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ATTRACTIVE AND REPULSIVE MAGNETIC SUSPENSION SYSTEMS OVERVIEW

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ABSTRACT

Magnetic suspension systems can be used in a wide variety of applications. The decision of whether to use an attractive or repulsive suspension system for a particular application is a fundamental one which must be made during the design process. As an aid to the designer, we compare and contrast attractive and repulsive magnetic suspension systems and indicate whether and under what conditions one or the other system is preferred.

The suspension design chosen depends upon the details of the application. There is no fundamental advantage of either attractive or repulsive systems. Rather, the specific characteristics of each system determine their applicability in any given situation. The parameters which are to be considered when designing the suspension system include size; suspension force; air gap; required suspension stiffness; volume available for magnets, coils, cooling, and controls; stability; required damping characteristics; required input power; and the operating environment, i.e., operating temperature, ruggedness,and DC or AC external magnetic field constraints.

Results of magnetic suspension studies employing permanent magnets, ferromagnets and superconducting magnets are presented. Specific examples of requirements for magnetic bearings for gas turbines and Maglev investigations are also presented.

MAGNETIC SUSPENSION REQUIRES A SYSTEM DESIGN

Introduction

Magnetic suspension design requires a systems approach. Design of a magnetic suspension system frequently involves many complicated interactions between disparate subsystems. To optimally design such a system, the designer must have an understanding of the various subsystems as well as a detailed understanding of the interface between them. Magnetic suspension systems may involve effects due to heat transfer, structural mechanics, electromagnetics, gravity, inertia, aerodynamics, material properties, thermal expansion, and cost. The system designer must be able to make intelligent technical trade-offs and compromises among these areas.

Magnetic suspension systems rely upon the concept of action at a distance, and they are primarily of interest due to the non-contact nature of the interface.

It is common to classify magnetic suspension systems according to whether the fields are attractive or repulsive. The fact that there are "fields," plural, means that at least two objects must interact and each object must have associated with it a magnetic field. In some cases, the magnetic field of one object induces a field in the other object where there would otherwise be no field. In practice, there are usually many interactions simultaneously occurring among several objects.

This paper will examine attractive and repulsive magnetic suspension systems. Detailed discussion of attractive and repulsive magnetically levitated trains will follow. The purpose is to highlight the need for a system's approach to select a system which best satisfies the goals of the program.

Attractive and Repulsive Systems

In general, attractive and repulsive systems can be described by the interaction of the equivalent currents of the interacting bodies. For non-ferromagnetic bodies the currents are simply the actual applied or induced currents. For ferromagnetic bodies, the total current is the sum of the actual currents and the equivalent currents. The equivalent currents are determined from an integration of the magnetization current density which is equal to the curl of the magnetization.[1,2] The external magnetic field of the body and all its interactions can be described alternatively as the result of a magnetization (with no current) or current (with no magnetization).

Figure 1 shows a schematic of attractive and repulsive coils. Magnetic flux lines and resultant force are indicated. Repulsive levitation occurs due to bucking magnetic fields while attractive levitation occurs due to parallel magnetic fields.

The force generated (either attractive or repulsive) as a function of air gap separation is shown in Figure 2. This figure shows that the same magnitude of the force is generated for attractive and repulsive systems (for the same geometry and current) and it is only the direction of the force which changes as the direction of the current is changed. The direction of the force is opposite for the two schemes: the force of the attractive scheme tends to increase in the direction of the force (coil separation is decreased) while the force of the repulsive scheme decreases in the direction of the force (coil separation is increased). (Both conclusions assume constant excitation currents.)

Since the goal is usually levitation at a constant height, the attractive scheme is said to be inherently unstable while the repulsive scheme is stable. By varying the excitation currents appropriately the attractive system can be made to be stable.

The methods to generate magnetic fields are permanent magnets, electromagnets, ferromagnets, and superconducting magnets. These magnets may be combined to produce attractive or repulsive forces. Table 1 shows the combinations of the magnets and the types of suspension systems possible with them.

Figure 3 shows a corporate structure of magnetic levitation systems as they are presently used.

There are limitations to existing technology which affect the choices for a given system. For example, although no energy is required to maintain a steady state magnetic field, superconductors will dissipate energy if subjected to varying magnetic fields. Therefore, great care is taken to isolate them from field variations. The repulsive pairing of superconductors with other superconductors and permanent magnets is not meant to imply any practical advantage of repulsive over attractive systems. The point is repulsive levitation is stable which makes plausible only small superconductor heating effects. Attractive levitation is unstable and would require significant supercurrent modulation which produces undesirable heating of the superconductor itself. Recent progress in high temperature superconductors suggests the possibility of varying supercurrents.

Material response at the operating temperature is one of the major issues for selecting magnetic suspension systems. The required operating temperature may be quite hot, ~1000 K in gas turbine engines. At high temperatures it is difficult to produce a high magnetic field. At moderate temperatures, such as room temperature, significant thicknesses of insulation are required to permit superconductors. Figure 4 shows a plot of magnet material temperature vs. magnetic field. Note the figure has a second x-axis which shows the equivalent pressure of the magnetic field. The limiting temperatures and fields for permanent magnets, ferromagnets, and high and low temperature superconductors are shown. This figure is meant to be suggestive rather than exhaustive. It is not the precise position of individual points which is important, rather the general trends. For relatively small magnetic fields at high temperatures, permanent magnets and ferromagnets generally have an advantage over superconductors. Alternatively, if higher magnetic fields are required, superconductors have a significantly greater capability than ferromagnetic materials.

Electromagnets utilizing ferromagnetic material are an important technique for magnetic suspension. The dissipated electrical power in the (normally) resistive wire, however, is the penalty of this method. Calculations of the power consumed by the attractive system are relatively sensitive to the input parameter values. In principle, the resistive power can be made arbitrarily small by using an arbitrarily large conductor cross section. It can readily be shown that for unsaturated ferromagnetic materials the power required for levitation increases linearly as the levitation pressure is increased. As the ferromagnetic material approaches saturation, the power consumed increases faster than linearly with increases in levitation pressure. Therefore, for ferromagnetic materials, there is a maximum magnetic levitation pressure.

Superconducting magnets consume no power during operation except for the refrigeration system. The power required for refrigeration is dependent upon the ambient temperature and the exposed magnet surface area and is relatively independent of supplied magnetic pressure. For liquid helium temperature superconductors the refrigerator power consumed is sensitive to the quality of insulation between the ambient environment and the superconductor. The superconductor characteristics determine the maximum levitation pressure. Magnet design must account for the critical magnetic field and the decrease in the critical current density at elevated magnetic fields. Therefore, for superconducting magnets, there is a maximum magnetic levitation pressure.

