The Wolfson magnetic levitation project is concerned with the construction of a 500 m long test track and vehicle, levitated electrodynamically by means of superconducting magnets. The general design features and present status of the project are described. The particular aspects which are discussed include the guideway design, the cryogenic system and superconducting coils, and both the linear synchronous and commutator motor propulsion systems having powered track windings.

The Wolfson magnetic levitation project

R. G. Rhodes and B. E. Mulhall

The Wolfson magnetic levitation project at the University of Warwick is directed towards building a short length of test track with an experimental vehicle to be levitated and guided electrodynamically using superconducting magnets and propelled with a linear synchronous motor. It will both demonstrate the feasibility of this method of suspension and propulsion for high speed ground vehicles and focus research effort into the problems of this, and in many cases also of other high speed transport developments. As the literature on electrodynamic suspensions is already extensive, this article will be concerned only with the status and current emphasis of the work at Warwick.

The levitation and guidance being examined is a modification of the well-known conducting sheet method, and incorporates many similarities to alternative designs being studied in America,[1] Canada,[2] and elsewhere. Basically, as shown in Fig.1, the vertical lift and lateral guidance forces are generated by the movement of the vehicle superconducting coils which bridge the gap between the two parallel aluminium strips along the guideway. As described later, a powered track winding located between the levitating strips and interacting with the vehicle magnets will provide the propulsive force for the vehicle.

Consideration of the track falls naturally into two aspects, namely the civil engineering on the one hand, and the electrically conducting aluminium sheet on the other. The case for separating these is particularly strong on an experimental track, where future changes in the guideway design cannot be excluded.

Other factors influencing the structural design include the limited life planned for the Wolfson project, the necessity from the point of view of magnetic interactions to avoid the use of ferromagnetic materials in any quantity, and the inevitable need to minimize cost. Thus the most natural solution, steel reinforced concrete, had to be rejected, and glass fibre reinforcement proved too costly at the present stage of development. The structure (designed by J.E.C. Farebrother and Partners) consists of concrete piers (1100 x 450 m) at 5 m intervals, spanned by timber joists (two per span, each 300 x 100 mm), and finished with a 1.3 m wide timber deck to which the electrical elements will be nailed. The track has a length of 550 m, is elevated on average by 1 m, and slopes uniformly at 1 in 1000. It has been designed such that dynamic deflections do not exceed 5 mm, even with a 500 kg vehicle, while warping and such distortion is expected to be small compared with the designed track-vehicle clearance of 50 mm.

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Design of the electrical and magnetic components is ultimately constrained by the need to provide levitation, guidance, and propulsion all without degradation due to mutual interference. In addition, a guideway configuration which would lead to minimum cost and operational problems (for example, route switching) in a full scale system would be desirable, though these factors are difficult to quantify. It is clear that much more research is needed before a truly satisfactory compromise is evolved, especially in the case where a linear electric drive, involving a powered track winding, is to be used.

The problems of combining the levitation and propulsion magnets arise purely from the fact that, for good machine performance, a much greater magnetic flux linkage is needed than that required to produce the suspension and guidance forces, and partly from the need to avoid excessive losses through coupling between the excited track winding of the machine and the levitation strips. Since, as a general rule, interference problems tend to increase with levitation height, they become exaggerated on a smaller scale model such as the Wolfson project. The design solution being adopted,

