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Novel Techniques of transportation systems

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Abstract

During the past decade, several methods have been proposed to improve the noncontacting intercity transportation vehicles.

This paper describes the novel alternative techniques conceived to replace the conventional wheeled vehicles.

Key words: Electromagnetic suspension, magnetic levitation, superconductor, control system.

1. Introduction

The need for improved urban and intercity transportation has motivated researchers and engineers to conceive novel alternatives to conventional wheeled vehicles developed and in use over the past century. Several methods for vehicle support have been considered, including cushions of water and air, and magnetic suspension to reduce or eliminate the disadvantages and limitations associated with wheel traction and support in conventional rail systems. Magnetic suspension mode is now recognized as the most appropriate for non-contact suspension in both urban transit and high speed intercity transportation. In 1912 the French engineer Emile Bachellet demonstrated the Foucault Railway, then in 1922 the German engineer Hermann Kemper extended that work to introduce the magnetic levitation method (1). The interest of using magnetic levitation system for high speed

transportation strated in the late 1950's. It was simulated by the possibilty of breaking the speed barrier imposed by the adhesion characteristics between steel wheels and steel rails, and by the potential advantages offered by MAGLEV systems, including improved reliability, lower operation and maintenance costs and improved environmental features (2,3,4.).

2. Transportation techniques

The popularity of the notion of suspension or levitation of passenger carrying vehicles travelling at 50 km/h originates from two projects in the late 1960's, namely, Aerotrain in France and the Tracked Hovercraft in England (5). both of these utilised the aircushion principle, however, besides the aircushion principle of supporting masses there are other electromagnetic methods, they are listed below :

- a. Attraction between magnets of fixed strength and ferromagnetic material.
- b. levitation using forces of repulsion and diamagnetic materials.
- c. Levitation using superconducting magnets or superconducting surfaces.
- d. Levitation by repulsion forces due to eddy currents induced in a conducting surface or a body principally at power frequencies.
- e. Levitaion using force acting on a current carrying linear conductor in a magnetic field.
- f. Suspension using a tuned LCR circuit and the electrostatic force attraction.
- g. Suspension using a tuned LCR circuit and the magnetic force of attraction between an electromagnet and ferromagnetic body.
- h. Suspension using controlled DC electromagnets and the force of attraction between magnetised bodies.
- e. Mixed μ system of levitation. Some of the principles mentioned are not used because of practical reasons and the disadvantages they present. The most potential technique will be emphasised in detail, and the others will be briefly explained below.

2.1. Levitation using diamagnetic materials :

Levitation in static magnetic fields can be achieved by employing diamagnetic materials, but even the two materials which exhibit most pronounced diamagnetic properties, Bismuth and Graphite, are so weakly diamagnetic

that only small pieces can be levitated. Some researchers (6) experimented this technique by suspending small pieces of bismuth and graphite, the conclusions drawn from the results are that it is not convenient to use such a technique in real application, but holds academic interest (5).

2.2. Levitation using forces acting on current carrying conductors situated in magnetic fields:

The force acting on a conductor of length l carrying a current I and situated in a transverse magnetic field of density B is given by the product BlI and acts in a direction normal to both the conductor and the magnetic field. An experiment was conducted for the levitation of a vehicle over two parallel superconducting rails carrying a persistent curent. The vehicle was supposed to carry two superconducting inverted troughs which ride over the rails without touching them. Levitation is effected by persistent currents which flow in the longitudinal wires of which the troughs are constructed. The researchers estimate that with a current of 300 KA and a trough radius of 0.5 m, a weight of 5000 Kg per metre run could be supported, however this technique presents some disadvantages as well as unsolved problems (5).

2.3. Suspension using tuned LCR circuits :

The use of electrostatic force of attraction as the electromagnetic force to obtain suspension of bodies has been investigated. in the electrostatic supsension the suspended body together with a fixed electrode form the capacitance element of a tuned LCR circuit in such a manner that the potential difference between the two electrodes increases as the distance between them increases, i.e. the circuit is tuned to resonate with capacitance values less than those at suspension gap. A high voltage is needed across the electrodes, the variation of inductance of an electromagnet in the proximity of a feromagnetic body on the separation between the two is utilised in this method to regulate the current and hence the force of attraction. This is achieved by incorporating the electromagnet within the LCR circuit tuned such that when the object to be suspended moves away from the electromagnet the circuit tends to become resonant thus increase the current and hence the force acting on it. However, when the body moves towards the electromagnet, the current and force of attraction diminish, Fig. 1

shows the experimental system and the relationship between force and distance. The stiffness of suspension using an AC tuned circuit method tends to be rather low for many applications, in general this technique is rarely used because of other disadvantages.

