Wolfson Magnetic Levitation Group

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The Electrodynamic System of Levitation and LSM Propulsion

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- Maglev Project Group, University of Warwick

1. Basic principles

There are essentially two basic systems for the magnetic levitation and guidance of high speed tracked vehicles which are at present receiving serious investigation world-wide, namely

i) the electromagnetic system (EMS),

ii) the electrodynamic system (EDS).

The EMS is based essentially on the attractive forces between conventional copper magnets with iron yokes on the vehicle and iron rails along the track. Because this is basically an unstable system, active control of the magnet currents is essential to maintain the clearance between the magnets and the rail, a distance of approximately 10 - 15 mm.

The EDS, on the other hand, relies for levitation and guidance on the repulsive forces which are generated between moving iron-free, superconducting magnets on the vehicle and conducting (aluminium) sheets (or coils) at ambient temperature on the track. In its application to high speed transport, some of the essential features of the EDS can be enumerated as follows:

1) The vehicle is magnetically levitated and laterally guided in a statically stable manner solely by magnetic forces generated in the aluminium guideway by the vehicle magnets.
2) The clearance between the vehicle and the guideway can be in the range of 100- 300mm.
3) The levitation and guidance forces are analogous to those produced by a resilient undamped spring with a resonant frequency of the order of 1-2 Hz.
4) The circulating currents induced in the aluminium guideway give rise to magnetic drag forces which have to be overcome by the propulsion system.
5) The superconducting magnets on the vehicle operate at liquid helium temperature (4.2K) in the persistent (short-circuited) mode and hence require no power on-board.
6) At standstill and low speeds up to approximately 40 - 50 km/h, wheels are necessary to support the vehicle.
7) From the point of view of the efficiency of a linear motor operating with air gaps of the order of 100mm, a linear synchronous motor would be used, the powered armature windings being installed along the track.

8) Power conditioning units spaced at intervals (5 - 15 km) would provide the three-phase current to the track windings which interacts with the vehicle superconducting magnets.

9) Various schemes for combining linear motor propulsion and guidance or, in the case of the Warwick design, combined propulsion, lift and guidance, are being examined.

2. Magnetic force characteristics

For a magnet moving at constant height above the conducting strip guideway, the lift force, F_L, first increases as V^2, where V = velocity and, as the induced currents in the track become saturated, it then levels off and approaches the image force, F_i, at speeds greater than about 120 km/h, i.e. the lift force becomes independent of speed Fig (1).

Because the aluminium track is resistive, energy is dissipated by the induced currents. This appears as a drag force which increases linearly with speed initially reaching a maximum at 10 - 20 km/h, depending on the vehicle coil geometry and thickness of the aluminium track. At higher speeds it decreases hyperbolically as (velocity)$^{-\frac{1}{2}}$ ($V^{-\frac{1}{2}}$). It is this decrease in magnetic drag at the higher speeds which allows the EDS suspension to function efficiently.

A number of fundamental studies of current-carrying coils moving above conducting sheets of varying geometries and arrangements have been carried out and there is considerable information on the variation of magnetic lift, F_L, and drag, F_D, forces with vehicle speed, levitation height and coil geometry. It can be shown in general that

$$\frac{F_L}{F_D} = \frac{V}{W}$$

over the whole speed range, where W is a characteristic velocity associated with the guideway size, thickness, material and configuration. With a simple magnet-track arrangement, $F_L/F_D \sim 35$ can be technically achieved at 500 km/h. It is evident, therefore, that the propulsion force required to overcome magnetic drag decreases with increasing speed while, at high speeds, the force needed to overcome the aerodynamic drag increases as V^2, and accounts for most of the energy expenditure.

2.1 Lift and guidance

A variety of arrangements of the vehicle magnets and guideway conducting sheet or loops have been examined and these essentially fall into two groups,

i) single magnets above plane sheets or strips of aluminium in the normal flux arrangements (the Japanese use conducting coils in the track in place of continuous strips).

ii) null-flux systems whereby double magnets on the vehicle, excited in opposition, induce currents in a strip or loop track positioned between them.

The main advantage of the null-flux system, i.e. a reduced drag force, tends to be compensated by the larger magnetic fields required for the vehicle magnets. Some of the different coil/ guideway configurations being studied are sketched in Fig. (2) and a comparison of their design details is given in Table (1).

2.2 Damping

Although the EDS systems are statically self-stabilizing, their self-damping is insufficient to compensate for dynamic instabilities caused by wind forces, track irregularities and other external perturbations. To meet the criteria for ride comfort, therefore, some additional active control must be provided in the critical frequency range 0.5 - 20 Hz. These damping requirements can be achieved either by additional actively-controlled coils mounted between the superconducting coils and the track or by means of a passive or active secondary suspension system. It is planned to examine both of these possibilities at Warwick and some preliminary studies have been started.

3. Vehicle dynamics

The split-track system being developed at Warwick combines the functions of lift, guidance and propulsion from a single array of superconducting magnets on the vehicle moving over a pair of aluminium strip 'rails' on the track with a powered armature winding in the gap between them (Fig. (3). From an analysis of a mathematical model of the system, together with impedance model measurements, it has been shown that the predicted behaviour and performance characteristics are equivalent to alternative electrodynamic suspension schemes and, in many respects, can be superior.

3.1 Impedance Modelling

The impedance modelling technique has been extensively used to study the magnetic force characteristics produced by the two-coil assembly of the Wolfson test vehicle being constructed for operation on the 550 m-long, test track on the university campus. Two copper-wound coils, 0.4m square, positioned in tandem (Fig. (4) and of opposite polarity are mounted above two aluminium 'track' strips and the apparent inductance and resistance of the coils are measured at different positions relative to the guideway strips. The lift and guidance forces are related to the gradient of inductance, the drag to the resistance and the speed to the frequency. The impedance method readily lends itself to full-scale modelling and, although the simulation of a moving d.c. excited coil by a stationary a.c. coil in a model can never be exact, it has been found in practice, that the results are in good agreement with theoretical predictions.

A number of experiments have been performed to determine the characteristics of the split-track geometry and also to confirm the predictions of the mathematical model of the systems. These include measurements of

i) the lift-to-drag ratios as a function of the conductor spacing, conductor width and thickness, levitation height, and frequency (speed).

ii) the guidance forces and the variation of lateral stiffness.

iii) heave frequencies

iv) the effect of guideway joints

The variation of the influential coil dynamic characteristics with conductor spacing is shown in Fig. (5). Roll stiffness and lift are essentially independent of conductor spacing while the lift-to-drag ratio and lateral stiffness are highly dependent. To generate desirable roll characteristics therefore only requires manipulation of the coil width, while the lateral stiffness is determined from the spacing between the conductors. To produce the required lift-to-drag ratio it is then necessary to thicken the track or increase the conductor width. In this manner any combination of coil dynamic characteristics can be obtained. It has also been found that cross-coupling between roll and sideslip is extremely small for the conductor spacings of interest while lift variation with lateral displacement is small. The Warwick geometry is the only electrodynamic system yet devised in which these latter terms are small enough to be ignored. Since, for many practical reasons of design and fabrication, a circular geometry for the superconducting coils and their cryostat assemblies is preferred to rectangular shapes, the force characteristics of these were examined. Design criteria have been established for finite radius, rectangular coils, as designed for maglev trains, by both an analytical approach and by impedance modelling. Measurements have been made of the effect on the lift-to-drag ratio and guidance stiffness using circular coil and rounded corner geometries.

