24.10.8

LEVITATION AND PROPULSION OF GUIDED VEHICLES USING SUPERCONDUCTING MAGNETS

E. Abel, A.E. Corbett, B.E. Mulhall, R.G. Rhodes

Paper presented at the Conference on

LINEAR ELECTRIC MACHINES

London, 21 - 23 October 1974,

and published in I.E.E. Conference Publication No.120, pp 223-229.

* * * * * * *

Summary

Levitation and guidance of high speed vehicles by means of magnetic forces between superconducting magnets on the vehicle and eddy currents set up in an aluminium track is described.

Linear motor propulsion is discussed and induction machines are shown to be incompatible with the levitation. In contrast synchronous or commutator machines, using the existing magnets as field excitation, and with a powered track winding show great promise. In particular the commutator machine, which has good starting characteristics, will be studied further.

The test track and research vehicle being built at the University of Warwick is described briefly.

LEVITATION AND PROPULSION OF GUIDED VEHICLES USING SUPERCONDUCTING MAGNETS.

E. Abel, A.E. Corbett, B.E. Mulhall, R.G. Rhodes.

Introduction

Of the several differing strategies being developed to meet future high speed land transport requirements, the air cushion and magnetic force suspensions are the main non-contact systems. For both of these linear electric propulsion is strongly preferred to any form of jet or air propulsion, for environmental reasons.

The type of levitation involving the repulsion force generated between superconducting magnets mounted on the moving vehicle and an electrically conducting (aluminium) guideway is being examined at the University of Warwick with funding from the Wolfson Foundation. The propulsion unit should be compatible with a large levitation height, without the need for a secondary suspension. The possibility of using a machine with a superconducting field winding on the vehicle and a linear track armature winding is apparent.

In this paper the general types of machines that may be used for the propulsion of a magnetically levitated (or Maglev) vehicle are considered, and the vehicle levitation and guidance characteristics discussed.

Levitation Characteristics

In the proposed Maglev systems the interaction between the guideway eddy currents and the vehicle magnets results in both lift and drag. These forces vary with vehicle speed, as sketched in Fig. 1, with the eddy current skin depth of the metal track determining the scale of the speed axis(1). Extensive theoretical investigations have resulted in solutions agreeing closely with experiment for many practical geometries, such as a rectangular coil moving over a wide track.

No simple expression for the skin depth has been obtained, but for an aluminium guideway (resistivity about 3×10^{-8} Ω.m) typical values are 10 - 20 mm. at speeds of 160 m/s. Hence for the situations envisaged, the very much simpler theory, valid at low speeds will usually be adequate. It is then found that there is a characteristic velocity, v_o, given by

$$v_o = \frac{2}{\mu_o \sigma d} \text{ m/s.}$$

where $\mu_o = 4\pi.10^{-7}$ H/m; σ conductivity of track mho/m; d thickness of track, m.

The lift and drag forces are related by(2)

$$\frac{F_L}{F_D} = \frac{v}{v_o} \qquad (1)$$

The above authors are all members of the Department of Engineering, University of Warwick.

and the lift is given by

$$\frac{F_L}{F_\infty} = \frac{\left(\frac{v}{v_o}\right)^2}{1 + \left(\frac{v}{v_o}\right)^2} \qquad (2)$$

F_∞, the maximum possible lift force, is approached at high vehicle speeds, and would be reached for a track with infinite conductivity i.e. a superconducting track. The value of F_∞ is determined by suspension height, and magnet strength and geometry; it is infact just the force between the vehicle magnets and their identical images reflected in the track.

Guidance Forces

Generally lateral guidance is provided by shaping the guideway, typically forming it as a channel section (Fig. 2(a)). It is important that the side flanges be electrically continuous with the track, for otherwise the vehicle will experience a destabilising lateral force(3). This behaviour can be simply explained as equivalent to shaded pole action, where the eddy currents induced in the aluminium are out of phase laterally, and so provide a lateral linear motor effect.

The vertical guide members can lead to route switching problems in a transport system, as well as being mechanically restricting. The extra image magnets created by the lateral guidance forces also produce extra drag - in fact Davis has shown(2) that equation 1 remains valid if F_L is replaced by the sum of the lift and guidance forces.