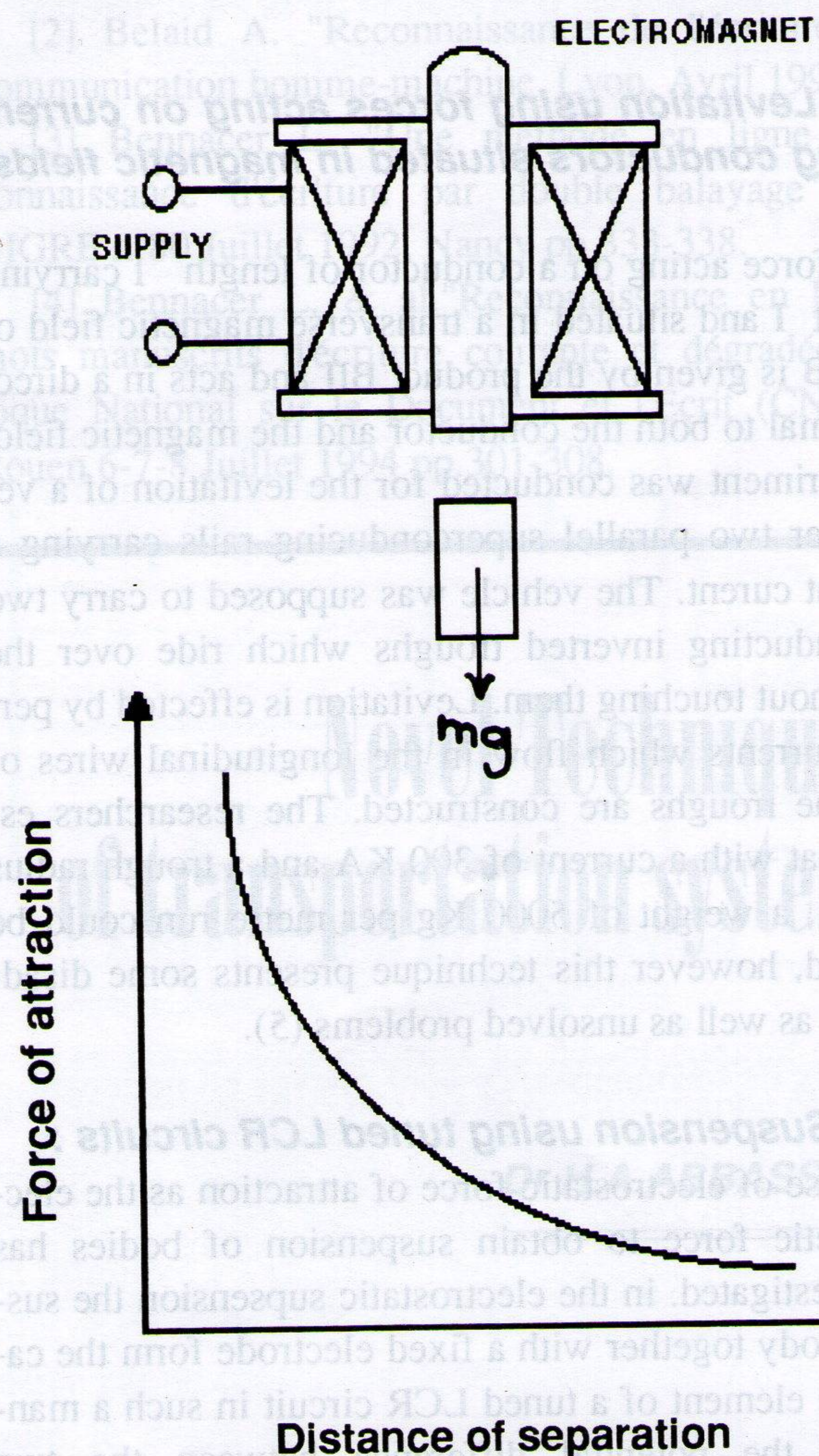


Figure 1: Geometry and force/distance curves for the tuned LCR circuits

2.4. Mixed μ system of levitation :

The stability of bodies with fixed charges of fixed current distributions in an inverses square law fields is impossible (7,6). However, where permittivity or permeability of the system is somewhere less than that of free space, stability is possible. A necessary condition for stability is $\mathbf{v} \cdot \mathbf{F} < 0$ (1)

Where $\mathbf{F}$ is the force vector on a body. Table 1 indicates how resultant force may depend on the nature of the system and not its geometry. It indicates that there

exists a class of mixed systems with materials both $\mu > \mu_0$ and $\mu < \mu_0$, e.g. iron and superconductors as well as normal conductors with eddy currents or constant flux coils which should provide stable levitation. This technique was experimented by many researchers for different systems, it needs more control investigation to prove its superiority over other techniques (5).

2.5. Levitation using eddy currents induced by mains frequency excitation :

A force of repulsion is generated between a coil, carrying alternating current and an electrically conducting surface, when placed in the proximity of the coil so that the alternating magnetic field of the coil induces eddy current in the conductor. this effect can be utilised for the levitation of conducting objects, such as passenger carrying vehicles. A single sided linear induction motor can be designed to produce large levitation forces in addition to its normal translational forces. The speed of the linear motor with respect to a composite reaction plate, consisting of conducting material backed by permeable material such as steel, increases, the force of repulsion becomes a force of attraction in normal design. Although all the techniques of levitation or suspension have been thought of at one time or another as capable of practical application, only three remain in contention, even on technical grounds, as applicable to advanced ground transportation or vehicle carrying passengers. They are explained in more details in the following sections (5).

3. Permanent magnet technique

During the past twenty years a new class of materials for making improved permanent magnets has been developed based on Cobalt and some rare earth elements. The improvement is so great that the cobalt-rare-earth magnets are in a class by themselves. In terms of their resistance to demagnetisation the new materials are 20-50 times superior to the previous best, Alnico, and their magnetic energy is two to six times greater. Corresponding poles of such magnets can be kept together without suffering more than a small percentage loss in magnetism, and even this loss is mainly recovered. Such magnets can be brought together an infinite times and after the first two or three times the force of repulsion does not change. A current carrying coil on one of these magnets can be energitised in a direction completely re-

versing the effective polarity of the combination, and yet when the current in the coil is removed the magnets remains virtually unaffected (5).