4. Ride Quality

Track roughness and cross-wind gusts have a major influence on the attainment of satisfactory comfort levels for passengers travelling in high speed trains. To assess the impact of such external disturbances on vehicle behaviour a simple mathematical model of the suspension has been subjected to a random input and the power spectral density (p.s.d.) output response then compared with the UTACV ride standard for passenger comfort. For this analysis the vehicle and suspension are simulated by a two-dimensional heave model as shown in Fig. (6). The purely passive suspension is considered although the air springs envisaged for the secondary suspension readily allow for active control of the damping.

To represent the lateral motion of the vehicle, the heave model is merely turned through a right angle, as it is assumed in the calculations that no coupling exists between the vertical and lateral motions. This assumption has been shown to be valid for small oscillations from the impedance modelling results for the coil characteristics. It is also assumed that an unsteady cross-wind acts entirely on the secondary mass. For this study the mass ratio, μ (= $M2/_{M1}$) was set at 4 where represents the primary mass, consisting of the magnet/cryostat assemblies, and M_2 the vehicle mass. (In the Canadian design, the total weight was 30 tonnes, including 5.1t for the magnet array and 1.5t for the secondary mechanical suspension).

In all cases the output p.s.d. response is given by

$$\phi_{out} = /H\ (w)\ /^{2}\ \phi\ in$$

where H(w) is the transfer function relating the output to the input.

5. Track roughness

The input spectrum from a rough track is usually given in the form

$$\phi\ (w) = AU/_{W^2}$$

where U = velocity of the vehicle

and A = a constant = 1.5×10^{-6} m

However, it has been found that a better fit to the available data is given by an input spectrum of the form

$$\phi\ (w) = \frac{A\ U}{W_O^{\ 2} + W^2}$$

where W_O corresponds to a low frequency cut-off.

The output p.s.d. has been obtained for four primary stiffness values between 0.75×10^6 and 3.0×10^6 N m $^{-1}$, while maintaining the secondary stiffness at 0.75×10^6 Nm $^{-1}$. The latter primary stiffness, corresponds to a natural frequency of 1.6 Hz for a 30t vehicle, with a secondary suspension frequency of 0.8 Hz (air springs could be used to obtain this frequency).

A number of velocity spectra have been proposed for longitudinal wind velocities in the lower part of the atmosphere and it was found that the most suitable for this study was the one most commonly used for 'building' aerodynamics. The acceleration p.s.d.'s for a 13.5 ms^{-1} cross-wind input were calculated for the suspensions previously considered. Likewise, the combined (track plus cross-wind input) lateral and vertical p.s.d. curves were obtained for different values of the lateral and vertical primary stiffness ratios. From a comparison with the UTACV standards, it would appear that a reasonably good ride would be obtained.

If active control is thought to be desirable to produce a satisfactory ride then the amount of active power required is small, because the p.s.d. curve exceeds the standard only slightly over a very narrow frequency range. This is in contrast to the electromagnetic system where the primary stiffness is sufficiently high so that active control of the secondary suspension is essential.

6. Aerodynamic characteristics

Aerodynamic forces and moments have an important effect on the behaviour and performance of a high speed vehicle and a study of vehicle shapes has been undertaken using small scale models. For example, a vehicle travelling at 135 ms^{-1} with frontal area 9 m^2 would experience a 10 tonne force for a force coefficient, C_F = 1.0. All the tests were carried out in the 0.9m square, low-speed wind-tunnel at the Lanchester Polytechnic. The forces and moments were measured on the models using a 6-component balance mounted within the ground plane. An overhead balance was also used for some of the measurements and a range of model lengths and tail shapes as shown in Fig. (7) were studied.

It was also found from these experiments that the vehicle experiences a large increase in lift when subjected to a cross-wind. This leads to a reduction in the restoring forces of the magnetic suspension and hence to less vehicle stability. Experiments were therefore set up to examine the influence of the vehicle body, cross section on the lift at four angles. The influence of different nose shapes on the aerodynamic behaviour were also investigated.

A problem yet to be resolved concerns the validity of conventional wind-tunnel testing with regard to the simulation of the ground effect and an experimental programme has been started to assess the errors likely to occur in conventional static ground testing of elongated bodies. Two approaches to this problem are being followed, a) the pressure distribution and forces will be measured on a 1/10th scale model running on the Wolfson test track. These results will be compared with measurements made on the same model in the low-speed industrial wind-tunnel at City University, b) measurements are being taken on a smaller scale model (1m long) running on a track constructed in the laboratory (18m long).

7. Rotating-wheel test facility

During the early stages of the Warwick maglev project analytical and computer studies were undertaken to assess the feasibility of the levitation and propulsion system. Modelling and small scale experiments were carried out to gain a better understanding of the theoretical predictions. However, in order to improve the accuracy of the measurements and to provide more realistic test data a large rotating wheel was designed and constructed. The essential magnetic force characteristics of the split-track levitation and guidance system being proposed at Warwick and predicted by mathematical analysis could now be confirmed.

In this 'split-track' design the vehicle guideway configuration (Fig. (3))utilizes a single set of superconducting magnets on the vehicle, interacting with two, separated, conducting aluminium 'track' strips for the generation of the levitation and guidance forces. Active power meander windings laid between the strips interact with the vehicle magnets to produce the necessary propulsion in thrust force. Although the lift and drag forces generated in a simple (infinite sheet) configuration have been extensively analyzed in theory and experiment, a complex guideway arrangement, like the Warwick split-track configuration in which the influence of the edge effects on the induced eddy currents is dominant, has not been fully studied in detail. This is partly due to the excessive computer times that would be involved and the research has therefore been concentrated on the impedance modelling technique. Using this method a larger number of results of the system characteristics, extending over a wide range of vehicle speeds, have now been accummulated.

The rotating wheel facility has recently been completed and commissioned and a test programme has recently been started to obtain the experimental data to validate the results of the impedance modelling technique.