By using the shaded pole action of the edge of an aluminium sheet, flat track guidance arrangements are possible which provide a magnetic potential trough for the vehicle. One such scheme is shown in Fig. 2(e). The requirement of a stabilising force to reduce lateral displacements is fulfilled simply if the guideway is subjected to a nett flux linkage increase as the displacement from equilibrium increases. The guidance forces can be measured on scaled models, by means of inductance measurements, as has been discussed by Iwasa(4). Iwasa also points out that the full-scale drag power can also be estimated from loss measurement on the model, though in practice it may be difficult to make the loss ('Q' factor) measurements with sufficient accuracy. The tentative results shown in Fig. 3 were obtained by this method, using a rectangular copper coil placed over two parallel strips of aluminium.

Track and Magnet Configuration

The split track of Fig. 2(e) appears to have a number of advantages, among which the more obvious are that it overcomes the mechanical problems of the channel guideway. It also requires appreciably less track conductor, perhaps as little as one half, though this is achieved at the expense of additional superconductor. For the Wolfson test vehicle for example, about twice as much superconductor will be needed, but since it will still cost less than 10% of the track conductor the trade-off is considered to be worthwhile. A more detailed optimisation will be carried out when the technical characteristics of the guideway are better understood.

A further advantage is that, since the magnets do not cover the full width of conducting track, the possibility now exists of combining the lift and propulsion without excessive interaction between track (armature) winding and the aluminium levitation strips.

A transverse flux arrangement similar to that suggested by Laithwaite and Eastham for linear induction machines(5) is also being considered, and appears to have advantages. In the literature on levitation, magnets which are long in the direction of motion are preferred, as having lower magnetic drag; then the lower reluctance of flux paths transverse rather than along the vehicle would allow some saving on superconductor cost; more significantly the stray field level in the passenger compartment is reduced, and screening becomes easier. Thus the arrangement of Fig. 2(f) is being evaluated.

Propulsion Machine Types

Essentially two main types of motor can be used for high speed transportation. The linear induction machine (LIM) is well known, and can provide useful thrust at a slip velocity. The linear synchronous motor (LSM) has received less attention, and its main drawback is that it cannot provide thrust for starting unless a variable frequency supply is available. A third type of machine, the linear commutator motor (LCM) is perhaps an extension of a LSM with trackside frequency control. Vehicle position would actuate a switch to energise the appropriate part of the track winding and produce frequency independent operation. Each machine type will be considered in turn.

Linear Induction Motor

The LIM has so far appeared in two basic forms for high speed traction. The double-sided and single-sided motors basically offer performance similar to their rotating counterparts, but for high speed application the discontinuity at entry and exit edges, and finite size and isotopy of the reaction rail, give rise to extra losses and degradation of performance.

An attempt to minimise end effect losses by adding compensating windings to the main stator block, has met some success(6,7) bringing thrust-slip, efficiency and power factor nearer to values suggested by an idealized LIM theory.

In all LIM's, the main stator winding provides the flux which induces eddy currents in the reaction plate. The machine is typically suitable for small gap clearances if reasonable power factor and efficiency are to be obtained. As a propulsion for Maglev vehicles, independent servo-control of the gap length might be necessary(2), and so the main advantages of the large gap and tolerance to surface irregularities would be lost.

If the stator unit of a LIM was mounted in the vehicle, this would present two further problems. The prospect of transferring several megawatts of power through a current pickup device is daunting although recent developments appear promising. The weight of the stator itself would reduce the effective payload of the vehicle, especially if on-board power conditioning equipment was included.

The transverse flux motor(5), to some extent, lessens the inherent problem of high speed operation of a LIM, as the core of the stator now need only carry tooth flux rather than the whole pole flux of a conventional machine, and hence the amount of iron can be reduced. Also, core depths are independent of pole pitch with this arrangement. The backing iron behind the reaction plate of a single-sided LIM can similarly be reduced.

Linear Synchronous Motor

The LSM has no inherent starting thrust, and so a means of providing propulsive power at essentially zero speed must be found. The normal methods of using induction starting present grave difficulties as the a.c. losses in the superconducting winding on the vehicle would be excessive unless an eddy current screen could be incorporated on the vehicle.

Low frequency starting(8) seems the most viable alternative, and trackside power conditioning units would be required at the stations to cover their 'accelerating' sections of track. Once at a synchronous speed, the LSM would be operating with track windings at a normal power frequency(9).