Repulsive Maglev systems usually use superconductors to induce eddy currents in coils along the guideway or ground to provide levitation. Most commonly these coils are normally resistive conductors but, in principle, the coils could be superconducting. The levitation force supplied depends only on the induced eddy currents and is independent of lateral speed. The power dissipated in levitation, therefore, can be made arbitrarily small by increasing the normal conductor cross section or zero by use of superconductor coils. It is interesting to note that levitation at standstill is possible with superconducting eddy current coils.

Figure 5 shows a plot of magnetic levitation pressure vs. input power for specific attractive and low temperature superconducting repulsive magnetic suspension systems which have been analyzed. For both systems, an attempt was made to present favorable but reasonable results. Both systems levitate a train with a capacity of approximately 100 passengers. The attractive system attracts upward to a ferromagnetic rail while the repulsive system uses ground coil levitation. This figure neglects magnetic drag. The gap for the attractive system is 10 mm and the gap for the superconducting system is 100 mm.

The figure shows a cross-over point between attractive and repulsive systems from a power consumption standpoint. For the systems analyzed, this cross-over point occurs between approximately 10 psi and 15 psi (70 kPa and 105 kPa). In essence, attractive ferromagnetic systems provide low magnetic levitation pressure at minimum power while repulsive superconducting systems provide high pressure with minimum power.

Improvements in properties of materials can sway the relative balance between attractive and repulsive system advantages. For example, high temperature superconductors (HTSC) have greatly reduced cryogenic requirements compared to low temperature superconductors (LTSC). HTSCs may be practical in some applications with a limited gap where LTSC materials are not practical due simply to a reduction in the required thickness of insulation. New ferromagnetic materials are under development which are extending the temperature vs. magnetic field envelope of attractive systems.

In essence, ferromagnetic materials make attractive suspension schemes practical and superconducting coils make repulsive systems practical.

Above we have touched upon some of the important general issues in the system design of a magnetic suspension system. Table 2 shows a listing of these and other issues.

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A discussion of each of these topics is beyond the scope of this paper. However, the effect of air gap is critical to any magnetic bearing system. The importance of the size of the air gap leads to the following discussion on scaling laws.

Scaling Laws

Scaling laws relate design parameters so the designer can easily see the effect of changing one parameter has on other parameters of interest. In the initial design stage, it is not so important to known the precise value of a parameter, as it is to understand how the situation changes by varying the parameter in a given manner.

Scaling laws can be developed to focus on any particular set of parameters. One would expect scaling laws to arise from limitations in three areas: thermal, electromagnetic and structural. The reader should note the issues involved here and use any particular scaling law only after careful consideration is given to the applicability of the law.

We consider the following systems: permanent magnet (PM) and current-based systems. The results presented here are for constant-gap scaling and scaled gap (full) scaling. Constant gap scaling is useful since in many circumstances the air gap is fixed by mechanical clearances and is relatively independent of size. Full scaling is used when the gap is increased in proportion to the size of the bearing. The magnetic energy in the gap is proportional to the load capacity of the bearing.

Generally the parameter of interest is the magnetic energy stored in the air gap. Table 3 gives the scaling laws for the magnetic energy for pressure within the gap for PM and current-based suspensions systems. The current-based systems are assumed to be limited by one of three phenomena: thermal, electromagnetic or structural. The results are given for constant gap and scaled gap. The scaling parameter, L, is the dimensionless scale factor by which a given system is scaled up ($L>1$) or scaled down ($L<1$).

Time-dependent effects are also important for system scaling. The ratio of the conductor thickness to the skin depth is referred to as the eddy current ratio (ECR). For ECR > 1, eddy current effects are important. Two common scaling relations for frequencies are constant frequency and reciprocal frequency scaling. Although the details differ, for both common frequency scaling laws ECR increases with increasing scale size. Hence, for small scale sizes, smaller eddy current effects are produced. This has important implications for small scale eddy current-generated repulsive suspension systems.

As shown in the table, the scaling law to be applied depends upon the situation under analysis and whether the gap is scaled. Current based magnetic suspension systems generally increase in gap magnetic energy at least as fast as PM-based systems, and possibly faster, depending upon the limiting factors. For current-based systems the slowest rate of increase in gap energy is for constant-stress systems, and the greatest increase in gap energy is for constant current density and constant boiling latent heat systems. Heat transfer-limited system are intermediate between constant stress and constant current density systems.

The advantage for current-based systems over PM systems as scale size increases becomes a disadvantage as scale size is decreased. For decreasing scale size, the gap energy of PM systems decreases no faster than the most favorable current-based system.

The generation of eddy currents is also sensitive to scale size. For the cases analyzed the effects of eddy currents increase with increases in scale size and decrease with decreases in scale size. Hence, eddy current repulsive magnetic suspension systems will readily scale up but will require careful system design for small scale applications.

In summary of the scaling laws, a system to be increased in scale size is preferably a constant current density, constant gap system and may be based upon eddy current repulsion. A system to be decreased in scale size is preferably a scaled-gap system with either PM or a stress-limited current and is not based upon eddy currents.

Thermal Management

In many applications, the management of thermal issues is an important, if not dominant, concern. In some applications, the ambient temperature may be very high. For attractive ferroelectromagnetic suspensions the power dissipated in resistive heating must be removed or the system will continuously increase in temperature. Repulsive superconductive levitation systems must provide cryogenic cooling to the superconductors.

Table 4 below shows some of the important properties of typical coolants. The purpose of this table is two-fold: to suggest why HTSCs offer such a significant improvement over LTSCs from a thermal standpoint, and to promote the consideration of LH_2 as a useful cryogen with excellent properties. The improvements of LN_2 over LHe can be seen to be in the heat of vaporization H_{fg} and in the refrigerator efficiency. Boiling LN_2 carries away 10 times the heat per kg as boiling LHe. The refrigerator efficiency is the electrical power consumed (W) per unit input thermal power (W), or Watts/Watt. As an example, if a LHe refrigerator has an input heat power of 4 Watts, the electrical power required to remove it is 7 kW.

Liquid hydrogen cryogen is becoming more commonplace as a result of two different circumstances: safety concerns are alleviated with the positive experience which has been gained handling liquid hydrogen from the space program, and the exceptional properties of materials at LH_2 temperatures are becoming well-known. In particular, the electrical resistance of high purity cryogenic aluminum will decrease by a factor of over 1000 when operated at 20 K. This makes several high current pulsed power applications feasible.[3,4]

The remainder of this paper discusses two specific applications of magnetic suspensions: magnetic bearing for turbine engines and magnetically levitated (Maglev) trains. Due to the limited volume available within the turbine housing, attractive magnetic bearings historically have been favored. As will be shown later, this observation agrees with the derived scaling laws. Attractive and repulsive Maglev systems have been developed in parallel by qualified and dedicated engineers. It appears that in this application the systems each have relative advantages and disadvantages with respect to one another. Non-technical factors increasingly become the basis for a system preference. Nevertheless, we shall discuss these relative advantages and disadvantages so the reader can understand the issues involved.