7.1 Design details

The rotating wheel facility consists of the following major components,

a) the wheel

b) support structure

c) drive motor

d) superconducting magnet and force balance harness

e) two aluminium levitation strips.

a) The wheel

A view of the rig and magnet assembly are shown in Fig. (8) and the design specifications are listed in Tables (II) and (III) respectively.

To satisfy the requirement of non-magnetic materials used in the construction the design consisted of a laminated wooden rim with an overall diameter of 3m, reinforced with glass-fibre/epoxy resin and supported by eight aluminium angle spokes.

b) Support structure

Plummer blocks, housing the bearings, are mounted on steel plates which have been anchored to two reinforced concrete plinths. The supporting plinths for the motor and shaft system are shown in Fig. (8).

c) Motor drives

The wheel is driven by a d.c. motor directly coupled to the shaft; speed control, loading/braking, etc. are achieved by means of the variable voltage control provided by the Ward-Leonard method, e.g. by varying the field current the motor can be made to act as either motor or generator, thereby either driving or loading the wheel.

d) Superconducting magnet and harness

A single superconducting coil, 130mm square, and contained in a commercial cryostat is mounted on the force balance, located above the test wheel on a fixed portal frame (Fig. (8). The magnet was successfully tested to liquid helium temperature and the field measurements of the energized coil showed good agreement with the design specification. The characteristics of the coil are listed in Table (III). The magnet harness and force measuring balance enable measurements of the magnetic forces to be made in the 6 degrees of freedom, i.e. lift, drag, lateral forces, pitch, roll and yaw moments.

e) Split-track aluminium conductors.

Two aluminium hoops (approximately 3m diameter) were formed from 6 welded strips. These were thermally shrunk to the rim of the wheel with a gap of 110mm separating the inner edges. The hoops have been designed to withstand the combined stresses due to the centrifugal forces of the rotating wheel up to 45 ms^{-1} and the thermal expansion produced by induced eddy currents. The results obtained from the impedance modelling technique have indicated that the influence of the welded joints of the aluminium strips on the lift/drag force measurements should be negligible.

A digital electronic control unit has been designed, and is at present being built, to replace the existing manual control of the wheel. This unit will be capable of accepting programmed jerk, acceleration and velocity profiles.

Analytical investigations on a design of a linear synchronous motor for experimental testing on the wheel facility have been completed. For these measurements an array of five superconducting coils will be mounted on a force harness above the wheel and these will interact with a 3-phase winding fixed to the periphery of the wheel and powered by a variable frequency supply. The results of this design study have been presented in an internal memo.

8. Linear synchronous motor propulsion

For environmental and other reasons only the linear electric motor is being considered for the propulsion of high-speed maglev vehicles and, in principle, there is a choice between the short stator induction machine, or the long stator synchronous machine. However, for the electro-dynamic system of levitation, utilizing superconducting magnets, the iron-free, long stator, synchronous motor would seem to offer the most promising solution.

The principal advantages of the LSM are as follows:

i) No power collection is required for the energy supply on the vehicle, i.e. the super conducting field magnets operating in the persistent mode, consume no energy except for minor thermal losses.

ii) The air-gap between the armature track windings and the vehicle magnets can be of the same order as the levitation height to attain reasonable efficiencies, i.e. 100 - 250 mm.

iii) Since only lightweight, iron-'free' magnets are carried on the vehicles, the overall weight is considerably less than with the conventional electromagnetic propulsion systems.

The basic mode of operation of the LSM is shown diagramatically in Fig. (9). Conventional flexible power cables are laid between the aluminium strips along the track in a meander pattern, to form a three-phase winding which thus generates a travelling electromagnetic wave. The vehicle magnets interact with this travelling electromagnetic wave so that the vehicle speed is synchronized with that of the wave, this latter being determined by the exciting frequency and the pole-pitch of the winding. The energy to the winding is fed in at intervals of 5 to 15 km from sub-station frequency converters, providing the current and variable frequency.

Since both horizontal thrust and a vertical force are generated by the motor, these two components can be adjusted independently of each other by the current in the armature winding and by the position of the vehicle magnets relative to the travelling waves, as measured by the slip angle. Hence, the thrust and velocity of the vehicle can be controlled from the trackside. Likewise, because of the vertical force produced, some control of the dynamic behaviour of the vehicle in heave motion is also possible, e.g. by controlling the slip angle. It has been shown that high machine efficiencies and power factors are possible with this design of LSM, e.g. η = 0.88 and cos ϕ = 0.93 at an optimum working point of $\lambda = 123^{\circ}$ have been calculated and confirmed in scaled model tests.

By the use of superconducting pole windings on the vehicle, high magnetic fields can be generated over a large volume (large airgap) and hence the power requirements for the primary windings in the track are reduced to a reasonable level. Typical LSM/magnet coils operate with approximately 500kAT at air gaps of 100 - 250 mm, producing 0.25 - 0.8T at the track conductor level.

9. LSM research

In the early stages of the Warwick project an alternative propulsion system was investigated, namely the linear counterpart of the thyristor-commutator d.c. machine. Its main advantage is that, since the length of track winding excited at any time is relatively short (of the order of the vehicle length), the power factor and efficiency are both high or, alternatively, fewer superconducting coils would be required on the vehicle.

An analytical study of this linear commutator machine (LCM) was undertaken which was concentrated on an adaptation of the standard d.c. machine analysis. In parallel with these theoretical studies a demonstration machine was constructed with windings around the periphery of a 0.5m diameter drum. A superconducting magnet, mounted over the wheel, provided the field excitation. This was the first demonstration ever reported of this type of linear machine and it should be noted that the Japanese are now using a similar LSM design for their maglev test vehicle.

The main features of the LCM which differ from those of the long stator LSM are,
i) the short, excited armature length and ii) the fact that the power conversion of switching equipment is distributed in small blocks at short intervals along the track whereas, for the LSM, much larger inverter units are located at longer intervals of a few kilometres, typically 5 - 15 km.

In an attempt to resolve these differences a cost analysis was carried out and a comparative study was made with other LSM machine designs, i.e. the Canadian and the MIT LSM designs.

However, in view of recent developments in pulsed current inverters, the decision was taken by the Warwick Group, to transfer the research effort from the LCM to the LSM. The latter appeared to offer the better prospects as a propulsion system for the Warwick split track design and therefore analytical studies of the performance capabilities and topological variation of a LSM propulsion were undertaken. These studies will be fully published in a forthcoming report.

10. A.C. losses in the superconducting coils

In the application of superconducting magnets for the levitation, guidance and propulsion of high-speed vehicles, the coils will be subjected to time-varying fluctuations superimposed on their d.c. bias fields because of field variations resulting from various external sources, acting on the vehicle, such as track irregularities, wind gusts, etc. Furthermore, the vehicle magnets will see the periodically-modulated, inductance coupling with the powered track winding of the LSM armature. All these variations in the magnetic environment of the magnets, superimposed on their constant flux (persistent current) mode, would result in the generation of power losses.