Another method of controlling the synchronous machine is to power the track in response to a vehicle position signal. The synchronous machine is then essentially a commutator or d.c. machine, and has the same speed-torque characteristics with a useful starting torque.

Linear Commutator Motor

As mentioned in connection with the LSM, if track loops are current or voltage forced in response to vehicle position, a linear commutator machine (LCM) results. Transverse flux arrangements are still valid, and can improve overall track efficiency. A solid state device, such as a thyristor, is the obvious choice for the switching operation, and although this will inevitably increase the track cost, it is worth noting that over the last few years thyristor costs have fallen by a factor of six, and power handling capacity has increased by a factor of 40. For a 30-tonne revenue vehicle a phase winding made from five turn windings will have a terminal voltage of about 2kV., and phase current of 1000 amps. For the Wolfson motor a track thyristor would need to withstand 1kV and pass about 400 amps.

Large "hockey-puck" thyristors with a high thermal inertia and a rating of 2000 amps r.m.s. or more are now available; the duty cycle imposed by vehicle headway (on a revenue system) would further ease their rating. As a rough guide, the cost of thyristors will probably be of the same order as that of the track conductors.

The system proposed for the Wolfson Maglev Project embodies a LCM, and the general arrangement might be as in Fig. 4. If the machine begins to fall out of step with a preprogrammed acceleration routine, position, velocity and acceleration feedback will enable the thyristor firing rate to be varied accordingly. Although the thyristor load would have an inductive component, forced commutation of the device may not be necessary if the current in the track is controlled, rather than the voltage. A motor speed control system which embodies this technique is known as the "controlled current and slip" inverter.

The performance of a LCM is more difficult to assess than a LSM, if a thyristor commutator is used. A simplified analysis is based on computer calculations for the mutual inductance of track and vehicle loop arrays, as vehicle motion proceeds. The relevant forces and couples on the vehicle can be evaluated, and this gives insight into vehicle dynamic behaviour for various track configurations and excitations. From preliminary calculations of this type it appears that two main problems will arise. One concerns the armature reaction on the field winding, since time varying fields or currents in the superconductor give rise to losses which may prove unacceptable. Fortunately design studies on rotating superconducting machines have shown how eddy current screens can be incorporated in the machine to alleviate such difficulties. The second concerns the vertical and lateral forces which the machine produces, and which can be of the same order as the forces produced by the eddy current levitating interactions. If the forces can be lift and guidance, there exists the prospect of significant enhancement of the overall performance of the system. However, the range of geometries for which this desirable state of affairs occurs is quite limited. Present efforts are directed to studying these and to ascertaining how stable the resulting dynamic behaviour of the vehicle would be.

The Wolfson Magnetic Levitation Project

The object of the Wolfson project is to demonstrate the feasibility of magnetic levitation by superconducting magnets, and to highlight some of the engineering problems that may be encountered in a revenue vehicle. To meet these objectives a test track and vehicle will be built and operated on the Warwick University Campus. A site permitting a straight run of 650m has been chosen, on which speeds up to 250km/hr. may be possible. The track itself will be a flat concrete roadbed, about 1m wide, onto which the aluminium guideway and armature will be fixed.

A vehicle, 4m long by 1m wide, weighing 600kg and having seating for two passengers intandem has been designed. Design of the cryostat and the superconducting coils is also in hand. Preliminary tests will be with the vehicle coupled to a towed trolley, but later a linear motor of the type discussed will be fitted as the propulsion unit.

To provide a foundation for the detail design of the suspension and propulsion theoretical and experimental studies, based on the ideas discussed on this paper, are being carried out. Models include rotating drums, the cylindrical surface of which is shaped to simulate a guideway, and a linear machine which consists of 12 coils (the armature winding) around the periphery of a 600mm diameter drum. Switching of the linear machine is by a mechanical commutator, though thyristors will be used at a later stage. Magnetic excitation is by permanent magnets but since the fields are too low to give really representative behaviour it is planned to use a superconducting magnet at a later stage.

Conclusion

From the qualitative discussion above it appears that the combination of levitation and guidance using superconducting magnets above a flat aluminium track, and propulsion by means of a linear commutator motor using the same superconducting magnets for field excitation is possible. Such a scheme is being considered for land transport at speeds above 300km/hr., and to this end a technical and economic evaluation is in progress.

References

1. Richards, P.L., and Tinkham, M.: "Magnetic Suspension and Propulsion Systems for High Speed Transportation", J. Appl. Phys., 1972, 43, (6), pp 2680-91.