3.1. Properties of permanent magnets :

Ferromagnetic elements have atoms in which one electron shell contains fewer than the maximum number of electrons. In such unfilled shells there are one or more unbalanced electron spins giving rise to a small magnetic moment and making the atom itself a tiny magnet. Ordinarily, in a large collection of such atoms the atomic magnets point in various directions and cancel one another. If a sample of ferromagnetic material is placed in a magnetic field, however, the individual atomic magnets tend to line up so that when the sample is removed from the field it retains a net residual magnetism. The total magnetisation indicated by the symbol M is the sum of the contributions of all the elementary atomic magnets. The magnetisation in any direction reaches its saturation value when all the atomic magnets are parallel and pointing in the direction. Magnetic materials are divided into two categories, hard or soft, depending on the ease with which they may be magnetised or demagnetised.

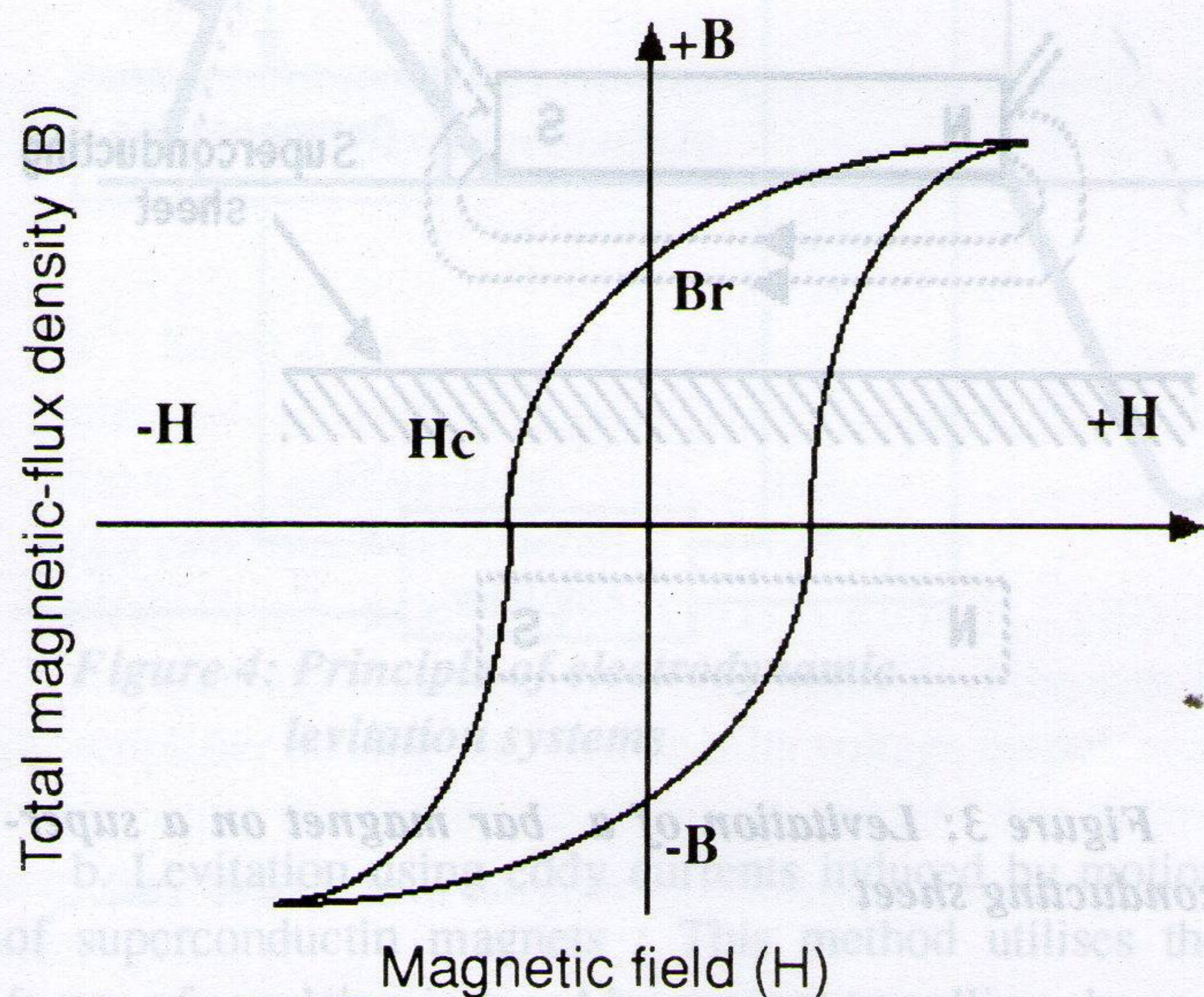


Figure 2: BH loop of permanent magnet

A hard material has a wide hysteresis loop and a soft material has a narrow loop. Each reversal of a loop represents energy lost. As a result materials are suited for electrical devices, such as transformers, where the material is subject to a reversal of magnetisation several times a se-

cond. Hard materials on the second hand, are what one is looking for in the application of permanent magnets, particularly those utilising the forces of repulsion, such as in suspension or levitation. Magnetic materials are generally described by their hysteresis loops, in which the vertical axis is the total flux density B rather than the magnetisation M , the total flux density includes the contributions of both magnetisation and field strength. Fig. 2 shows the relationship between the magnetic flux density and the magnetic field, the upper left hand quadrant of a B/H loop is important from the point of view of an engineer trying to determine the quality of permanent magnets. Three points on this part of the curve are significant, the first is the crossing of the vertical axis, i.e. where the magnetising field has been removed but the material retains its magnetisation, it is named remanence B_r . If the magnetising field is actually reversed, the value of the imposed field H_c which reduces the total flux density to zero is called the coercive force. Furthermore each point on the loop represents some value of the product BH , the point where this value reaches maximum is known as the maximum energy product $(BH)_{max}$, it is used as an index of quality for permanent magnets (5).