A research programme is being undertaken jointly with the Rutherford Laboratory to investigate and develop experimental techniques suitable for the measurement of ac. losses in multifilamentary superconducting wires. The main objective of this research is to improve the understanding of the different loss mechanisms as a function of the physical geometry and metallurgical treatment of the superconducting materials.

The helium boil-off technique is being used to measure the losses in short samples and non-inductively wound samples are also being used for determining the self-field losses over the frequency range up to 100 Hz. A number of interesting results have been obtained to date and the apparatus is at present being modified to improve the sensitivity in the very low frequency range.

11. Wolfson test facility

11.1 Guideway

A guideway structure for the testing of model vehicles has been constructed on the university campus over a distance of 550m (Fig. 10). The construction consists of concrete piers at 5m intervals, spanned by timber joists and finished with a timber deck (1.3m wide). The dynamic deflection at centre span is less than 5mm for a 500 kg vehicle. Aluminium strips (200 x 10mm), spaced 380mm apart, serve as the running rails for the maglev test vehicle. Propulsion for the vehicle is provided by a towed trolley being attached to a continuous cable driven through a capstan by a stationary petrol engine (Fig. (10)).

The test vehicle is mounted on the trolley by means of flexible bearings so that its dynamic behaviour can be measured, using miniature tape recorders for recording the readings of force-measuring transducers.

11.2 Test vehicle

A model vehicle (3m long, weighing 150 kg), consisting essentially of a stream-lined glass-fibre body shell, with provision for the superconducting magnets, has been constructed and tested on the track up to a speed of 35 ms^{-1}.

11.3 Superconducting coils and cryostat assembly

Two superconducting coils (0.4 x 0.4m) and their helium cryostat assembly have been constructed and are presently being tested. The coils themselves are contained in a welded, stainless-steel vessel with helium cooling for several hours operation. Up to 18 litres of liquid helium is stored in three cylindrical vessels extending the length of the cryostat, Fig. (11). By sealing the cryostat and allowing the helium gas pressure to rise to 2 atmospheres an operation time of from 3 - 4 hrs. without helium replenishment has been calculated. A stainless steel radiation shield and liquid nitrogen reservoir surround the coils in the vacuum space. The coils will be operated under short circuit conditions by means of a heavy copper, shorting connection across the terminals (Table 4).

11.4 Problems of magnet design

By virtue of the application of superconducting magnets for the suspension and propulsion of a high speed vehicle, they would be subjected to severe dynamic conditions and hence the design of the coils and their cryostat assembly differ radically in several important respects from the conventional designs for stationary operation. For the split-track levitation/guidance system in particular, square or rectangular coils are necessary. This, in itself, presents new problems in providing mechanical reinforcement against the very high magnetic forces generated in the straight-sided limbs of the coils. By contrast, these problems are very much easier in the case of circular coils where the forces are uniformly distributed. The design problem is further compounded by the constructional and operational difficulties associated with the sharp corners of the coils, the migration of the winding and stress concentration. A study was undertaken to establish design criteria for finite radius rectangular coils, using both the stress analysis technique and impedance modelling measurements and the general conclusion from this study was that a reduction in lift-to-drag ratio of the vehicle must be accepted with increasing corner radius in order to maintain the same guidance stiffness. Another consideration is that the coil shape, to a large extent, determines the geometry of the cryostat assembly which, in the Warwick design, consists of the two square coils, housed in a tandem arrangement inside a rectangular vacuum box, together with the nitrogen thermal shield and helium storage vessels. Very severe mechanical problems associated with the large flat areas of the vacuum vessels had to be overcome and, in particular, because of the limited distance between the coils and the aluminium track the vacuum and thermal insulation for the helium vessel had to be severely restricted in the design. A further difficulty which is not normally encountered in the design of conventional superconducting magnets is that of the transmission of the mechanical support forces from the coils at liquid helium temperature (4.2K) through the vacuum thermal insulation to the outside of the cryostat at ambient temperature. No previous experience in solving these design problems could be found in the U.K. However, with the advice and considerable help that has been received from the Rutherford Laboratory, most of these difficulties have now been resolved and it is confidently expected that the cool-down and operation of the magnets should now proceed without further trouble.