Magnetic Bearings for Turbines

Magnetic bearings for high speed rotor and turbine applications have been receiving an increasing amount of attention.[5,6,7,8,9] This is primarily due to the increasingly severe requirements of the applications, the limits on conventional bearings and the non-contact nature of magnetic bearings. Other advantages of magnetic bearings are: no temperature limit of the suspended body, although, of course, the bearing material itself has limits; better bearing reliability; reduced maintenance requirements; improved perturbation damping capabilities; and magnetic follower control. This last concept is interesting since it allows an eccentric rotor to spin within the limits of the bearing housing.

In the most demanding applications, bearings for aircraft gas turbine engines, magnetic bearings may allow a 50% increase in the DN rating over conventional bearings. The DN rating is the product of the shaft diameter (in mm) and the rotational frequency (in rpm) and is presently in excess of 2.2 million with efforts under way to exceed 3.3 million.

Table 5 gives an example of the magnetic bearing requirements for a high performance gas turbine engine.

Magnetic Levitation for Transportation

Magnetically levitated (Maglev) trains are a good example of magnetic suspension systems not only because of the obvious reason, but also because from a different perspective Maglev is a System of systems. Maglev is 80% about moving people and freight, gaining right-of-way and in-flight meals and only 20% about technical issues. Levitation is but one of four or five important technical issues. Therefore, the issue of how levitation is actually achieved, although important, cannot be decided upon without due consideration of other important issues, some technical and some non-technical. We shall point out some of both types of issues below.

The attractive magnetic suspension is implemented with normally resistive electrical conductor and highly permeable cores. Attractive systems lend themselves to either the linear induction motor (LIM) or the linear synchronous motor (LSM) for propulsion.

The repulsive levitation scheme is implemented with low-temperature superconducting (SC) magnets on-board the vehicle and normal (resistive) conductor coils either on the ground or on the guideway vertical side-wall.

Superconductors dissipate energy due to alternating currents. As shown above, this energy is expensive to remove (1750 W/W for LTSC systems) and increases the possibility of SC quench. Hence, the apparent frequency of the LIM is deleterious to SC operation and operation in the LSM mode is preferred. However, there are studies being pursued presently which will examine the possibility of a superconducting LIM.[10]

Figure 5 conceptually shows the attractive and repulsive Maglev systems. Table 6 shows the operating characteristics of Maglev trains.

In the following subsections, we discuss each Maglev suspension scheme in additional detail.

Maglev Attractive Scheme

The overall weight of the vehicle determines the upward force required from the magnet. The available magnetic pole area then determines the required magnetic pressure, which determines the air gap magnetic field. The material hysteresis curve then determines the drive current required to achieve the specified field. The drive current determines the dissipated power. Due to non-linear magnetic saturation, this design procedure generally is repeated until the designer is satisfied that either all parameters are reasonable or an entirely new design is required.

As shown in the table above the overall mass of the attractive system is greater than for a repulsive system. Because the attractive system is weight sensitive, the levitation system has been highly optimized[11] and the greatest achievable levitation force per unit current is attained by design.

The support magnets are distributed uniformly down the length of the train. Each of the support magnets independently determines its air gap. Uniform distribution has the advantage of reducing the peak force loading on the guideway. Independent suspension has the advantage of minimizing the nominal air gap due to guideway perturbations. For example, if all magnets down the length of the train had to be set for the largest required air gap then the magnet currents and dissipated power would increase.

An advantage of the ferromagnetic attractive system is the inherent magnetic field shielding provided by the fact that the magnetic flux is confined to ferromagnetic materials and has only a small air gap to traverse. This advantage is often overlooked and should not be minimized. Although the effects of either low level direct current (dc) or alternating current (ac) magnetic fields on people are not well-known, there are many people concerned about potential effects thereof and this issue will have an impact on the acceptance and cost of Maglev systems.

The iron-cored long stator linear motor operates in combination with the magnetic levitation subsystem. Essentially, the excitation magnets of the motor also perform the chores of suspension magnets.[12] The guidance magnets are a dedicated subsystem operating on the attractive principle (attract-left, attract-right). With this system, the lateral acceleration is positively controlled in both directions.

It is an interesting fact that the attractive suspension system only attracts upward. Vertical perturbations in the guideway can only be positively responded to if they require an upward force. The downward force requirement is supplied only by gravity. A vertical acceleration of ± 1 g is generally sufficient for transportation applications but in force-transducer applications a greater range is frequently desired. A greater range of acceleration, of course, can readily be supplied by a levitation system which attracts downward to a ferromagnetic rail. Modulation between the upward and downward systems can provide the desired forces and accelerations.

The necessity of accurately following the guideway perturbations increases the requirements on the secondary suspension system. The secondary suspension system is the interface between the support magnets and the passengers. The function of the secondary suspension system is to smooth the ride for the passengers.

Large gap attractive magnetic suspension schemes are possible but require large ferromagnet masses, large dissipated power and large reactive power capacity.

Maglev Repulsive Scheme

The dominant technical feature of an air core superconducting maglev system is the magnetic field of the superconducting (SC) magnets. The functions of propulsion, guidance, levitation and inductive power transfer to the vehicle are accomplished by utilizing this stray flux.

Figure 6 shows a superconducting repulsive maglev system. In the figure, the vehicle is imagined to come out of the page and the view is of the right hand side of the vehicle. The left hand side is symmetrically designed. Note that there are two air gaps: one vertically and one horizontally oriented.

Lateral guidance is achieved by cross-connected propulsion coils as shown in Figure 7a and b. Drive current is supplied at one location as shown. The crossing of conductors under the guideway provides the proper field orientation for propulsion. This connection also serves to provide for balanced repulsion from the guideway walls. When the vehicle is laterally centered, Figure 7a, the flux passing through each coil is the same, the voltages are equal and opposite and no net current is induced. If the vehicle is displace laterally, as in Figure 7b, more flux passes through the closer coil and less through the coil further from the vehicle. The flux difference drives a current which repels the vehicle from the closer coil and attracts it to the further coil--a lateral restoring force.

Figure 8 shows the coils in simplified rectangular wire form. The figure lists the dominate force interactions which provide the vehicle propulsion, guidance and levitation.

A quench of a superconducting magnet is possible during Maglev operation. If this occurs while the Maglev train is traveling at high speed, sufficient safety mechanisms must be provided to prevent train contact with the guideway. One design approach is simply to have excess levitation capability in reserve so that, when degraded by a quench, sufficient lift remains. An implementation of this concept is shown in Figure 9.