3.2. Levitation using permanent magnets :

The development Earnshaw's theorem shows that is impossible for a body to be held in equilibrium against displacements in all directions if the system is constituted of permanent magnets only. When all restoring forces are generated by repulsion between permanent magnets there remains at least one direction for which the body is in unstable equilibrium; the smallest displacement in this direction brings into being a force which tends to increase the displacement. It is, however, perfectly feasible to achieve complete levitation when a combination of permanent magnets and controlled electromagnets is used. In common with other systems of levitation and suspension, permanent magnets offer the advantages of eliminating friction, noise, vibration and reduced maintenance. It is also not necessary to provide energy continuously to obtain lift, however, the main disadvantage might be that the permanent magnet track would be prohibitively expensive. Even if it turns out feasible to produce the very large quantities of Barium-Ferrite or preferably Cobalt-Samarium magnets required to lay the track.

3.3. Force estimation of permanent magnets :

The calculation of forces of repulsion between magnets is difficult, and in general based on experimental results, the scaling up may be subject to considerable errors. Many methods have been experimented for different types of permanent magnets, they show that the repulsion force increases with the decrease of the distance. It can be concluded, that the force of repulsion depends on the magnetic material, the arrangement of poles, the shape and the thickness of the magnets, the distance of the repelling faces and dimensions of any steel parts used. Whereas, not many attempts at predicting the forces of repulsion analytically appear to have given satisfactory results, although the expression below would not seem very difficult to evaluate.

$$B^2/2\mu_0 \quad (2)$$

In the case of attraction systems the implicit assumption of uniform flux density in this expression is more or less satisfied but it is far from true for magnets in repulsion. To obtain a correct estimate it is necessary to consider the influence of one magnet on the magnetisation of the other. This may be possible by considering each magnet top consist of a distribution of poles, dipoles or current loops.

4. Superconductor techniques

There are two ways in which superconduction can be utilised to obtain levitation. The first is the Meissner effect, i.e. rejection of magnetic flux making the superconducting body behave as a perfectly diamagnetic body ($\mu_r=0$). The second, which is the more practicable for application to vehicles, relies on the force of repulsion between superconducting magnet moving on a conducting plate or guideway. This method was originally proposed by Powell and Dandy. Just as the advances in permanent magnet have led to the interest in their application to passenger carrying vehicles, similarly, developments in the technology of superconductivity attributable largely to the development of materials have spurred on the development of its application to the vehicle technology (5,8).

4.1. Properties of superconductors :

Superconductors form part of a category of materials at temperatures approaching 0 K called superfluids. Two types of superfluids are known, one is represented by liq-

uid helium when cooled to 2.19 K, and the other type is represented by the superconducting state of electrons. Hence certain metals and alloys when cooled to a temperature approaching 0K become superconductors. The superconducting state is indicated by the complete absence of electrical resistance, and once initiated, current will continue to flow. This is also accompanied by rejection of magnetic flux in the superconducting body, the effect is known as the Meissner effect which causes superconductors to behave as perfectly diamagnetic bodies ($\mu_r=0$) (5).

4.2. Principles of superconducting levitation :

Two methods of using the superconducting phenomenon were mentioned earlier. The first method is the Meissner effect, it is suitable for levitating gyro rotors. The second utilises forces of repulsion arising from the interaction between a superconducting magnet and eddy currents induced in a conducting sheet as a result of relative motion between them. This phenomenon is suitable for the levitation of passenger carrying vehicles, both methods are explained below (5).