2. Reitz, J.R., Borcherts, R.H., Davis, L.C., Hunt, T.K., and Wilkie, D.F.: "Preliminary Design Studies of Magnetic Suspensions for High Speed Ground Transportation", March 1973, Ford Report for U.S. Dept. of Transportation, FRA-RT-73-27; PB223237 of U.S. N.T.I.S.

3. Coffey, H.T., Cotton, J.D., and Mahrer, K.D.: "Study of a Magnetically Levitated Vehicle", February 1973, Stanford Research Institute. Report for U.S. Dept. of Transportation, FRA-RT-73-24; PB221696 of U.S. N.T.I.S.

4. Iwasa, Y.: "Electromagnetic flight stability by model impedance simulation", J. Appl. Phys., 1973, 44, (2), pp 858-62.

5. Eastham, J.F., and Laithwaite, E.R.: "Linear Motor Topology", Proc. I.E.E., 1973, 120, (3), pp 337-43.

6. Naser, S.A.: "Certain approaches to the analysis of single-sided linear induction motors", ibid., 1973, 120, (4), pp 477-83.

7. Yamamura, S.: "Theory of Linear Induction Motors", 1972, Wiley, New York.

8. Canay, M.: "Methods of starting synchronous machines", Brown Boveri Review, 1967, 54, (9), pp 618-29.

9. Thornton, R.D.: "Design Principles for Magnetic Levitation", Proc. I.E.E.E., 1973, 61, (5), pp 586-98.

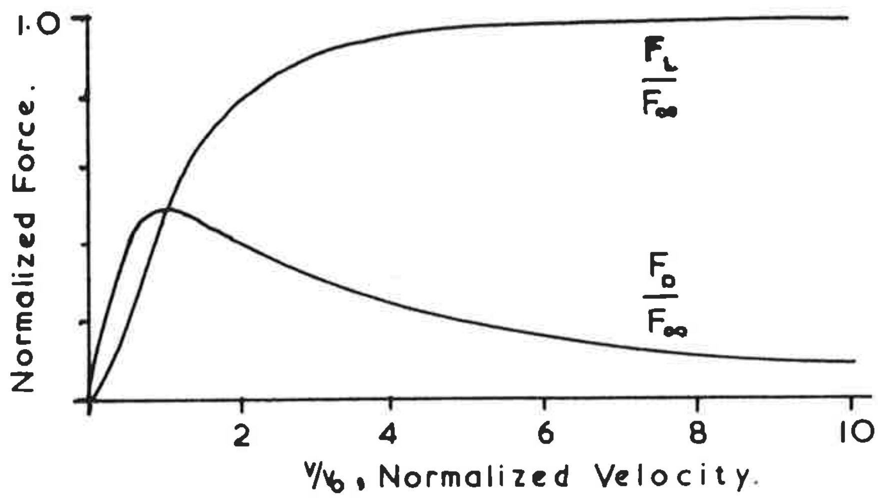
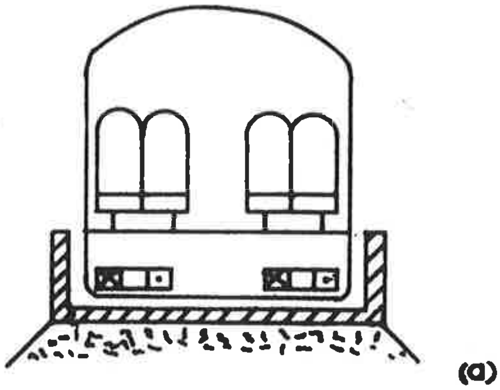


Fig. 1. Lift and Drag Forces.



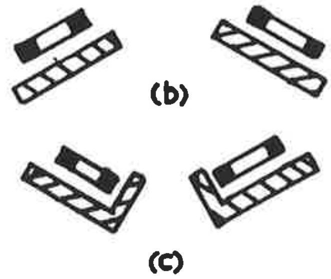
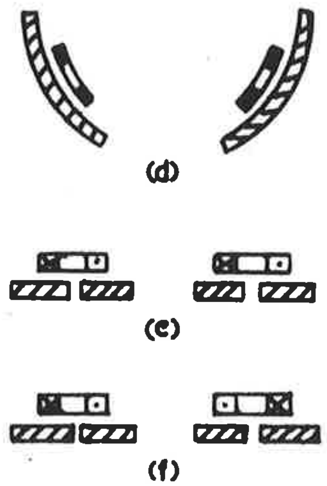


Fig. 2. Guideways.



