MAGLEV VEHICLE OSCILLATIONS AND DAMPING MECHANISMS

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Summary

For high speed ground transport, magnetic levitation, using repulsion between moving high field (superconducting) magnets and an electrically conducting guideway may be considered. The same magnets may be the field windings of a linear synchronous motor for propulsion.

The nature of the magnetic and other forces acting on the vehicle are discussed. For acceptable ride characteristics additional damping is needed, probably provided by an active control system.

The Wolfson sponsored project to build a demonstration maglev vehicle at the University of Warwick is described.

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R. G. Rhodes, B. E. Mulhall, E. Abel*

Introduction

The possibility of overcoming wheel friction, wear and vibration by contactless suspensions for high speed vehicles is being investigated at a number of centres throughout the world. Both the air cushion or hovercraft principle and levitation by magnetic forces are being actively developed for future ground transport systems. Of the several magnetic suspensions proposed, utilizing either attraction or repulsion between magnetic poles, the one involving the repulsion force generated between superconducting magnets mounted on the vehicle and an electrically-conducting aluminium guideway is being examined at the University of Warwick supported by the Wolfson Foundation.

This method of levitation, generally referred to as 'maglev', has the desirable feature of being inherently stable in contrast to the alternative 'attraction' system which requires a control loop for its stability.

Magnetic Levitation

The basic principles of the maglev system are fairly simple and reasonably well understood and the applications to vehicle suspension and guidances have been exhaustively studied and described by a number of authors.[1,2,3,4] In brief, the relative movement of the d.c. vehicle magnets induces eddy currents to flow in the surface layers of a conducting sheet (or loop) guideway. These transient currents circulate in such a direction to produce repulsive lift forces. The force increases rapidly with speed and in the high speed limit it is equal to the 'image' magnet force, i.e. an imaginary magnet replacing the conducting sheet, carrying an equal and opposite current to the real magnet and situated the same distance below the guideway as the vehicle magnet is above it. In practice the lift force approaches its upper limit at a vehicle speed which depends on the magnet coil dimensions (the length to width ratio of rectangular coils) and the thickness of the aluminium guideway, but is typically a few tens of km/hr. However, the eddy currents flowing in an aluminium guideway of finite conductivity dissipate a certain amount of power in the form of Joule losses which appear as a drag force on the vehicle magnets. This drag force passes through a peak value at low speeds of a few km/hr and then decreases continuously with speed approximately as $1/v^2$.

To achieve the levitation forces that would be consistent with levitation heights of 200 - 300 mm which are considered desirable for high speed ground systems, very large currents are needed in the vehicle magnets. These can only be provided economically by the use of superconductors and the superconducting magnet, having virtually zero resistance, consumes no power in operation other than the small amount necessary to keep it a low temperature (4.2K). With a vehicle-track clearance of this magnitude the ride quality should be relatively independent of the surface smoothness and irregularities in the guideway.

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The propulsion of a levitated vehicle by methods similar to aircraft would be quite unacceptable at ground level for obvious environmental reasons. Linear electric motors would appear to offer the best solution, therefore, and both the induction and the synchronous types are being considered for this purpose. However, partly because of its weight, and partly on account of the stringent requirement for a small gap (approximately 1 cm) between the stator winding on the vehicle and the reaction rail on the track of the induction motor propulsion this type would probably not be compatible with the large-gap of the maglev suspension. The linear synchronous motor, on the other hand, can still operate at reasonably efficiency with air gaps if several centimeters and with the very high d.c. fields provided by the superconducting coils on the vehicle, it is natural to consider propulsion by this type of motor, the armature winding being laid out along the track. With this arrangement of powered track a variable frequency supply is necessary for acceleration and deceleration of the vehicle. To provide for this an alternative system, being investigated at Warwick, is to switch the track winding in a manner analogous to the commutator in a d.c. machine; the switch, however, would be remotely operated by solid state SCR devices and a three-phase power supply would be used.

The Wolfson Project

With a grant from the Wolfson Foundation a small team has recently been set up to both demonstrate the feasibility and to test the performance of a magnetically levitated vehicle model with the object of high-lighting those engineering problems to which a full-scale revenue vehicle may be subjected.

A straight and level track of approximately 600 m in length and 1 meter in width, allowing test speeds up to 250 km/hr, will be constructed on the University campus. A vehicle 3 m by 1 m and weighing 500 kg is being designed with accommodation for two passengers. For levitation and guidance the vehicle will carry two or more superconducting coils approximately 0.8 m square with a field of 7×10^4 A-turns, providing a net vehicle-track clearance of about 100 mm.