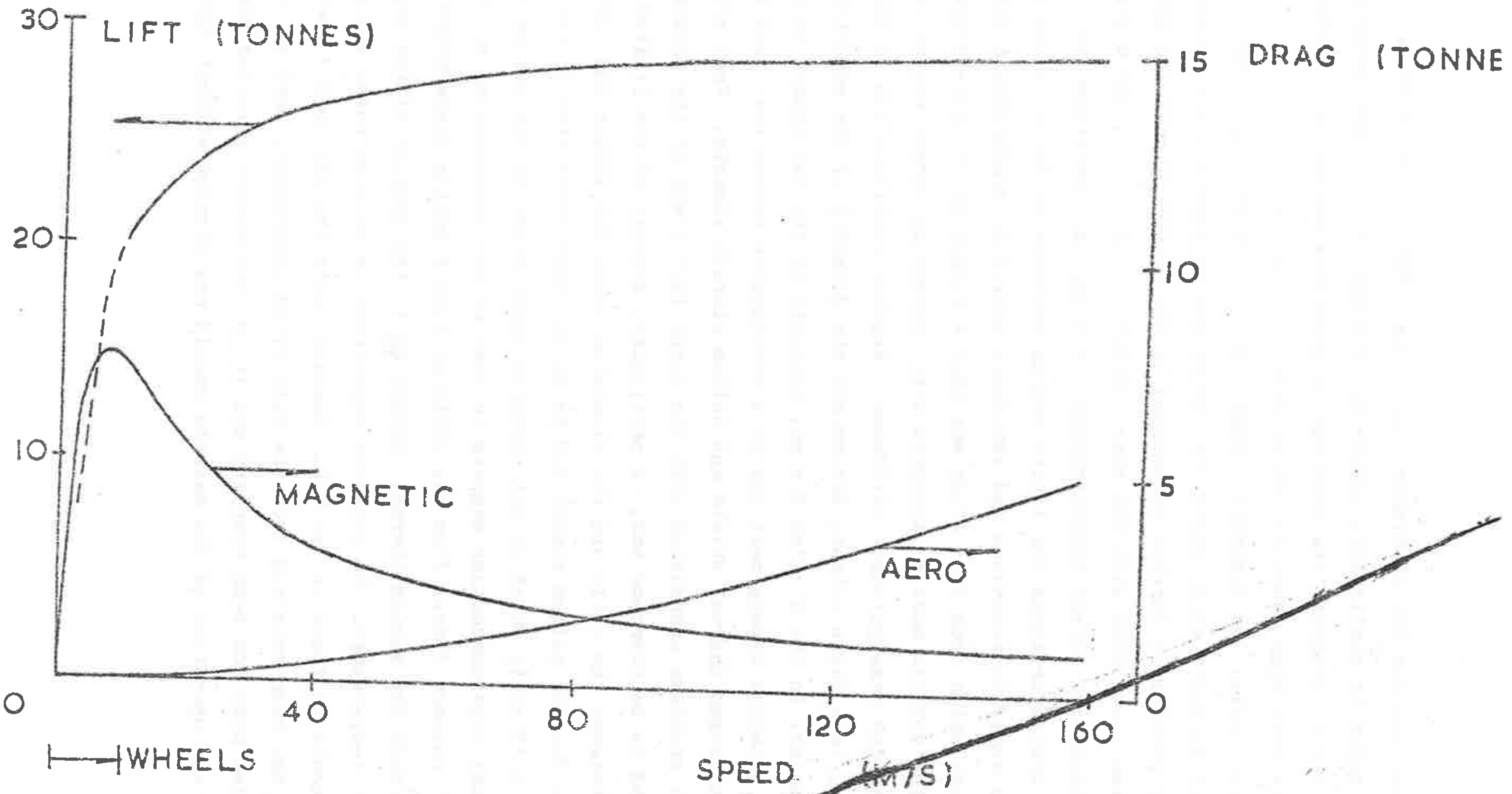


FIG. 1 LIFT AND DRAG FORCES AS A FUNCTION OF SPEED FOR A CONDUCTING SHEET SUSPENSION