An electrical schematic of the null flux coils is shown in Figure 10. The functional operation of these coils is very similar to that of the guidance coils. The center of the SC magnet tends to pass with equal flux passing through the upper and lower loops. If the SC magnet dips below the equal-flux point, currents are generated which tend to raise the SC magnet. If the SC magnet is above the equal-flux point, currents are generated to pull down the SC magnet. Thus the loaded vehicle rides displaced slightly downward to induce levitation forces equal to the vehicle weight.

CONCLUSIONS

We have reviewed the physics of attractive and repulsive magnetic suspension systems, discussed methods to engineer such systems, shown figures and tables of materials properties which indicate operating envelopes and regions, briefly identified some of the systems issues, discussed scaling laws, and discussed thermal issues. In addition, we presented two examples of magnetic suspensions, magnetic bearings for turbines and magnetically levitated trains.

There does not appear to be any inherent physics advantage of either suspension system. The difference between systems is in the details of the requirements for the particular application. In some applications, attractive systems have unique advantages while in other systems repulsive systems have especially desirable qualities.

Magnetic suspension design requires a systems approach. After a comprehensive system-level analysis the decision of an attractive or repulsive suspension system properly can be made.

REFERENCES

1. Jackson, J.D., Classical Electrodynamics, John Wiley, New York, 1975, p. 188.

2. Landau, L.D., and Lifshitz, E.M., Electrodynamics of Continuous Media, Pergamon Press, New York, 1975, p. 119 ff.

3. Cope, D.B., Snyder, M.D., Weisman, R.M., "The Magnetic and Structural Design of a Liquid Hydrogen-Cooled Magnet Utilizing High Purity Aluminum Conductors and a Boron/epoxy Composite as Structural Reinforcement," Advances in Cryogenic Engineering, Vol. 35, Ronald Fast, ed., Plenum Press, New York, 1990.

4. Eckels, P.W., et al, "Crogenic Generator Cooling," Advances in Cryogenic Engineering, Vol. 35, Ronald Fast, ed., Plenum Press, New York, 1990.

5. Ulbrich, H. "Elements of active Vibration Control for Rotating Machinery," NASA Technical Memorandum 102368, May, 1990.

6. Itoh, M., Ishigaki, H., and Hida, A., "Fabrication of Y-Ba-Cu-O Superconductor for Magnetic Bearing," IEEE Trans. on Mag. Vol. 25, No. 2 March, 1989, p. 2518.

7. Knoth, E., Barber, J., "Magnetic Repulsion Bearings for Turbine Engines," IEEE Trans. on Mag., Vol. 24, No. 6, November, 1988, p. 3141.

8. Tichy, J.A., Connor, K.A., "Geometric Effects on Eddy Current Bearing Performance," Transactions of the ASME, 88-Trib-15,

9. Nonami, K., "Vibration and Control of Flexible Rotor Supported by Magnetic Bearings," NASA Technical Memorandum 10088, June 1988.

10. Contract from USDOT to Intermagnetics General Corp., William R. Mischler, technical contact, (start date July 1991).

11. Meins, J., and Ruoss, W., "The Support and Guidance System," Transrapid Maglev System, Transrapid International, 1989, p. 79.

12. Ibid.

13. Cope, D., "Cryogenic Inductor Program," Final Report WL-TR-91-2037, Wright Laboratory, Air Force Systems Command, Wright-Patterson AFB, OH, June 1991, p. 2-20.

14. Clessow, G., et al, "The Long-Stator Propulsion System and its Power Supply," Transrapid Maglev System, Transrapid International, 1989, p. 50.

Table 1. Combinations of Magnetic Poles

Pole 1 --> Pole 2	Ferro-magnet	Electro-magnet	Permanent Magnet	Super-conductor
Ferromagnet	X	A - 1,3	A	A
Electromagnet	A - 1,3	A - 5, R - 5	A - 4, R	A, R - 2
Permanent Magnet	A	A - 4, R	R	R
Superconductor	A	A, R - 2	R	R

KEY:
X No interaction
A Attractive System
R Repulsive System

1. (Maglev) German Transrapid system, British Rail Birmingham Line, Japanese Air Lines High Speed Surface Transportation
2. (Maglev) Japan Rail Group (formerly Japan National Railway), MLx-nnn series
3. Turbine magnetic bearings
4. Turbine bearing (hybrid system: permanent magnets with ferroelectromagnets)
5. Metal forming due to pulsed magnetic fields and induced eddy currents.

The normal magnetic force ("levitation") can either be attractive or repulsive.

Table 2. Magnetic Suspension Issues

- Air gap dimension
- Levitation force
- Air gap pressure
- Levitation stability
- Operating temperature
- Mass of suspension system
- Power (active and reactive)
- Speed
- Suspension stiffness
- Effect of stray magnetic fields
- Aerodynamic forces of high speed trains and turbine bearings
- Inertial forces
- Thermal expansion due to guideway differential movement

Table 3. Magnetic Suspension Scaling Laws

System	Conditions	Constant Gap		Scaled Gap	
		Energy	Pressure	Energy	Pressure
1. Permanent Magnet Systems		$\sim L^4$	$\sim L^2$	$\sim L^3$	$\sim L^{o}=1$
2. Current -based Systems					
2.1 Heat Transfer-limited	h=constant	$\sim L^5$	$\sim L^3$	$\sim L^4$	$\sim L^1$
	h scaled ~ $L^{0.6}$	$\sim L^{5.6}$	$\sim L^{3.6}$	$\sim L^{4.6}$	$\sim L^{1.6}$
	latent heat = constant	$\sim L^6$	$\sim L^4$	$\sim L^5$	$\sim L^2$
2.2 Current Density-limited	J = constant	$\sim L^6$	$\sim L^4$	$\sim L^5$	$\sim L^2$
2.3 Stress-limited	σ = constant	$\sim L^4$	$\sim L^2$	$\sim L^3$	$\sim L^{o}=1$

Note: h is the surface heat transfer coefficient of units (W/m^2-K) and is scaled according to the ref.[13], J is the conductor current density of units (A/m^2), and σ is the mechanical stress of units (Pa).

Table 4. Properties of Coolants

Coolant	T_{boil} (K)	H_{fg} (J/kg)	C_p (J/kgK)	dT (K)	C_pdT (J/kg)	Refrig. Eff. (W/W)
LHe	4.2	21,000	4500	1	4500	1750
LH_2	20	443,000	10,000	5	50,000	400
LN_2	77	200,000	2000	10	20,000	95
H_2O	373	2,500,000	4200	75	315,000	-

It is noteworthy that many the magnetic properties of ferromagnetic materials improve as the temperature is decreased. This may be a fruitful area for future research.