Some of the major elements of hardware, in particular the concrete track structures and aluminium guideway, terminal facilities, and vehicle body, cryostat and superconducting coils, are being designed.

The design is such as to permit maximum flexibility in the configuration of the levitation, guidance and propulsion elements, since parallel theoretical and laboratory studies of these are still in a preliminary stage. A major part of the design study, and testing of the vehicle, will be devoted to the dynamic behaviour with a view to determining how far the natural characteristics of the levitation will need modifying, either by passive or by active control. At this stage it is already possible to state the problem in broad terms and identify particular areas.

Vehicle Constraints

The steady, or slowly-varying forces on the vehicle are its weight, aerodynamic drag (including the sideways component due to crosswinds), magnetic lift, guidance and drag forces from the guideway, and electromagnetic thrust (and in general also vertical and sideways forces) from the propulsion system. Although there is inherent stability in the vertical direction it is not obvious a priori that the same is true of other modes e.g. roll, or indeed that sustained oscillations cannot develop from the linear motor propulsion. It is already known that the magnetic forces are associated with very little damping, and hence even in a stable mode any disturbance may be expected to produce oscillations only decaying over many cycles.

The object, nevertheless, is to provide a ride of sufficient smoothness to be not only acceptable from the point of view of passenger comfort, but also to be better than present day ground transport systems, and ideally even better than modern aircraft can provide. The question of acceptable standards is considered extensively elsewhere [5]; our purpose is to investigate what is required of the system design to meet them. The main sources of disturbance will include :

a) aerodynamic, from wind gusts, passing vehicles, nearby structures and the like.

b) aerodynamic oscillatory forces arising from vortex shedding in a steady wind flow over nearby structures or over the vehicle itself [6].

c) track roughness and undulations

d) the periodic structure of the track windings, where these are used for levitation in place of a continuous sheet or where certain types of linear motor, such as the linear commutator motor, are used, giving rise to oscillatory disturbances.

e) acceleration and deceleration, or centrifugal forces.

Because of the large gap and consequent relatively low compliance of the magnetic forces the motion is on the one hand less sensitive to track roughness, and on the other more sensitive to other disturbances, than the much stiffer suspensions of traditional transport systems.

Magnetic Forces

The magnetic forces are best understood, in the sense that they are completely prescribed by the system design. Moreover, given a fairly simple system the lift and guidance forces can easily be computed in the high speed limit (they are just the forces between the vehicle magnet and its images). In more complicated geometries the high speed limit forces can be deduced from inductance measurements on scale models, provided that the measuring frequency is high enough for the 'skin effect' in the model to be well developed.

Three different guideway patterns are being seriously considered, as sketched in Figs. 1. In Fig. 1(a) lift and guidance are produced by the horizontal and vertical surfaces respectively, and in general motions along the two axes are decoupled. However, the presence of the vertical members is expensive of track material, is physically restricting (though this may be advantageous in case the magnetic system should fail), and has increased drag on account of the extra image magnets created.

Somewhat less restrictive physically, and with the ability to shed debris, is a V or inverted V track. A variant of the V is the semicircular track of Kolm and Thornton [4], which is claimed to allow the vehicle to roll to the correct angle of bank on bends. Unfortunately it may be shown [1,5] that the coupling of roll and sway gives rise to instability in most practical situations (suspension from an overhead track is an exception). Means to overcome this, for example, by providing additional perpendicular surfaces (Reitz [5] et al) or by a magnetic 'keel' (Thornton [4]), have been proposed.

From the point of view of track costs, visual acceptability, ease of switching, freedom from the accumulation of debris, and compatability with other vehicles, the scheme of Fig. (e) is interesting. The lift is reduced relative to scheme (a), thus requiring perhaps 50% more superconductor, but this is more than offset by the savings in aluminium. Typical lift and guidance behaviour is sketched in Fig. 2; this does not however show the couples generated in roll, and the conditions for vehicle stability have not as yet been deduced.

Other Forces

A considerable amount of data is available on aerodynamic forces on vehicles, some of which is summarised by Reitz et al [7]. The most significant point is that, for typical revenue vehicles, the magnetic forces dominate. The same authors also present an extensive discussion of the characterisation of guideway roughness.