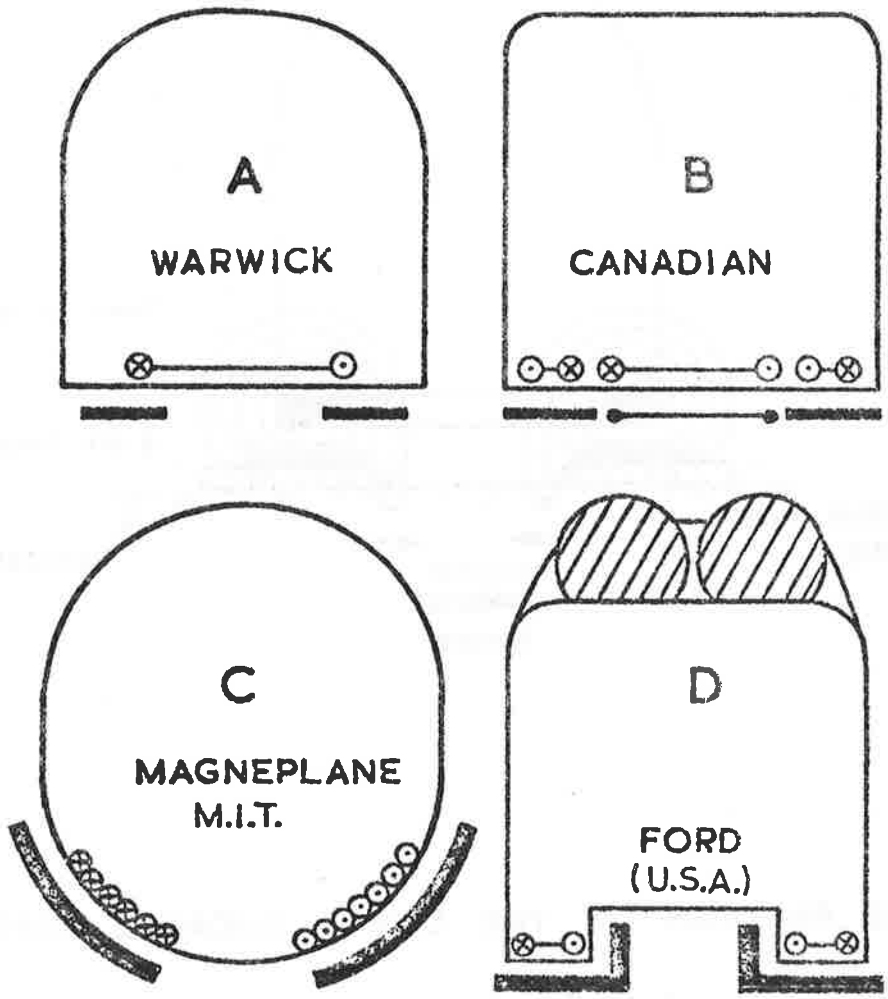
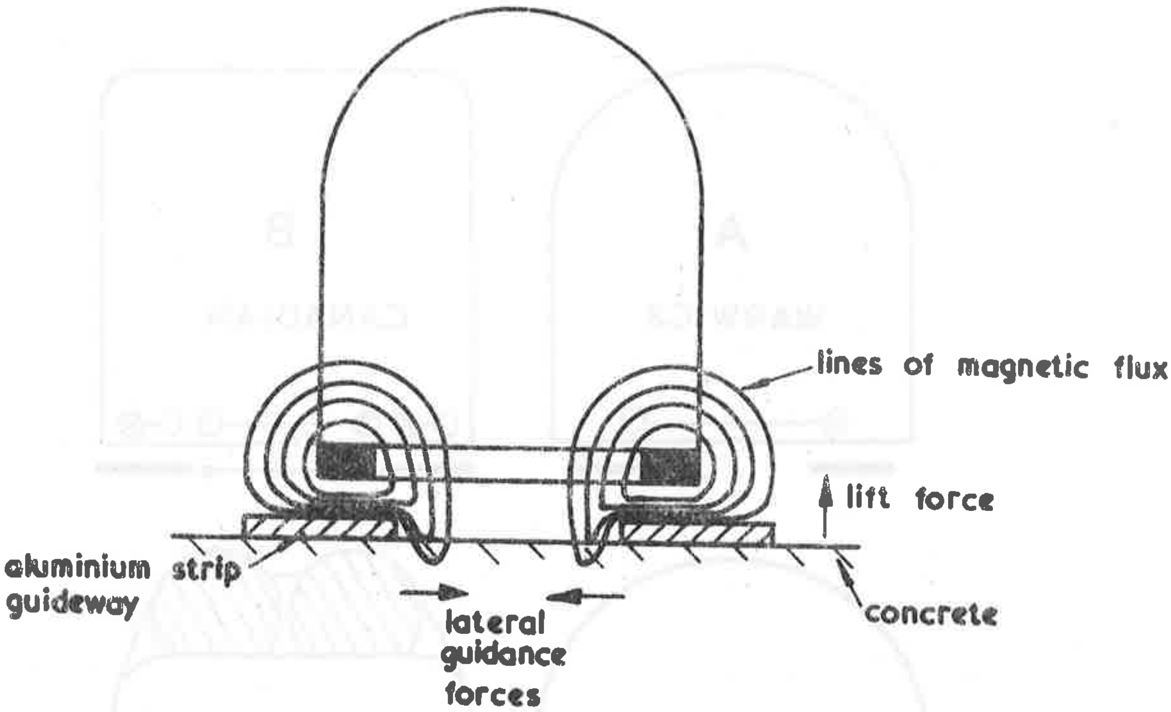
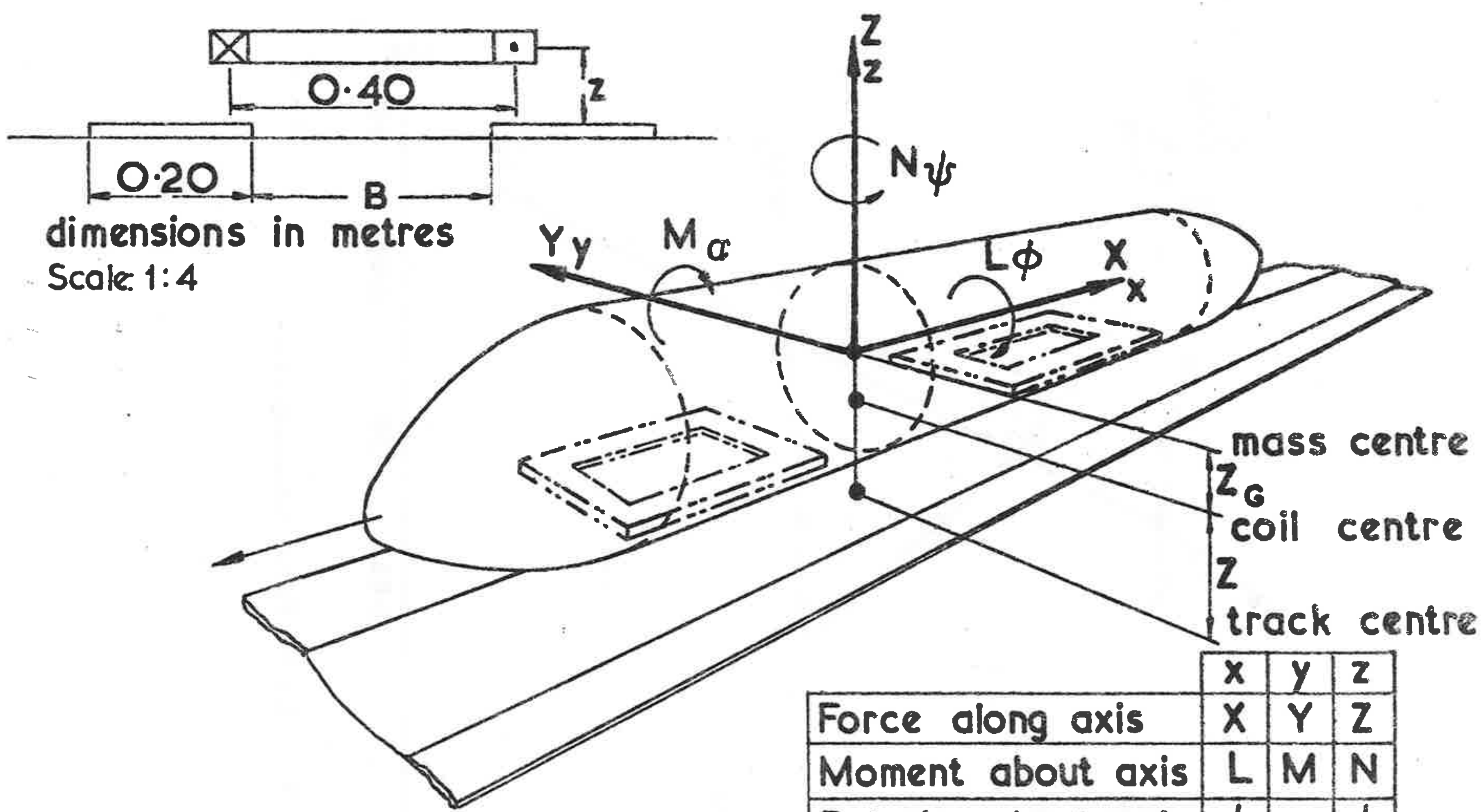