Table 5. Example Magnetic Bearing Requirements for Aircraft Turbine Engines

Parameter	Value
DN Rating	> 3 million
Equivalent Speed	> 170 m/s = 400 mph
Diameter	5"
Rotor Speed	26,000 rpm
Axial Thrust	~4000 lbs.
Radial Load	~1000 lbs.
Bearing Compartment Temp.	1000 K
Stiffness	100,000 lb./in = 17 MN/m
Air Gap	0.010"

Table 6. Characteristic of Maglev Trains

Parameter	Attractive Lev.	Repulsive Lev.
Designer	Transrapid 06[14]	Foster-Miller, Inc.
Levitation Height	10 mm	100 mm
Number of Passengers	200	152
Number of Vehicles	2	2
Maximum Speed	400 kmph	500 kmph
Minimum Lev.	Standstill	25 m/s
Train Mass	122 T	66 T
Support Magnets	Distributed	Concentrated
On-board Power Consumption	240 kW	120 kW
Reactive Power	15 MW	Negligible
Aerodynamic Drag	50 kN	27 kN
Motor Type	LSM	LSM
Magnet Lift/Weight	10	7-9

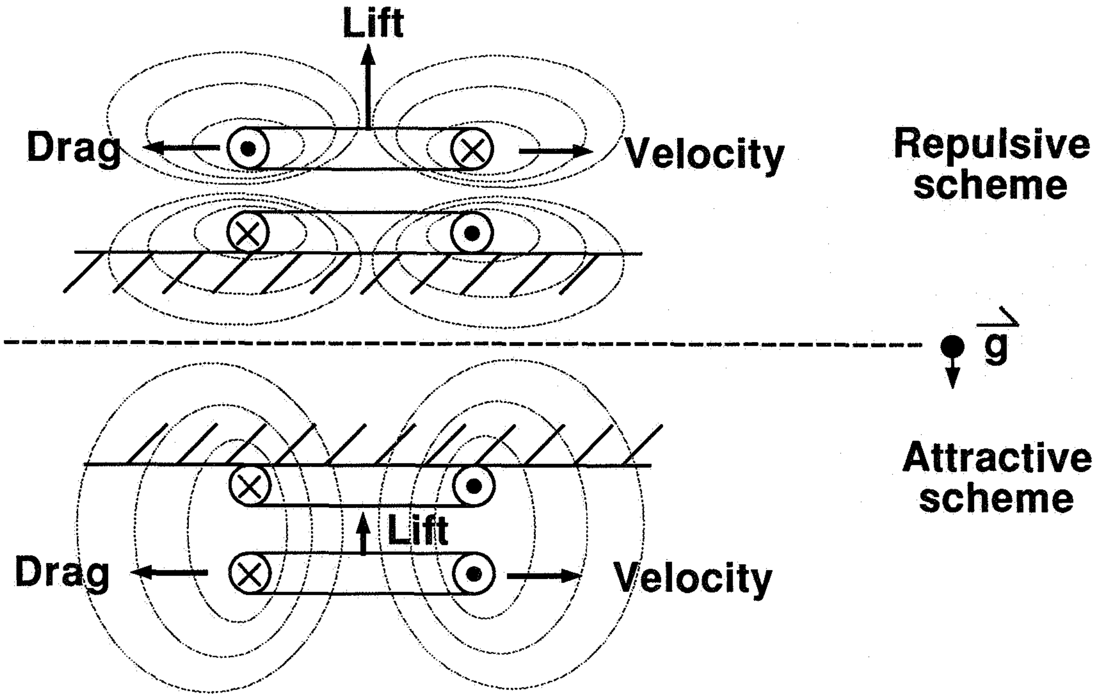

Figure 1. Attractive and Repulsive Coils