Analysis of Motion

Given quantitative data on the forces discussed in the preceding section, analysis of the motion of a magnetically levitated vehicle is in principle relatively straight forward. Indeed, since aerodynamic forces in general appear to be small, it should be possible to derive the response (transfer function) of the vehicle from a knowledge of the magnetic forces alone; the disturbing forces are then an input to which we wish to make the system insensitive.

Difficulties arise because the equations in fact are highly non-linear, and because all possible modes of motion may be present equally and will in general be more or less strongly coupled. Thus, although analyses of vehicle behaviour have been published [8], they are restricted in that the equations are linearised (and hence are only appropriate to small oscillations about equilibrium), and some degree of decoupling has been assumed so that only two or three modes are considered simultaneously. To a large extent the linear approximation is of interest, since the limit of validity appears to be of the same order (vibration amplitudes of a few millimetres) as the limit of acceptable ride quality. Nevertheless, it will also be necessary to demonstrate that motions of the largest amplitude that could arise infact represent a safe situation.

How far the assumptions of decoupling are valid is not a present clear. It has already been demonstrated that with the most economical guideways there is strong coupling between modes.

A similar situation arises where a linear electric machine is used for propulsion, since as well as thrust there will be vertical forces, and also lateral forces if the vehicle winding is displaced laterally relative to the track winding; moreover these forces are similar in magnitude to those produced by the magnetic levitation schemes described. The natural conclusion is that in the interest of efficiency and economy the levitation and propulsion should be designed to aid, rather than oppose each other. Unfortunately we have not, at the time of writing, sufficient results to show dynamic stability.

Methods of Control

The work of the Stanford [8] and Ford [5] groups has shown that the natural damping of magnetically levitated systems is insufficient for passenger comfort. Damping can be added by means of short-circuited coils situated between the levitation magnets and the track, though for best performance these should be cooled, to reduce their electrical resistivity (typically to 80 - 100°K). With this passive damping, however, it is difficult to damp out the fundamental vehicle frequency of approximately 1Hz, fixed essentially by the large suspension height. Reitz et al [5] propose a secondary suspension, but suggest it would be difficult to produce satisfactorily as its own natural frequency should be 0.4 Hz or less.

The general conclusion is that for acceptable ride quality, some form of active control is required. The problems of active control centre on the choice of output device for the control system and three possibilities have been considered:

(1) the levitation coils themselves

(2) auxiliary coils, which may replace the passive damping coils

(3) aerofoil surfaces

The last method has been discussed, for control of vertical oscillations by Reitz et al [7], who found that the simple flaps considered were too large in area to be readily acceptable. Thus, although this work is not definitive, the prospects for this type of control are not good.

Both the Ford and Stanford groups have discussed electrical control systems, and find that the control power needed for typical guideway roughness is rather modest. However, figures are not quoted for smoothing out the effects of strong wind gusts; since the force produced by a 100 kph gust is likely to be several times that of guideway undulations of 10 mm or so, the total control power required might be increased by an order of magnitude. Under these circumstances it will be preferable to use auxiliary control coils rather than the levitation coils themselves, for two main reasons :

(1) the power losses in the superconductor, when subject to the control current fluctuations, would prove unacceptably large.

(2) by placing the control coil nearer the track than the main coil (it would typically be on one of the cryostat vessels forming the thermal insulation for the superconducting coil) less reactive power would be needed.

The design of such a system is included in the Wolfson Project.

Conclusion

The problems of designing a magnetically levitated vehicle to afford good riding qualities have been outlined. It is concluded that a satisfactory system will incorporate auxiliary coils in the cryostat, probably as part of an active control system.

The Wolfson project at the University of Warwick, directed specifically to prodce a demonstration and test vehicle has been described. A vehicle is being designed, and calculations and model tests to establish the stability of the guideway illustrated in Fig. 1e are being undertaken. Propulsion of the model by a linear synchronous or commutator motor is being considered; initial theoretical and model studies of the motor are in hand, to be followed by an analysis of its effect on the vehicle's dynamic behaviour.