FIG. 2. ALTERNATIVE GUIDEWAYS



FLUX LINE PATTERN OF THE LIFT & GUIDANCE FORCES

FIG 3



	x	y	z
Force along axis	X	Y	Z
Moment about axis	L	M	N
Rotation about axis	ϕ	a	ψ

FIG. 4 . AXIS SYSTEM AND COIL - TRACK CROSS SECTION.

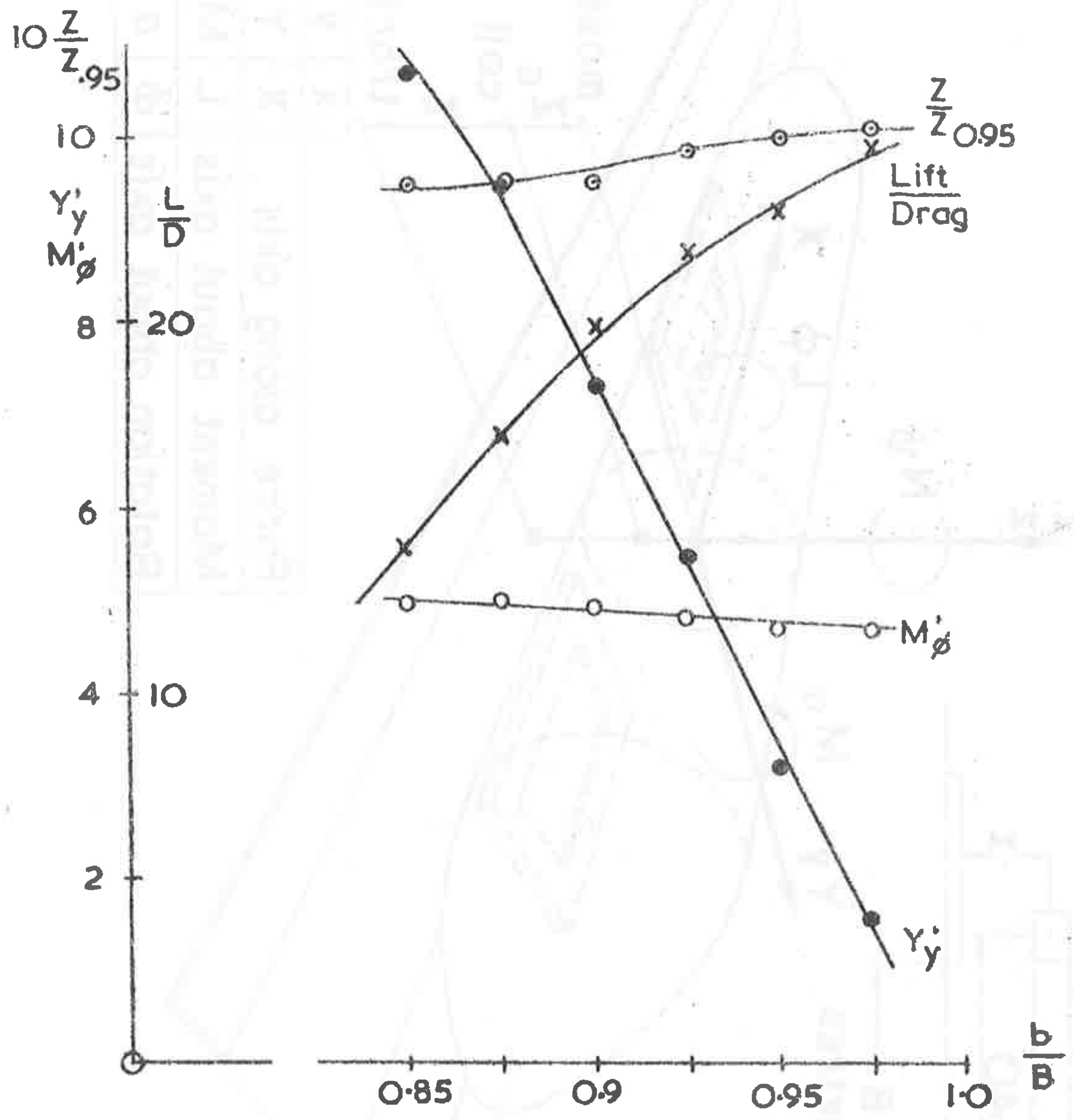


FIG. 5 Coil Force Characteristics.

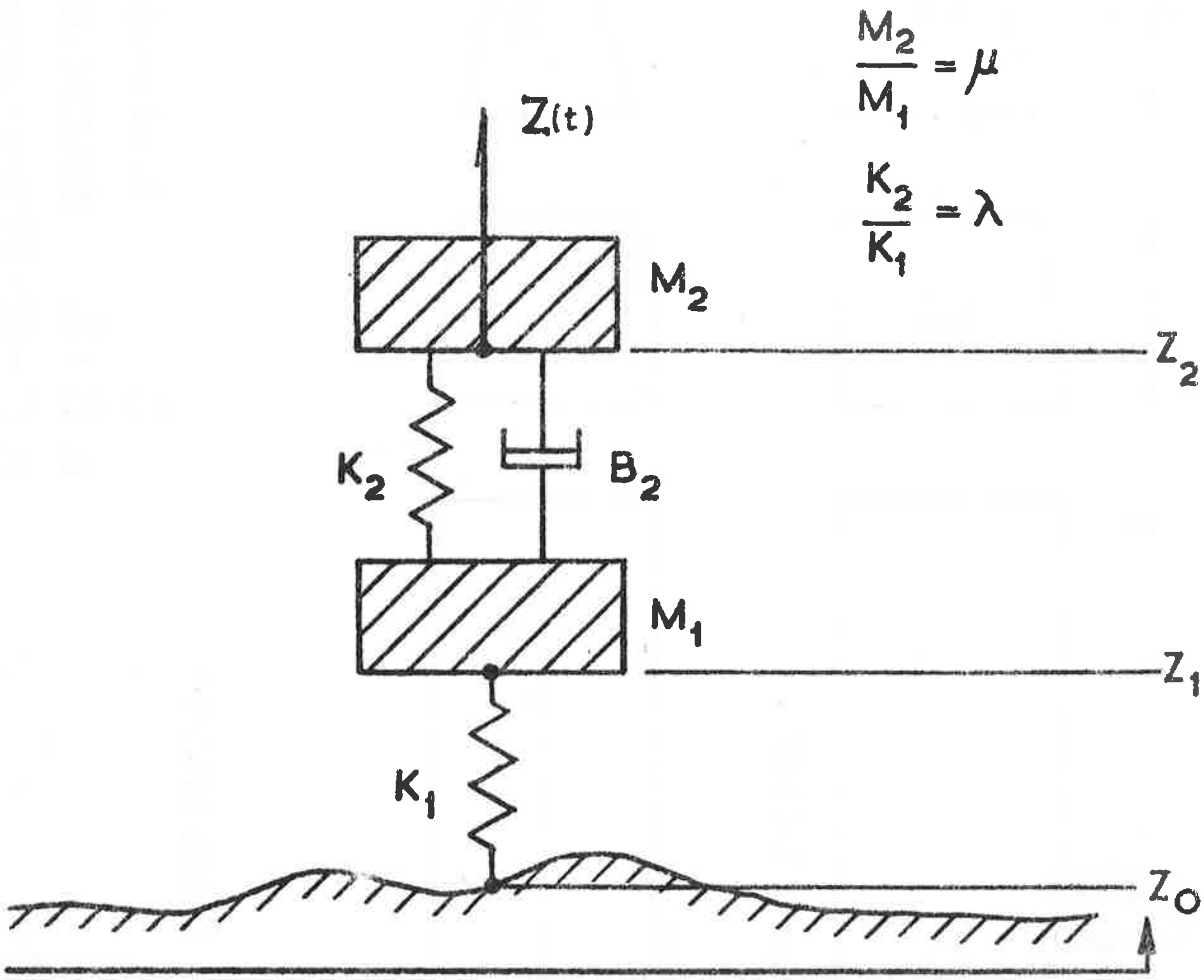


FIG. 6 SCHEMATIC OF SECONDARY SUSPENSION.