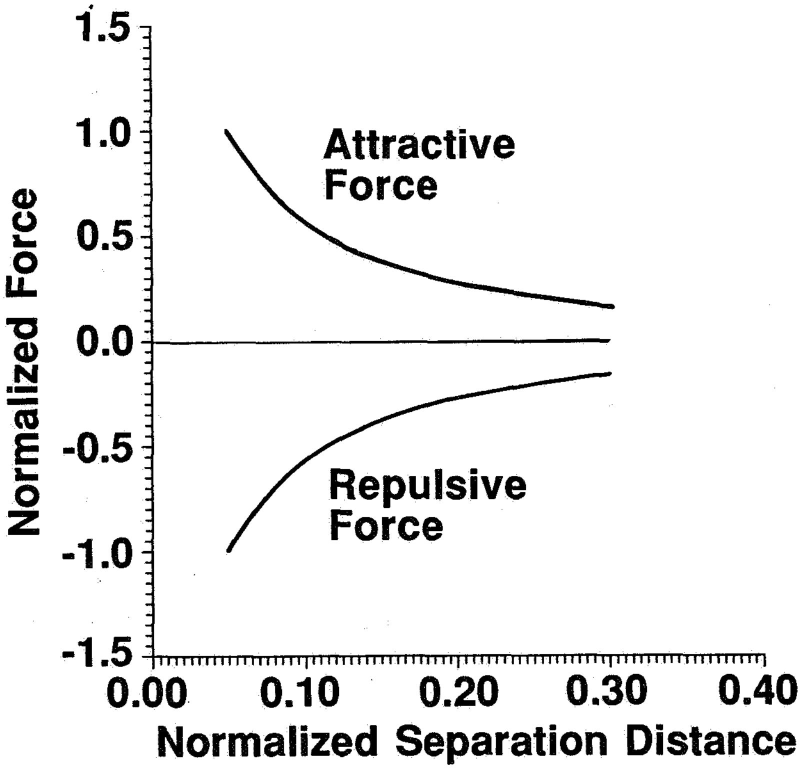

Figure 2. Axial Force vs. Coil Separation

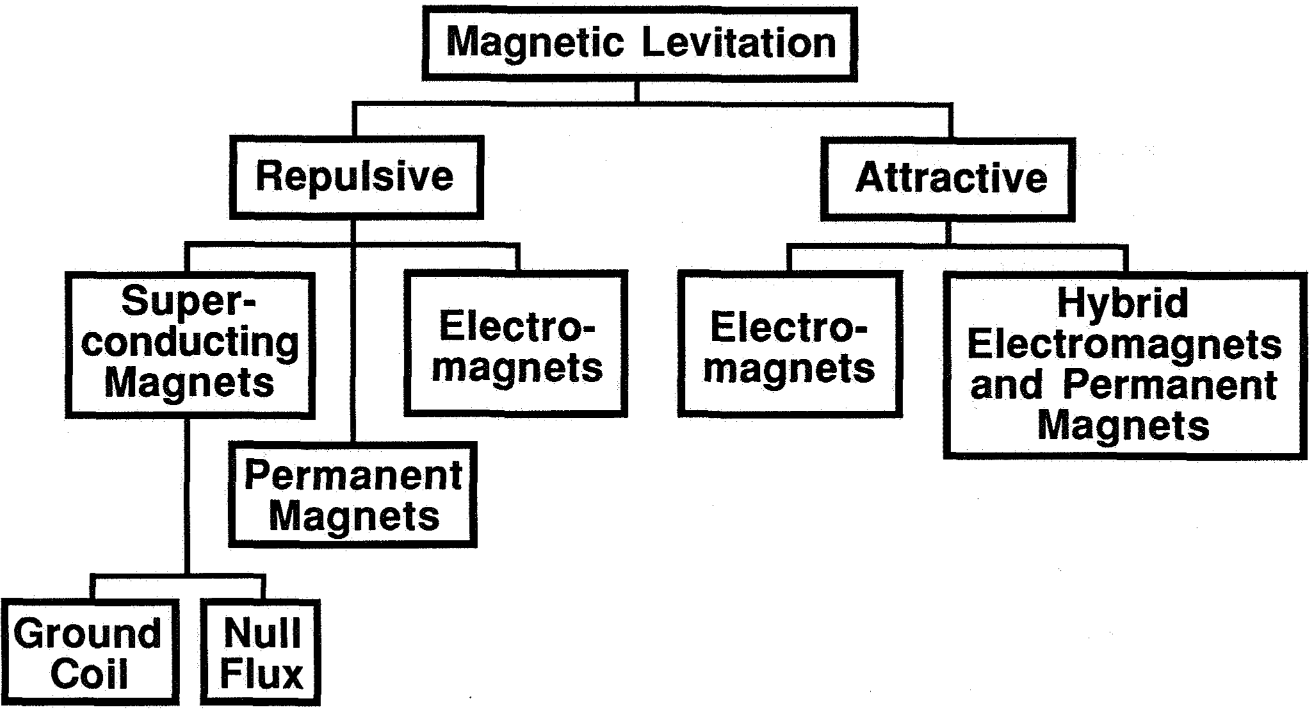

Figure 3. Magnetic Levitation Systems Corporate Structure

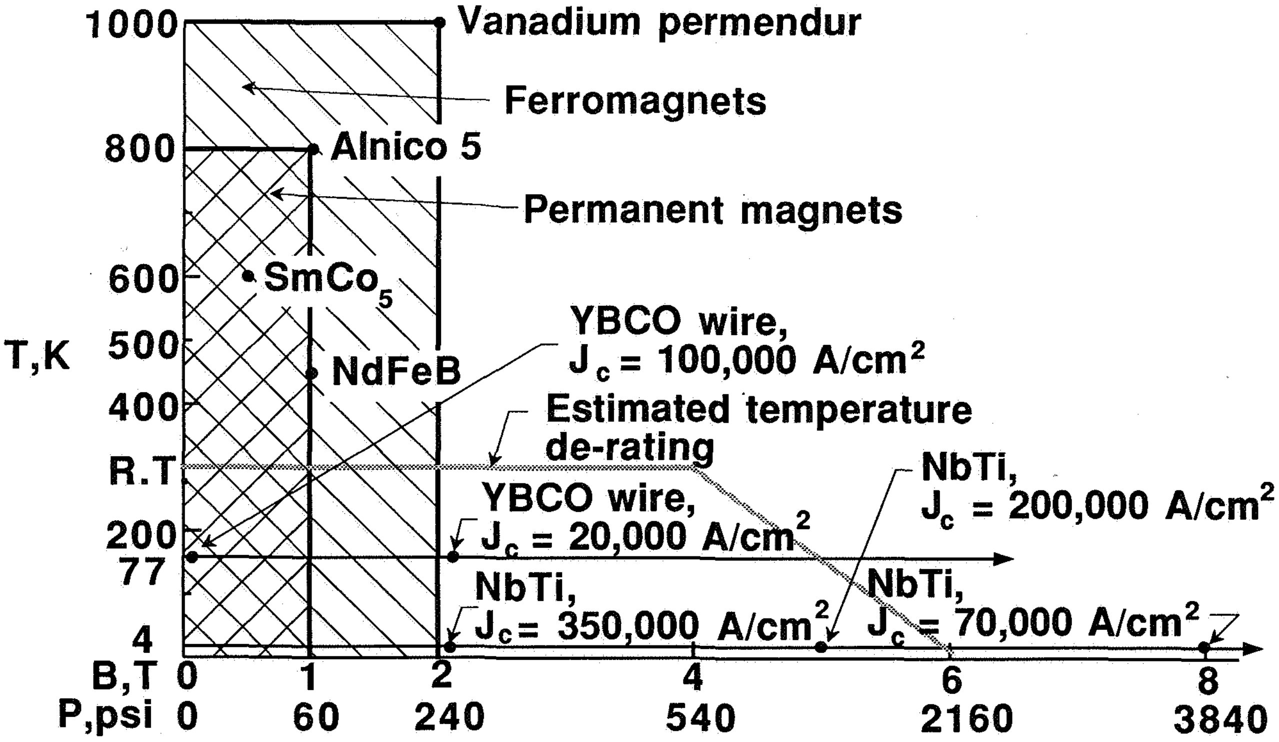

Figure 4. Temperature vs. Magnetic Field

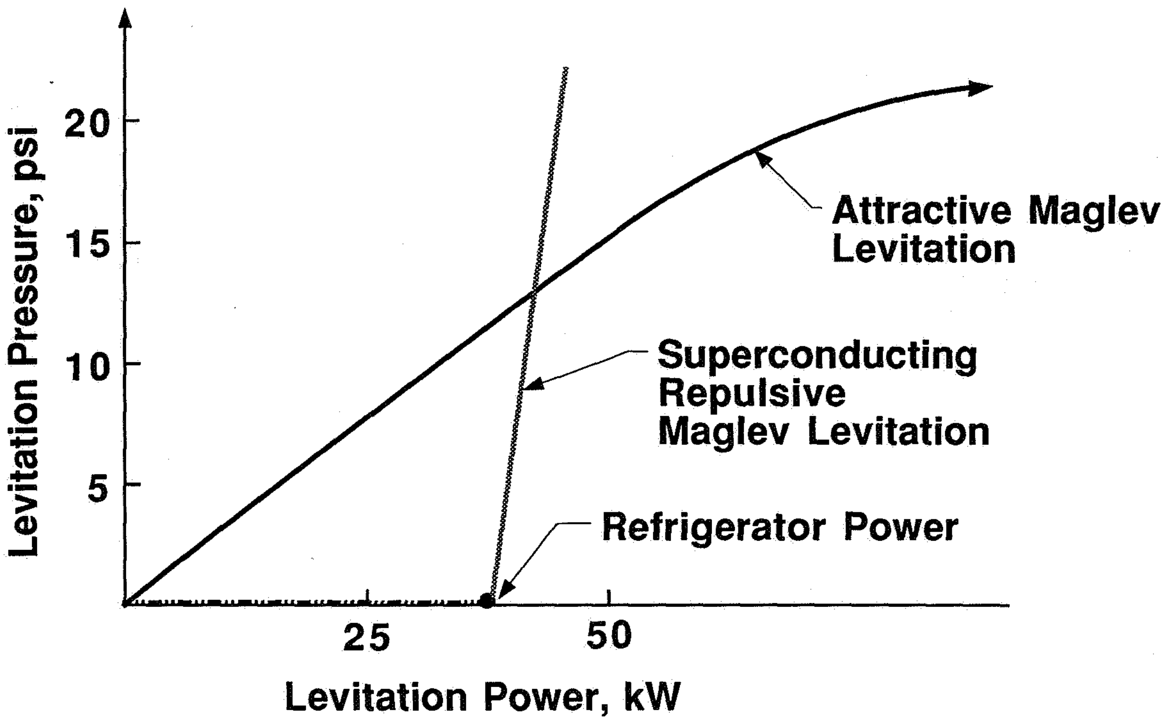

Figure 5. Levitation Pressure vs. Required Power

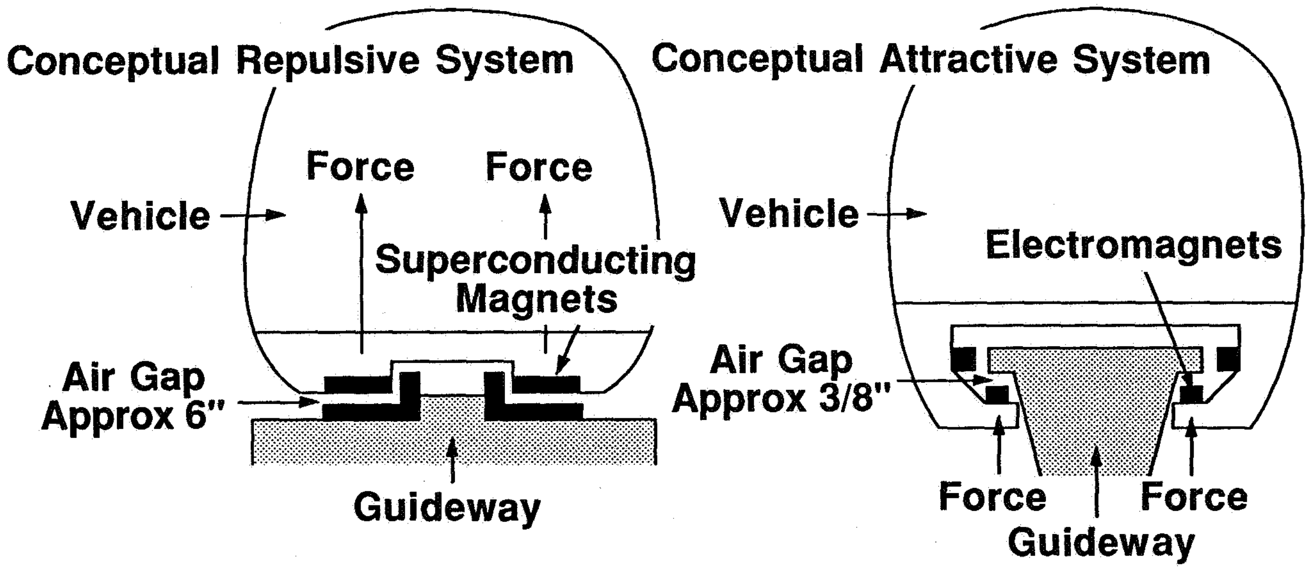

Figure 6. Conceptual Attractive and Repulsive Maglev System