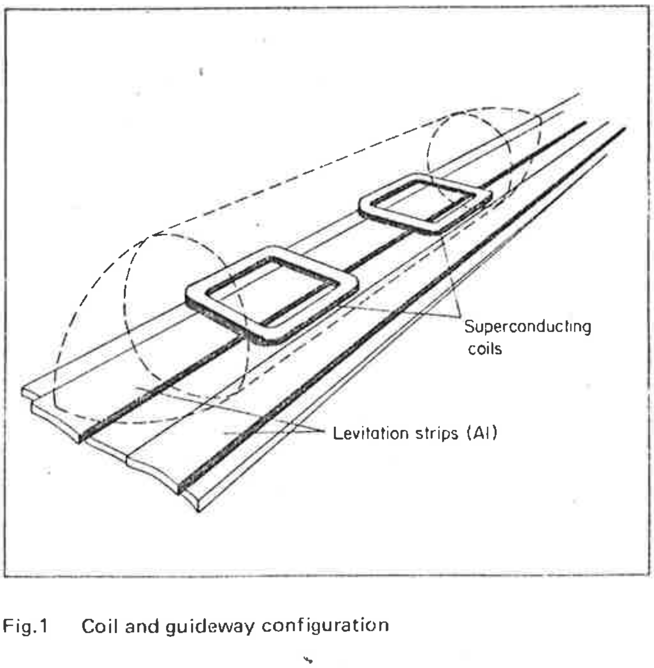

Fig.1 Coil and guideway configuration

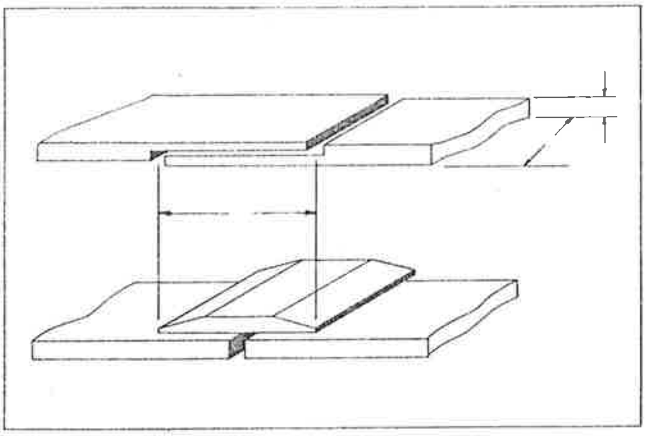

Fig.2 Possible expansion joints

Fig.1, uses a single magnet system (2 vehicle coils) with most of the flux available for propulsion and only the fringeing field used for levitation and guidance. In fact, the lift represents only about 3% of that which is theoretically possible over an infinite sheet.

The induced eddy currents flowing along the inner edge of the levitation strips give rise to guidance forces; in fact the guidance force can be designed to be far stronger than is reguided in practice but, as it is inevitably accompanied by an increase in magnetic drag, it must be carefully optimized. Part of our present programme is, as reported elsewhere,[3] devoted to studying the guideway force characteristics and the resulting pseudo-static, that is, moving with uniform velocity, and dynamic behaviour of the vehicle. The modelling technique used [4,5] also allows the drag and the speed dependence of the forces to be estimated.

This same technique is also being used to explore such design features as the construction of satisfactory expansion joints in the levitation conductors (two solutions which can cause little perturbation of the vehicle motion are sketched in Fig. 2), and track modifications to reduce magnetic drag. Magnetic drag is of particular importance, since with the simple conducting sheet suspensions being studied it can contribute significantly to the running costs of the vehicle, even though the aerodynamic drag dominates at operational speeds. In general, drag can be reduced either by reducing the track resistance, or by weakening the track eddy currents (and increasing the strength of the superconducting magnets to maintain the lift). The latter is achieved by making the track conductor parallel to the local field produced by the magnets, that is, decreasing the normal component of the field (the component of the field due to eddy currents is ignored). In the extreme, as in the 'null-flux' systems, the normal flux component is made zero by placing the guideway conductor at the plane of symmetry between two opposed vehicle magnets. In general, however, there exists for any levitation system only a very small number of 'null-flux' surfaces which are uniform in the longitudinal direction. Preliminary results suggest that, by this approach or by thickening of the track along lines of greatest eddy current density, a doubling of the lift/drag ratio may be possible.

Vehicle

The present vehicle will be approximately 2.5 m long by 0.5 m wide and weigh 150 kg. At 1 g acceleration and braking, velocities of up to 80 m s^{-1} could be achieved on the test track.

In view of the high acceleration needed, inertia outweighs both magnetic and aerodynamic drag. However, other aerodynamic forces, such as those generated in pitch and yaw, cannot be neglected, and thus preliminary wind tunnel studies are being made. The main conclusions [6] are that most forces on the vehicle, with the exception of the drag, the side force due to cross winds, and the yawing moment, are strongly dependent on ground clearance and on the cross-sectional shape of the vehicle body. In particular, there is a significant lift force which varies noticeably with yaw angles greater than 0.1 radian (equivalent to a 10 m s^{-1} cross wind at a vehicle speed of 10 m s^{-1}), and with pitch angle, and also a pitch moment which varies with pitch angle.

The chassis of the vehicle now being constructed is the cryostat, containing two square superconducting coils (0.4 x 0.4 m). It has been designed as one large (1.5 x 0.5 m) vacuum-shielded enclosure which will allow flexibility in both coil size and arrangement. Other factors considered include the future requirement of incorporating damping coils between the main coils and the guideway, maximizing the clearance between the ground and the cryostat outer wall, minimizing the weight, and the desirability of operating for several hours without replenishment of cryogenic fluids, but with helium gas recovery. The design finally chosen consists of thin sheet aluminium alloy for the top and sides, suitably ribbed transversely, and with a flat base plate (10 mm thick). Although this arrangement is simple and allows flat coils to be used, the base accounts for more than half the weight of the cryostat shell, and 10% of the total coil-track clearance; clearly there is considerable scope for improvement in the design for a full-scale vehicle.