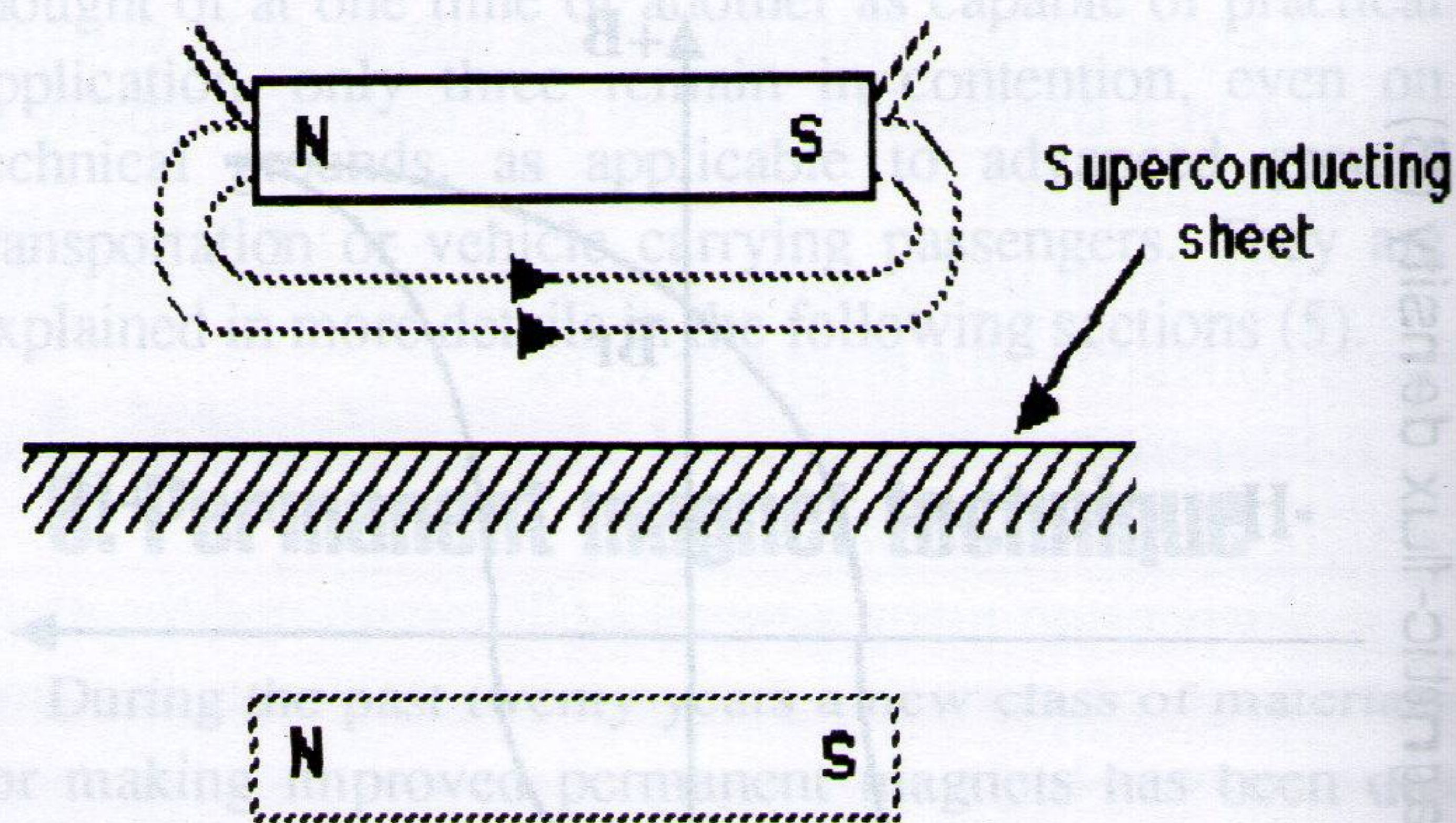


Figure 3: Levitation of a bar magnet on a superconducting sheet

a. Levitation using Meissner effect : When a bar magnet is brought near a horizontal superconducting surface, the flux may be regarded as being compressed into the space between the magnet and the magnetically impermeable surface of the superconductor as shown in Fig. 3. Provided the compression of the flux does not lead to the critical flux density being exceeded, the magnet will float on the superconducting surface in stable equilibrium in

the vertical direction. If the surface is sufficiently large in relation to the size of the magnet, it will be in neutral equilibrium in the horizontal plane.

Many experiments of using superconducting surface have been performed, they show that usually a superconducting object is levitated by flux from more than one magnet and that the levitated object is usually a rotor. The magnets are usually superconducting rings or coils which carry persistent currents (5).

