchronous motor. In the EMS system, the vehicle carries iron-cored electromagnets slung underneath the ferromagnetic guideway components. The suspension must be dynamically stabilized by feedback control of the magnet excitation. The suspension gap is an order of magnitude less than that of EDS, but is speed-independent. Propulsion systems that are compatible with

EMS are the linear induction motor or the iron-cored linear synchronous motor. The vehicle can be guided either by alternatively offsetting the suspension magnets with respect to the track rails or the separate controlled guidance magnets. Some of the characteristics of EDS and EMS systems are listed in Table 1

Table I. Characteristics Of Electrodynamic And Electromagnetic Suspension Systems

Characteristics	**Electrodynamic suspension systems (repulsive mode)**	**Electromagnetic suspension systems (attraction mode)**
Magnets	Superconducting coils	Iron cored electromagnets
Guideway components	Aluminium strips or multiturn coils	Laminated or solid ferromagnetic strips
Lift-off speed	40-80 km/h	Magnetically suspended at all speeds
Guideway	100-150 mm	10-15 mm
Stability	Dynamically stable. No feedback control necessary. Damping required for good ride quality	Inherently unstable. Feedback control necessary to maintain dynamic stability
Compatible drive system	Air-core linear synchronous motor	Iron-cored linear synchronous motor, or linear induction motor

III. PROPULSION AND GUIDANCE

Propulsion is achieved by linear motors instead of conventional motors. The linear motor is similar in concept that is cut and laid flat. This is shown in Figure 4. The linear motor can be either short stator or long stator. In case of short stator the primary is on the vehicle and secondary on the track. In case of long stator it is vice-versa.

There are two types of linear motors:

1. Linear synchronous motors (LSM)
2. Linear induction motor (LIM)

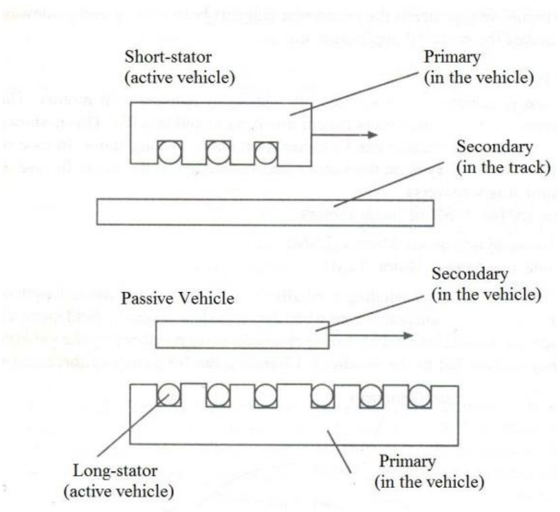

Fig. 4 Linear Motor Principle For Propulsion In Maglev Vehicle

LSM has a three phase winding normally distributed over the whole length of the guideway. Propulsion is achieved when the secondary magnetic field mounted on vehicle gets locked into the travelling magnetic wave produced by the variable frequency current fed to the windings. Changing the frequency of three-phase supply controls speed. As the power is supplied to the track, vehicle becomes passive and lightweight is case of LSM. There are several variations of secondary magnetic field of LSM. Electromagnets, permanent magnets, superconducting magnet are one of those variations. EDS mode uses air cored LSM at high magnetic strength are produced by onboard dc superconducting magnets. The vehicle carries the three phase winding of LIM and the reaction plate fixed on the guideway. Three-phase power supply can either by directly fed into the vehicle or converted by on board inverters from dc supply. In EMS mode guidance may be provided by magnetic guidance forces generated by interaction of separate set of electromagnets carried by vehicle and ferromagnetic rails on the sides of the guideway structure. Alternatively, the suspension magnets themselves can generate guidance force by laterally offsetting them with respect to ferromagnetic rails, in case of low speed operation. In EDS system the guidance is provided by the principle of null-flux which is achieved by cross coupling the conducting coil mounted on the guideway are also used as the armature of LSM, for propulsion. In PMS mode the guidance is provided by mechanical guide wheels.

IV. PERMANENT MAGNETS (MPS)

Permanent magnet suspension systems include repulsive and attractive type. The attractive type is a variation of EMS where the lift is achieved by Special permanent magnet (Ne-Fe-B) fitted to the vehicle. The mechanical air gap controller consists of lever with wheels is used for stabilization of attractive force. For the vehicle model with mechanical levitation control system it the weight of vehicle body increases, the upper control lever will move up which will then cause the lower control lever to rise. This will then raise the undercarriage while the guide wheels remain fixed to the guideway surface. The decrease of the air gap by the upward displacement of the undercarriage yields an increase in the attracting force of the permanent magnet. By balancing the additional vehicle weight and the increment of the magnetic force, no vehicle load of the guide wheel can occur. Though the guide wheel is always in contact with guideway, the vehicle is completely supported mechanically. The repulsive type needs the permanent magnets both vehicle and guideway, which makes the practical application difficult equations.

V. EFFECT OF HIGH TEMPERATURE SUPERCONDUCTIVITY ON MAGLEV VEHICLE

The Japan National Railway started the development of high speed Maglev in 1969 based on conventional Helium cryostats and temperature of 4K (-269º C) is attained for achieving superconductivity. The cryostats are carried on-board to produce high strength DC magnetic fields for levitation. Yttrium-Barium-Copper Oxide (Y1Ba2Cu3O7) ceramic compound was found to have a critical temperature of 90 K well above the boiling point of nitrogen (77K). Though Maglev is not a technology, which is suddenly made feasible by the discovery of high temperature superconductivity, magnetically suspended high speed ground transportation was recently brought to public attention by this discovery in early 1987. Because of high temperature superconductive magnets with nitrogen cryostats the Maglev technology could become very attractive for ease of operation. However, this development will not have any significant effect on capital cost of present day Maglev systems including that of Japan. But Maglev system could be developed afresh based on high temperature superconductivity technology.

VI. ADVANTAGES OF MAGLEV TECHNOLOGY

The advantages of Maglev, as compared with conventional railways, are as follows:

- Greater safety; the guideway system reduces the possibility of derailment.
- Less noise and vibration due to the absence of physical contact.
- Faster travel; higher maximum speeds allow fast service from city center to city center, permitting reduction in total travel time.
- Less maintenance work; the non-contact system eliminates rail displacement, wheel renewal and catenary rewiring.
- Spin-off benefits; development of the latest technologies, such as cryogenics and superconductivity, can be expected to produce spin-off benefits for other industries, along with technical feedback to conventional railway engineering.

VII. APPLICATIONS OF MAGLEV TECHNOLOGY

A. MAGLEV FOR HIGH SPEED APPLICATION

The maglev technology has the following strong feature making it one of the most appropriate technology for the future.

- High speed and good maneuverability
- Potential for low cost applications
- Environmental acceptability
- Ride comfort
- High dependability
- Energy efficient
- Low wear and tear
- Suited for automated operation.

Non-contacting characteristic is the main feature of Maglev, which is concentrated on high speed operation and environmental acceptability. There are certain areas, which require further attention such as breaking at high speeds in case of power failure. One of the deterrent factor is high level of investment already made in wheel-on-rail technology. It could be strong contender for dedicated corridors rather than replacement or extensions of guideways.

B. MAGLEV FOR URBAN TRANSIT SYSTEM

The features of Maglev technology, low noise and good ride comfort at middle or low speed operation, is applicable for urban mass transit system. The small guideway structure is also possible with the feature of Maglev technology with linear motor propulsion. It would be suitable for intra-city needs such as people move as compared to light rail transit system due to the advantages listed earlier.

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