The coils themselves will be contained in welded, stainless-steel vessels, although a longer term development to save weight and space would be to have 'potted' coils, either on a helium-cooled backing plate or of hollow conductor. Cooling for several hours operation is provided by up to 15 l of liquid helium, mostly stored in three cylindrical vessels running the length of the cryostat. These vessels are sealed so that over the working period the pressure rises to almost 2 atmospheres, and the temperature to about 4.8 K; header space of about 10 l ensures that over half of

Table 1. Coil parameters

Inner width	330 mm
Outer width	440 mm
Cross-section	55 x 37 mm^2
Excitation	2 x 10^5 At
Mean current density	100 A mm^{-2}
Peak field	2.2 T
Current	35 A

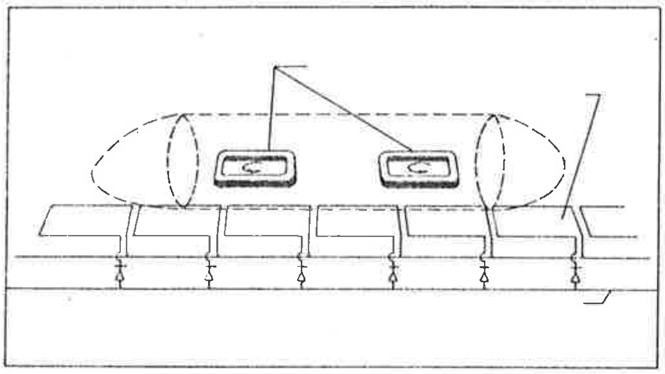

Fig.3 Schematic of linear commutator motor

Table 2. Linear commutator machine parameters

	Revenue vehicle	Wolfson test vehicle
Vehicle weight, tonne	30	0.15
Speed, m s^{-1}	140	80
Power, MW	5.6	0.14
Track current, A	180	95
Terminal voltage, kV	12.2	0.6
Pole pitch, m	0.52	0.8
Efficiency,% } at machine terminals	88	85
Power factor, % } at machine terminals	97	97

the helium evaporates during this process, so that use is made of the latent heat of the liquid. A stainless steel radiation shield and liquid nitrogen reservoir surrounds the coil space; the bottom being closed with a sheet of high conductivity aluminium.

Two square coils are being made, with the dimensions and ratings (of each coil) set out in Table 1.

Current will be supplied from a battery, but not regulated, so the coil behaviour will approximate that of the constant flux mode. The choice of conductor is determined partly by the cryostat losses – since the cryostat is pressurized it is most convenient to use simple, end-cooled current leads with relatively high losses, which would be only tolerable at (or below) the low current chosen – and partly by the possibility of ac losses arising from vehicle motion or from the armature (track winding) reaction of the linear machine. Preliminary estimates suggest that the latter field variation will dominate, but will be less than 0.02 T; at this level either a single-core or untwisted filamentary conductor will give minimum losses. Under the rated current, field, and temperature conditions the design current density is, of course, well below typical short sample ratings for niobium–titanium wire.

Propulsion

Linear synchronous machines have been proposed as being most compatible with the relatively large levitation heights (20–30 cm) obtainable with superconducting magnets. Put in the simplest way, it is more favourable to provide a steady air-gap magnetization with superconducting magnets, than to provide alternating magnetization (as in a linear induction machine) from the main power supply, with the consequent low power factor. However, for acceleration and controlled deceleration a variable frequency power supply is required, whilst good efficiency and power factor appear to be attainable only by using, on the vehicle, a large number of magnets, with the associated problems of screening and weight of the cryogenic equipment.

For these reasons it is valuable to investigate in depth alternative machine concepts, such as the linear commutator machine being studied at Warwick. Fig.3 is a simplified diagram of the machine. The main feature, not obvious from the diagram, is that each track loop is activated only when it can provide useful thrust or braking. To date, a demonstration machine, with the armature laid around the periphery of a 0.6 m drum has been operated, and an experimental machine based on a 3 m diameter drum is being built. Table 2 gives preliminary design figures for both the Wolfson and a possible revenue system, though neither is yet optimized. Despite the large number of solid state devices required along the guideway, the overall costs appear to be comparable with those of a linear synchronous machine. However, a better comparison can only be made after further studies of some of the problems involved, for example, the method of remote switching of the thyristors, control of the thyristors to avoid damaging current surges, optimization of the track winding arrangement etc.

Conclusion

Now under construction are the 550 m long track and an experimental 150 kg vehicle for the Wolfson magnetic levitation project. In addition, laboratory and theoretical studies are being made of particular aspects of magnetic levitation; at present particular emphasis is being laid on designing guideway configurations for minimum drag, on the stability of vehicles subject to magnetic and aerodynamic forces, and on linear commutator machines.

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