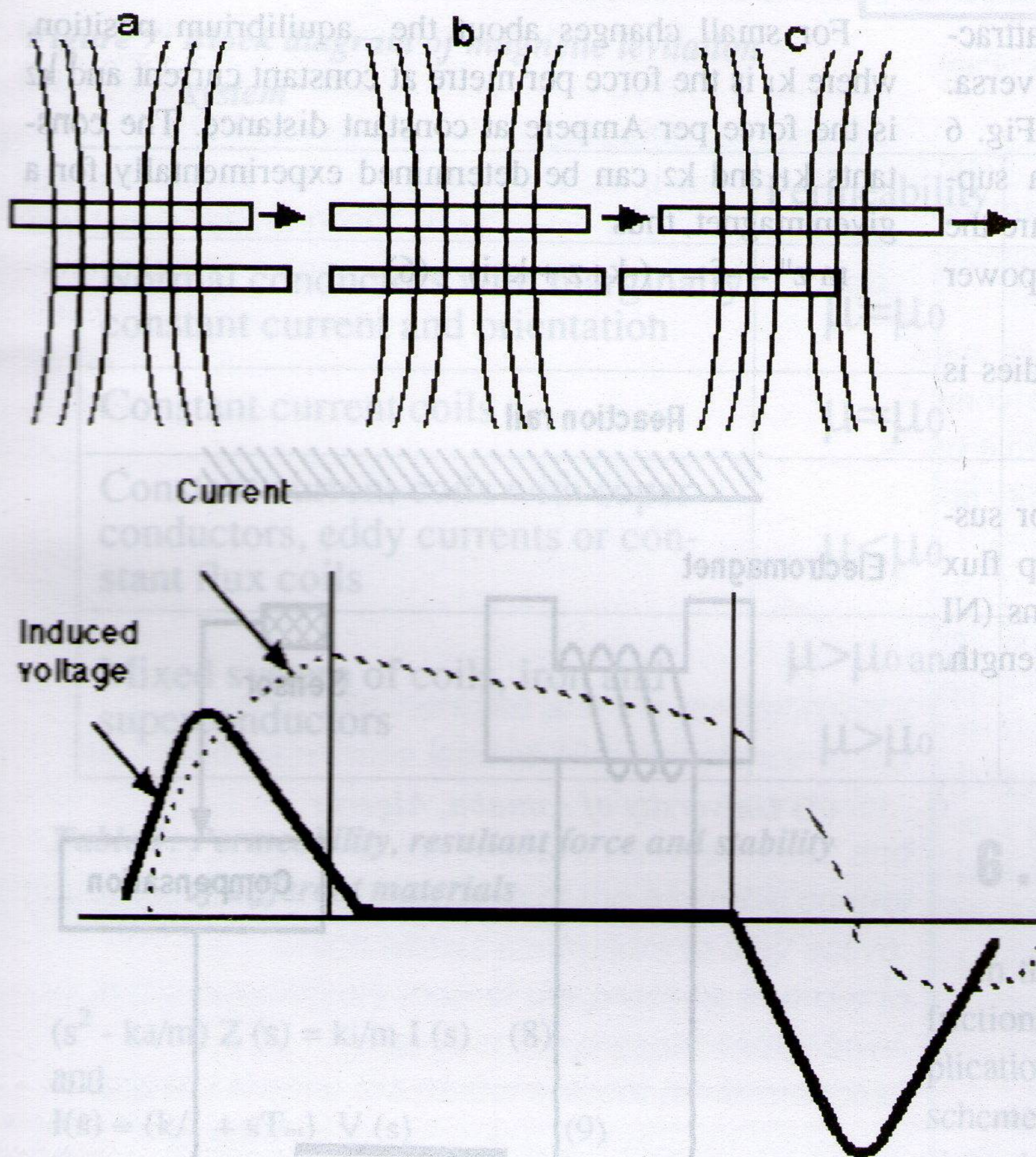


Figure 4: Principle of electrodynamic levitation systems

b. Levitation using eddy currents induced by motion of superconductin magnets : This method utilises the forces of repulsion induced by magnet travelling above a conducting surface. Conventional electromagnets or permanent magnets are only capable of producing induced levitation at small clearances. They are incapable of producing magnetic fields of the size and intensity required for anything heavy, such as, a passenger carrying vehicle. The principle of electromagnet levitation, as this phe-

nomenon is now called, is shown in Fig.4, the upper loop of the figure, which is assumed to be carrying a current, it also assumed to be in motion with respect to the lower loop, and it will thus induce an EMF in it. The induced current persists in the stationary loop for some time after the travelling loop has passed over it, and is called an eddy current wake. The main characteristics of electromagnet levitation can be explained by the following basic principles. If a current carrying coil accelerates at a constant height above a conducting guideway it experiences a lift force at first proportional to the square of the velocity, but eventually reaching a limiting value. The drag force is at first proportional to the velocity but then passes through a peak and decreases inversely as the velocity. At high speeds the drag decreases more slowly because of the skin effect which makes the apparent resistance of the guideway higher. The lift force is proportional to the product of the perpendicular and parallel components of the magnetic field, and the drag is proportional to the square of the component of the magnetic field perpendicular to the surface of the guideway. The lift-to-drag ratio is, therefore, proportional to the ratio of the parallel component to the perpendicular component of the magnetic field. This relationship gives some insight into the way the configuration of the magnets on a vehicle can be optimised (5).

5. Electromagnetic suspension technique

This technology is, at the present time, by far the most advanced, and is the subject of worldwide investigation not only for advanced ground transportation schemes but for application in contactless bearing for high and low speeds. Both in these and in vehicle applications, energy requirements, elimination of noise and reliability appear to be important features as contributing to the success of this method. Combinations of permanent magnets with controlled excitation also appear technically feasible, and might lead to further reduction of energy requirement (5,8).

5.1. Principle of suspension using controlled DC electromagnets :

It was explained earlier that systems using permanent or electromagnets without control are unstable. Therefore, to achieve stable suspension it is necessary to devise a means of regulating the current in an electromagnet using position feedback of the object to be suspended. The effect of this is to modify the force/distance characteristics such that the current, and thus the force of attraction, decreases as the airgap decreases and vice versa. Fig. 5 shows the force/distance characteristics, and Fig. 6 shows a general form of the use of this method for a suspended vehicle. The main elements of the system are the position detector (sensor), a compensator, and a power amplifier (8,9).

The force of attraction between magnetised bodies is given by

$$F_m = B^2 / 2\mu_0 * \text{area} \quad (3)$$

In the case of electromagnets, such as those for suspension systems operating with an airgap, the gap flux density is directly proportional to the Ampere turns (NI product) and inversely proportional to the gap length. Therefore the previous equation can be rewritten as