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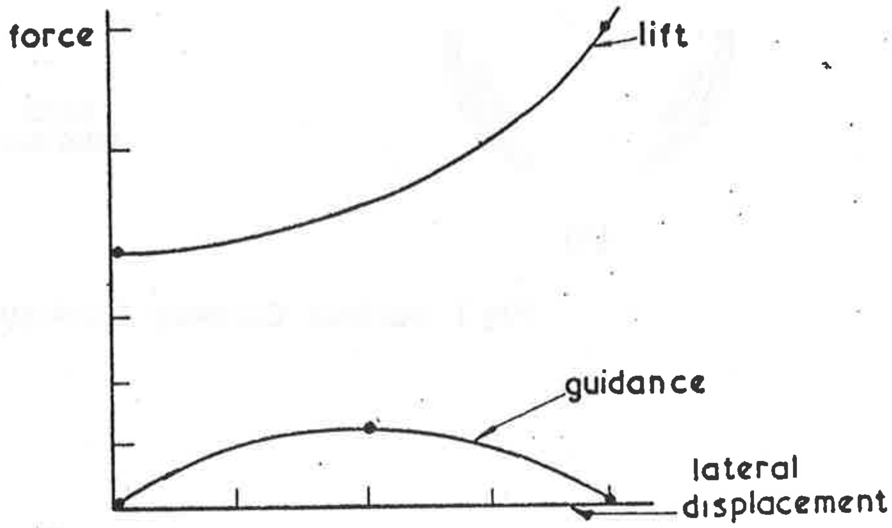

Fig 2. Typical Force Characteristic for guideway

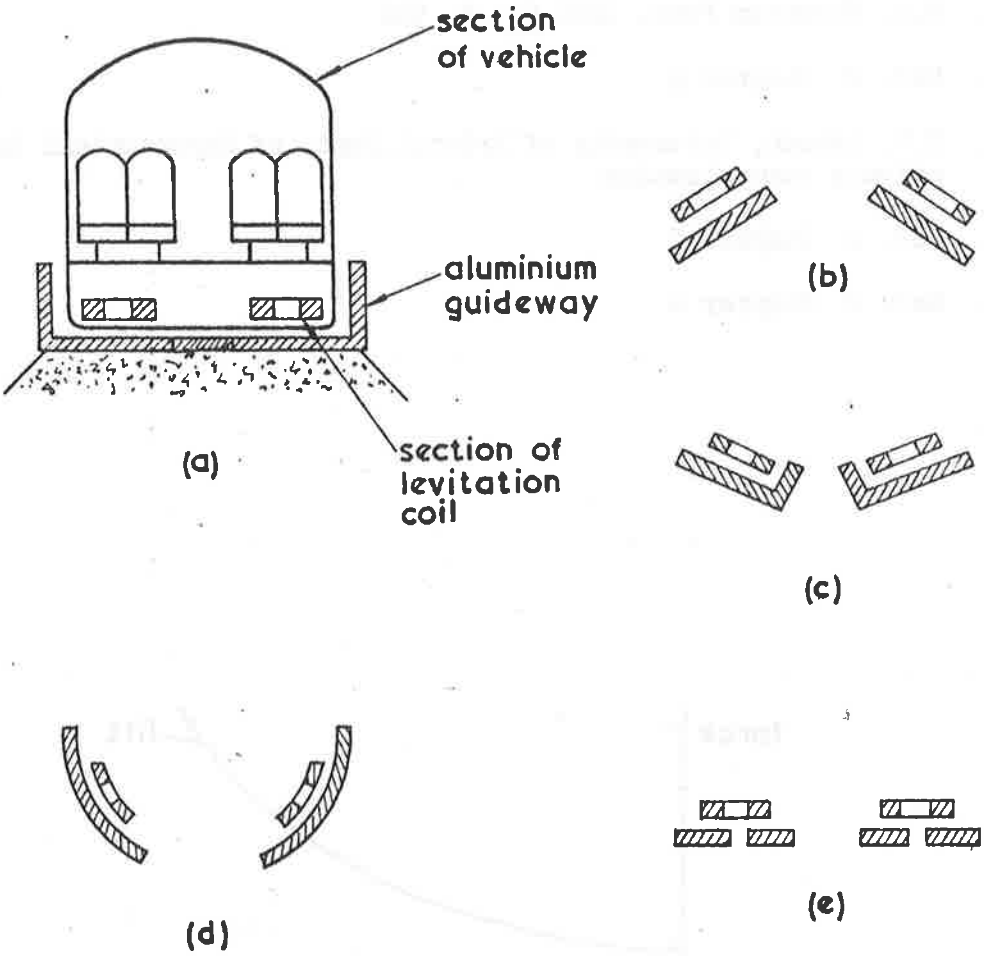

Fig I. Various Guidway Configurations