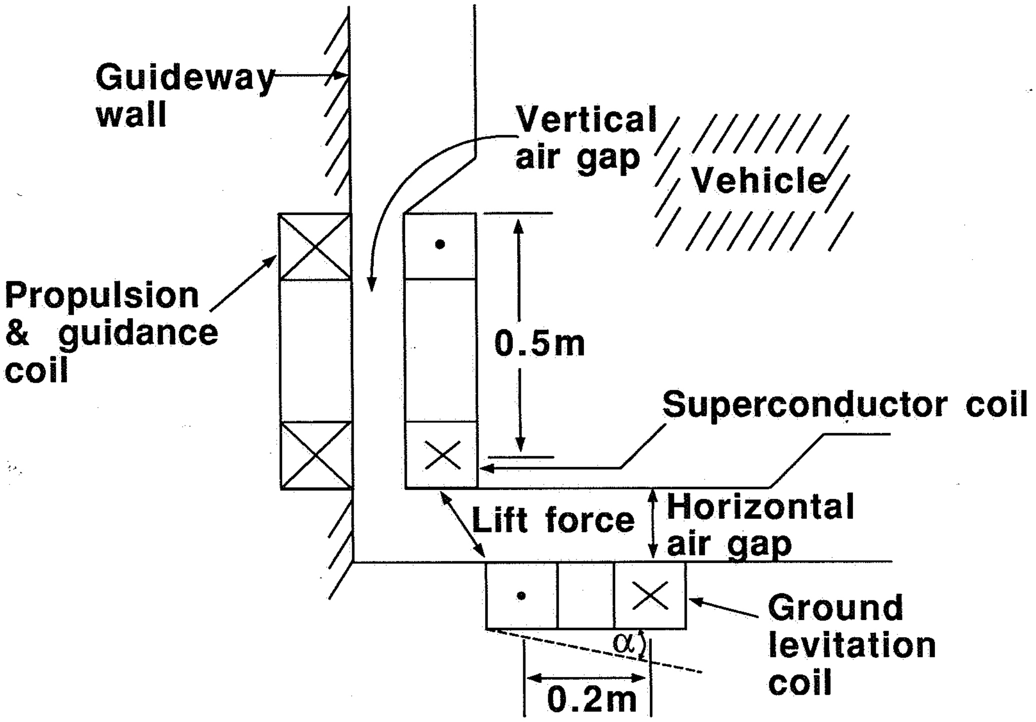

Figure 7. Ground Coil Levitation Design

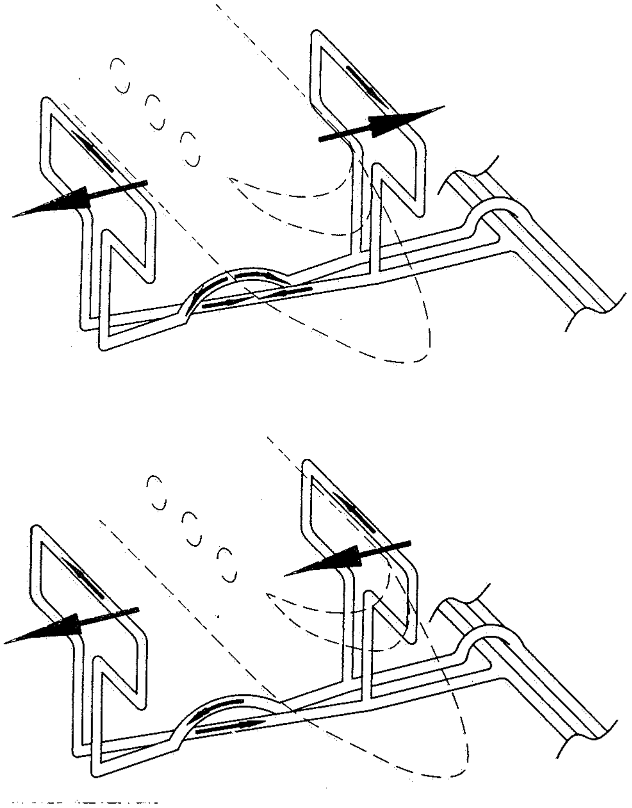

Figure 8. Guidance Coil Schematic

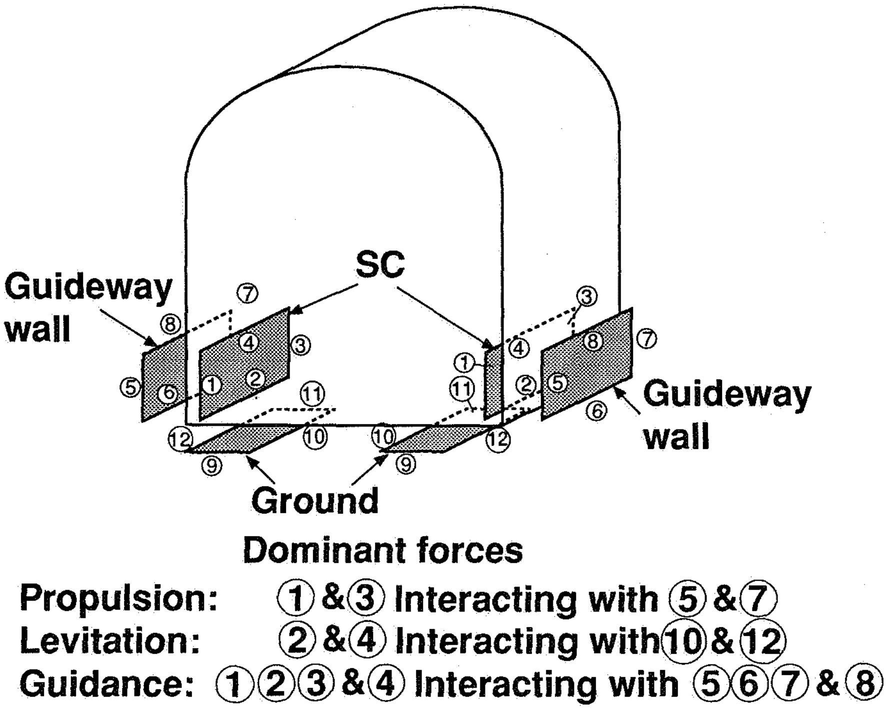

Figure 9. Ground Coil Dominant Forces

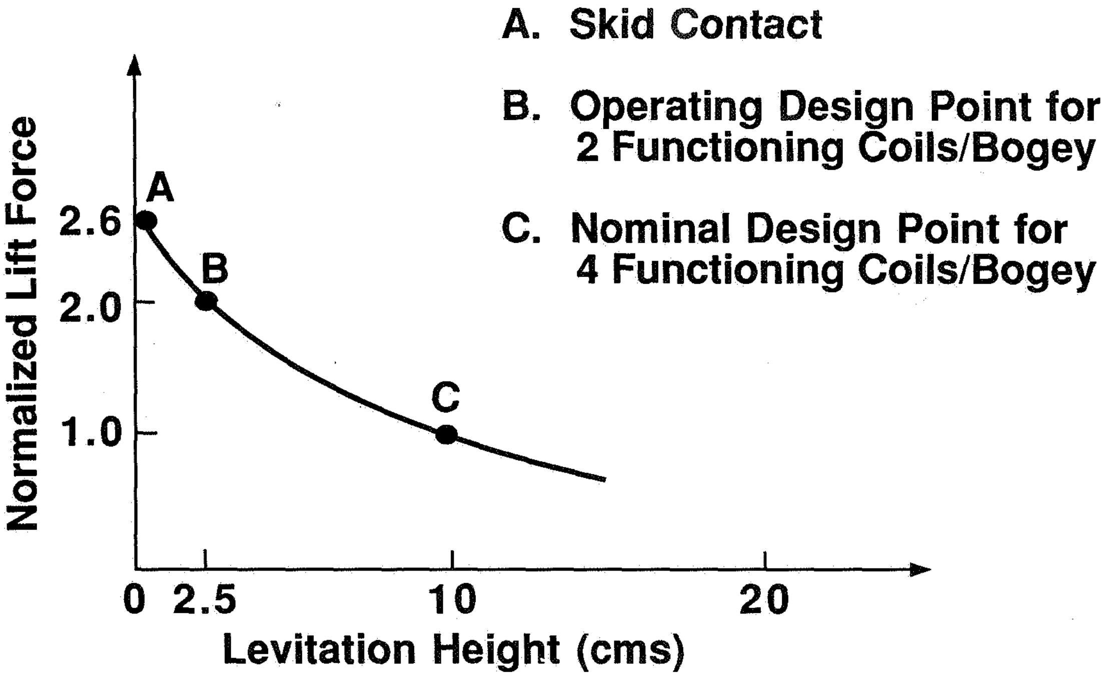

Figure 10. Magnetic Levitation as a Function of Height

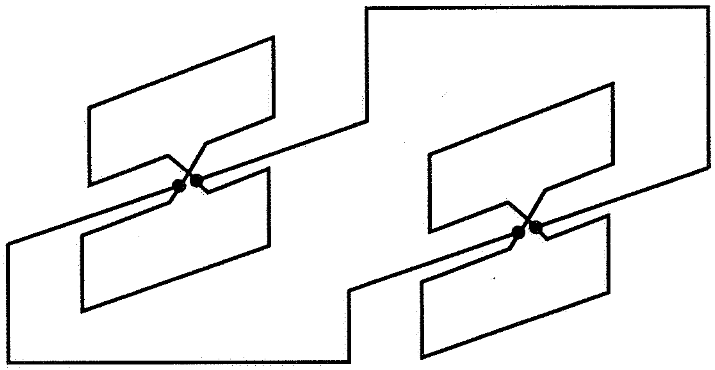

Figure 11. Null Flux Coil Electrical Schematic