$$F_m = \mu_0 / 2 (NI/g)^2 * \text{area} \quad (4)$$

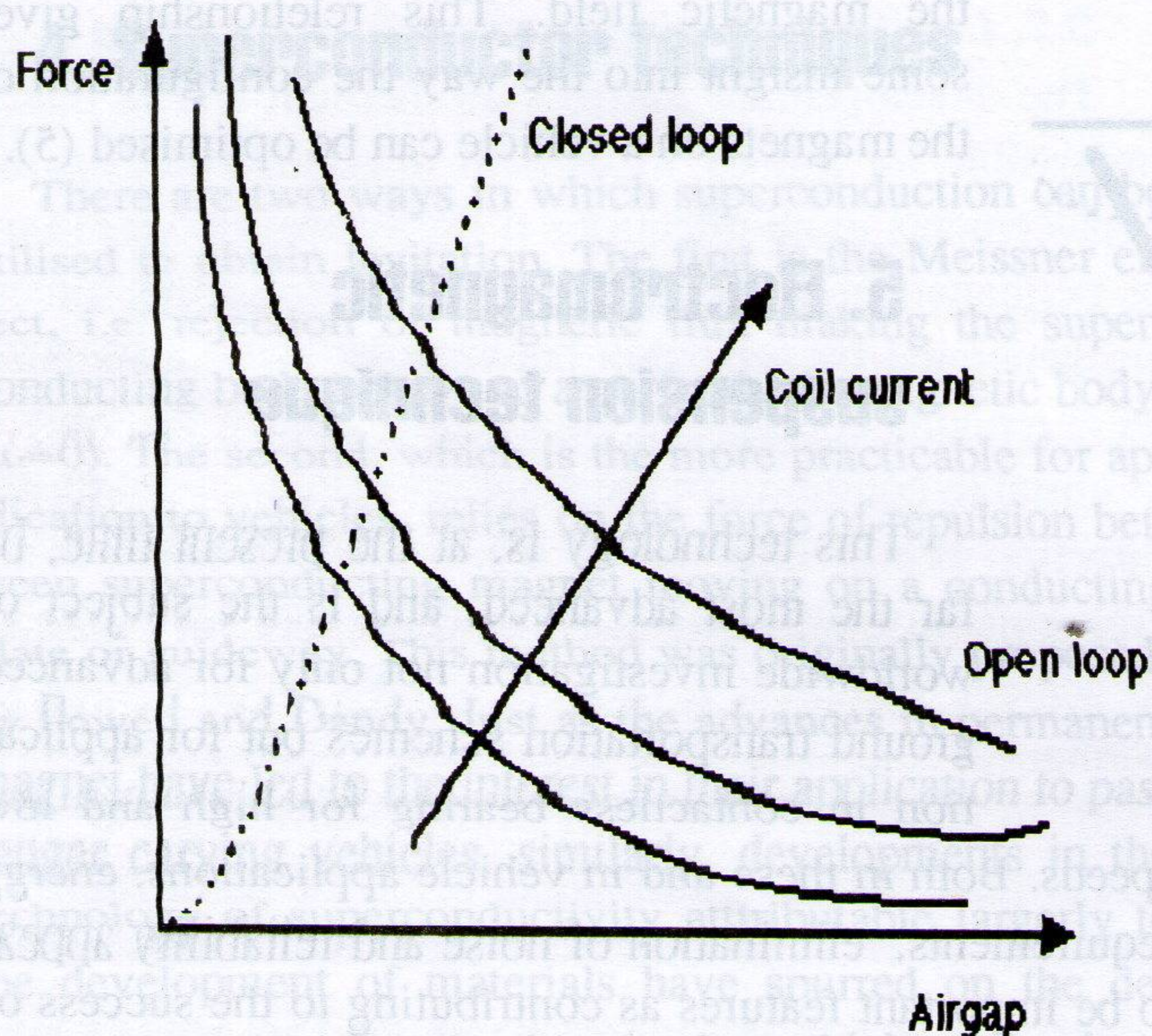


Figure 5: Open loop and closed loop characteristics

It is obvious from this equation as well as the force/distance characteristic (Fig.5), that the system is a highly nonlinear position regulator. An adequate insight into the nature of the control problem can, however, be gained by

looking at the linearised model. At the nominal required gap the magnet current i_0 generates a force equal to the weight to be suspended. Any displacement z from this position requires a change i in the current. It is assumed in the first instance that the change in the force of attraction is given by a linear function of the gap and current changes (8,9). The linearised equation is, therefore

$$f = -k_d z + k_i i \quad (5)$$

For small changes about the equilibrium position, where k_1 is the force per metre at constant current and k_2 is the force per Ampere at constant distance. The constants k_1 and k_2 can be determined experimentally for a given magnet, thus