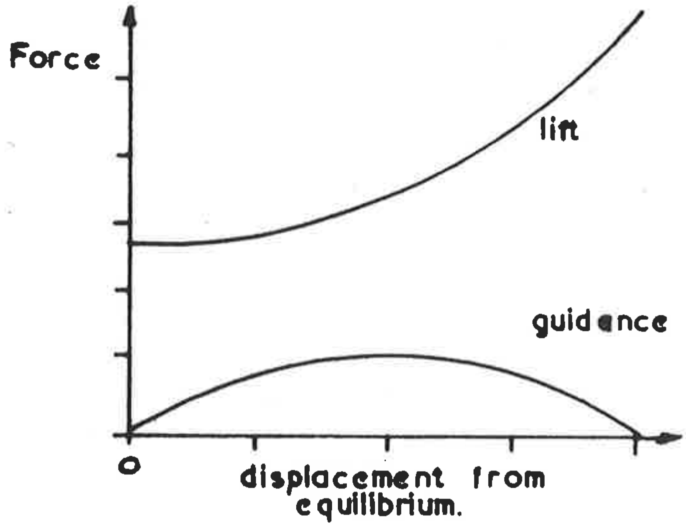


Fig. 3. Typical Force Characteristic.

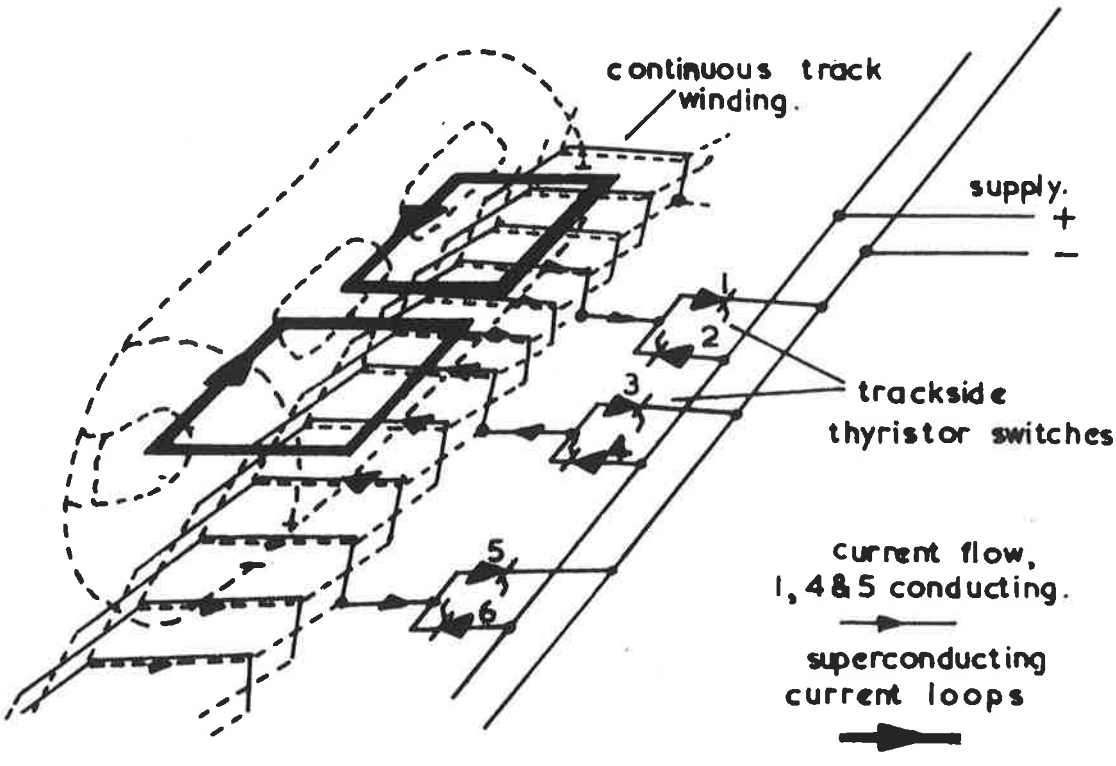


Fig. 4 Linear Commutator Motor.