$$m z'' = -f = -(-k_d z + k_i i) \quad (6)$$

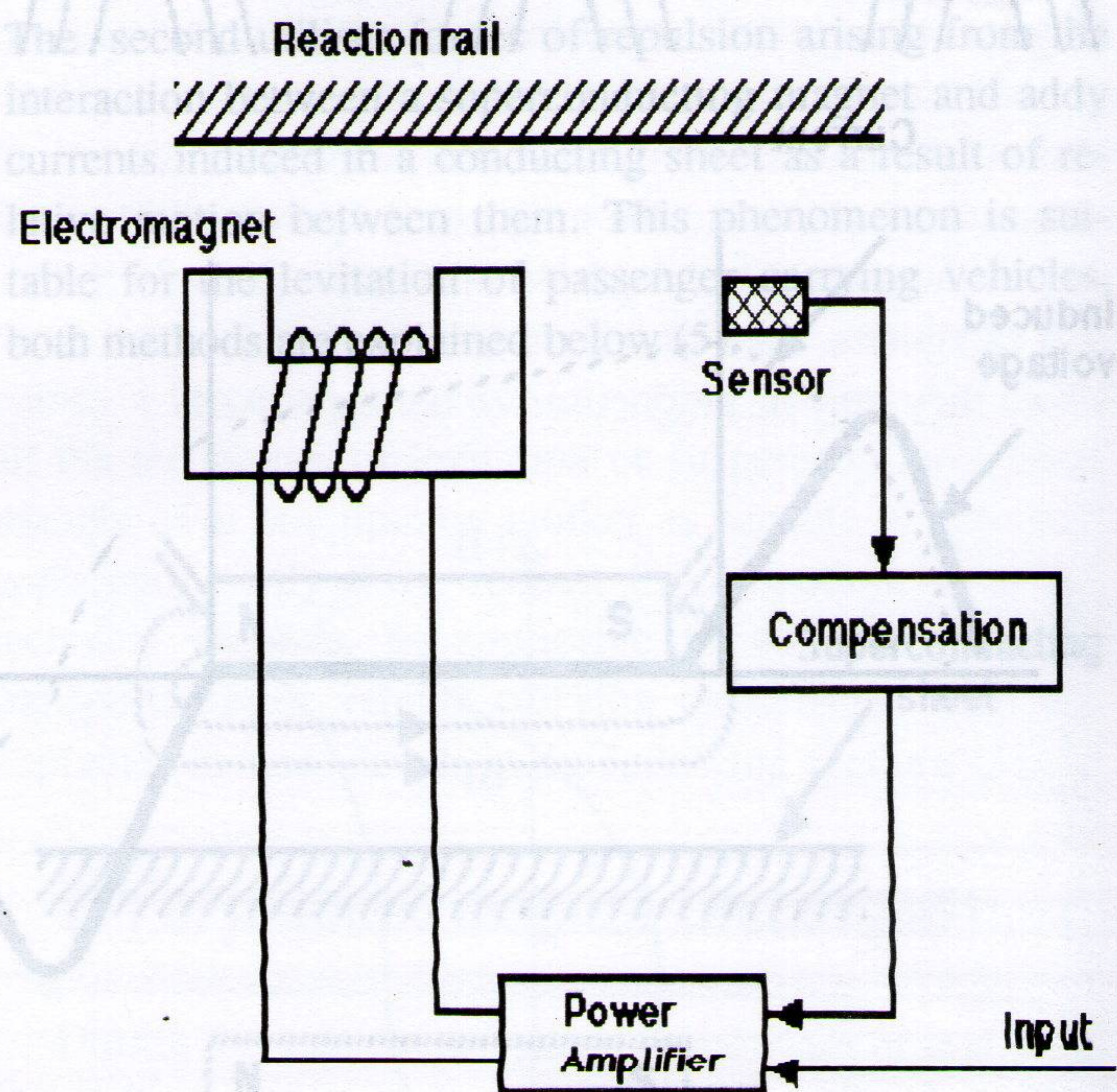


Figure 6: Suspension of magnet under steel rail.

Where m is the mass of the suspended body.

The relationship between the magnet current and voltage is

$$R i + L di/dt = V \quad (7)$$

The transformation of the two previous equations to Laplace notation gives

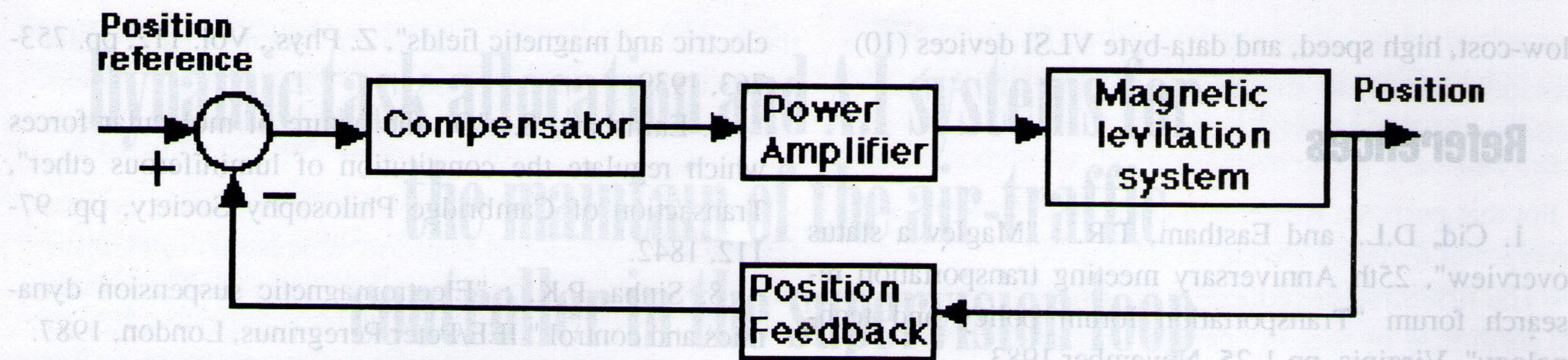


Figure 7: Block diagram of magnetic levitation system

	Permeability	DIV F	Stability
Normal conductors with marginally constant current and orientation	$\mu=\mu_0$	$= 0$	Stable
Constant current coils	$\mu=\mu_0$	> 0	Unstable
Constant current coils with superconductors, eddy currents or constant flux coils	$\mu<\mu_0$	< 0	Stable operation possible
Mixed system of coils, iron and superconductors	$\mu>\mu_0$ and $\mu>\mu_0$	> 0 and < 0	Stable operation possible

Table 1: Permeability, resultant force and stability of different materials

$$(s^2 - k_d/m) Z(s) = k_i/m I(s) \quad (8)$$

and

$$I(s) = (k/l + sT_m) V(s) \quad (9)$$

The two equations combined together give

$$(Z(s)/V(s)) = -k k_i / (m(1+sT_m)(s^2 - K_d/m)) \quad (10)$$

The quantity that may be directly controlled through a DC amplifier driving the magnet is its voltage output, and T represents the lag in the resulting current due to the magnet inductance. The second term $(s^2 - k_i/m)$ represents poles at

$$\pm \sqrt{(k_d/m)} \quad (11)$$

on the real axis in the s plane and the positive pole contributes to the instability (8). The block diagram of a closed loop magnetic suspension system is shown in Fig.7.

6 . Conclusions

In the application of magnetic suspension systems to frictionless bearings there is a very wide range of applications possible, with controlled DC electromagnet schemes being most practical (5). The cost of the suspension element seems to dominate the thinking, and for this reason the superconducting magnet schemes do not figure predominantly. Although the control aspect is a great deal more difficult, controlled permanent magnets offer the possibility of very small suspension power requirement, it is also capable of operating satisfactorily in the most hostile environmental conditions (5,8). However the associated open loop instability, and the non-linearity of the force-current and the force-distance characteristics are the major drawbacks of this technique. The instability problem have hitherto been eliminated by the use of precision analogue controller (10). This technique, however is limited by its inflexibility and the drifting of the analogue components. These limitations can be overcome by using digital techniques implemented on

low-cost, high speed, and data-byte VLSI devices (10)

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