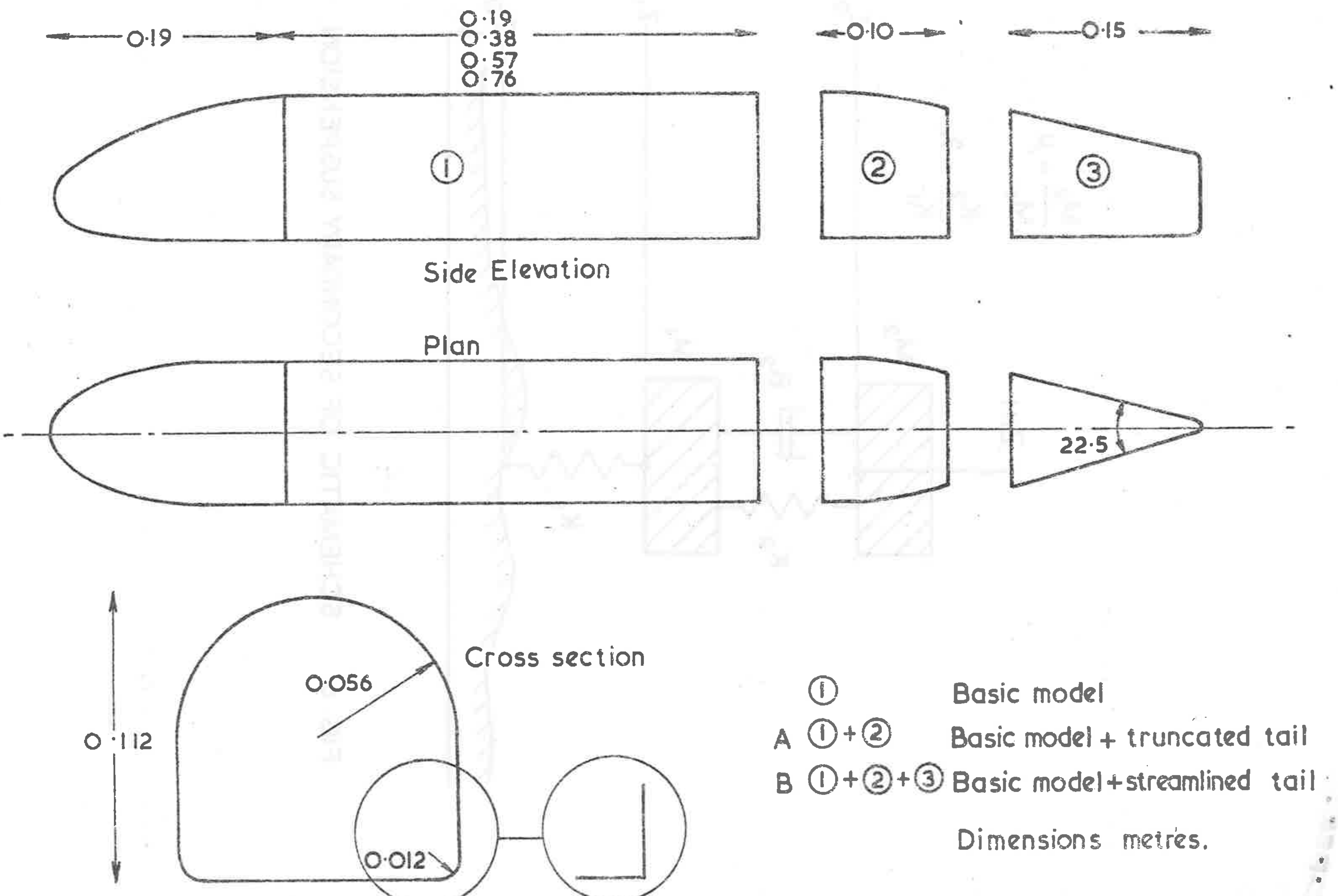


FIG. 7 WIND TUNNEL MODE

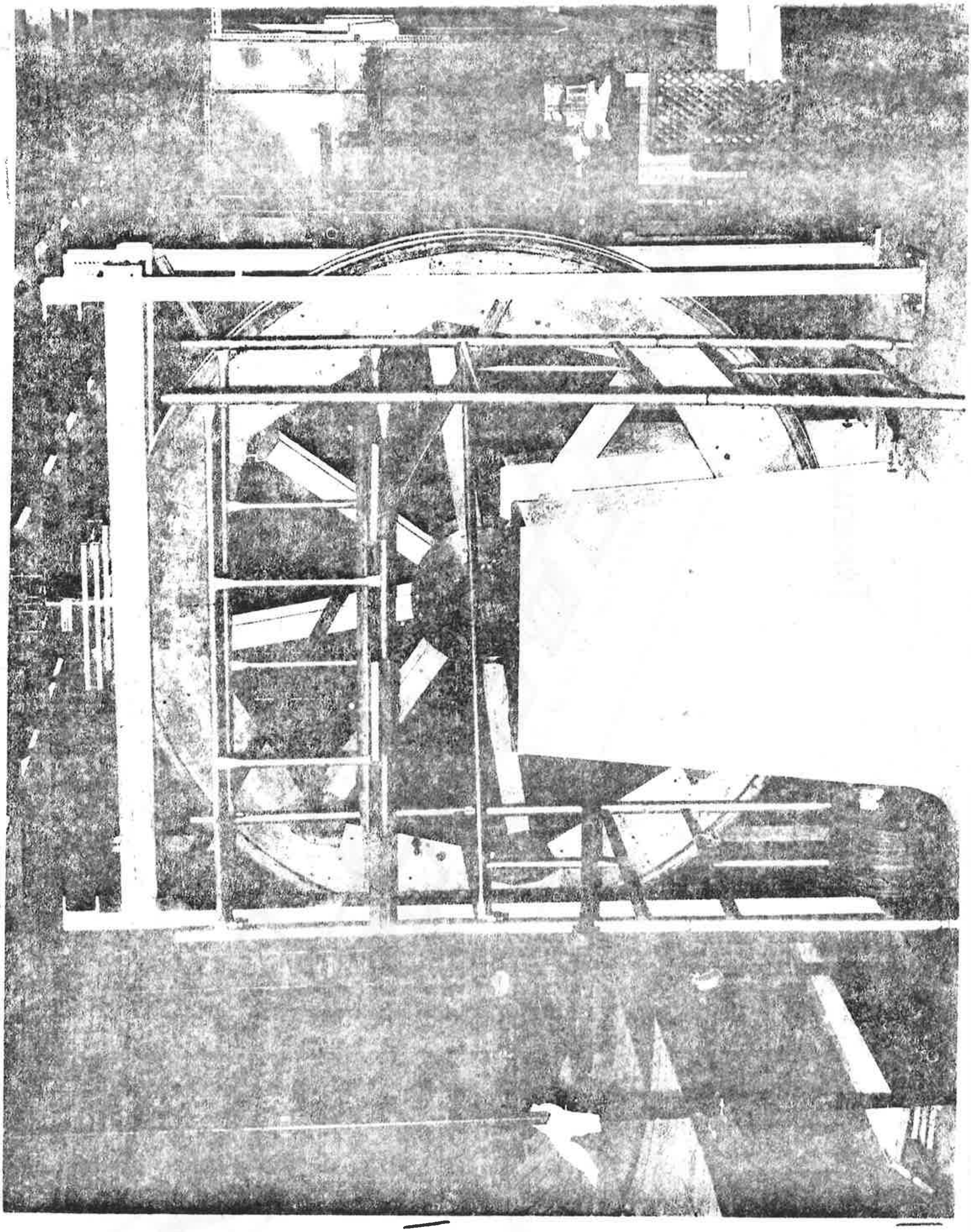


FIG. 8. Test Wheel.

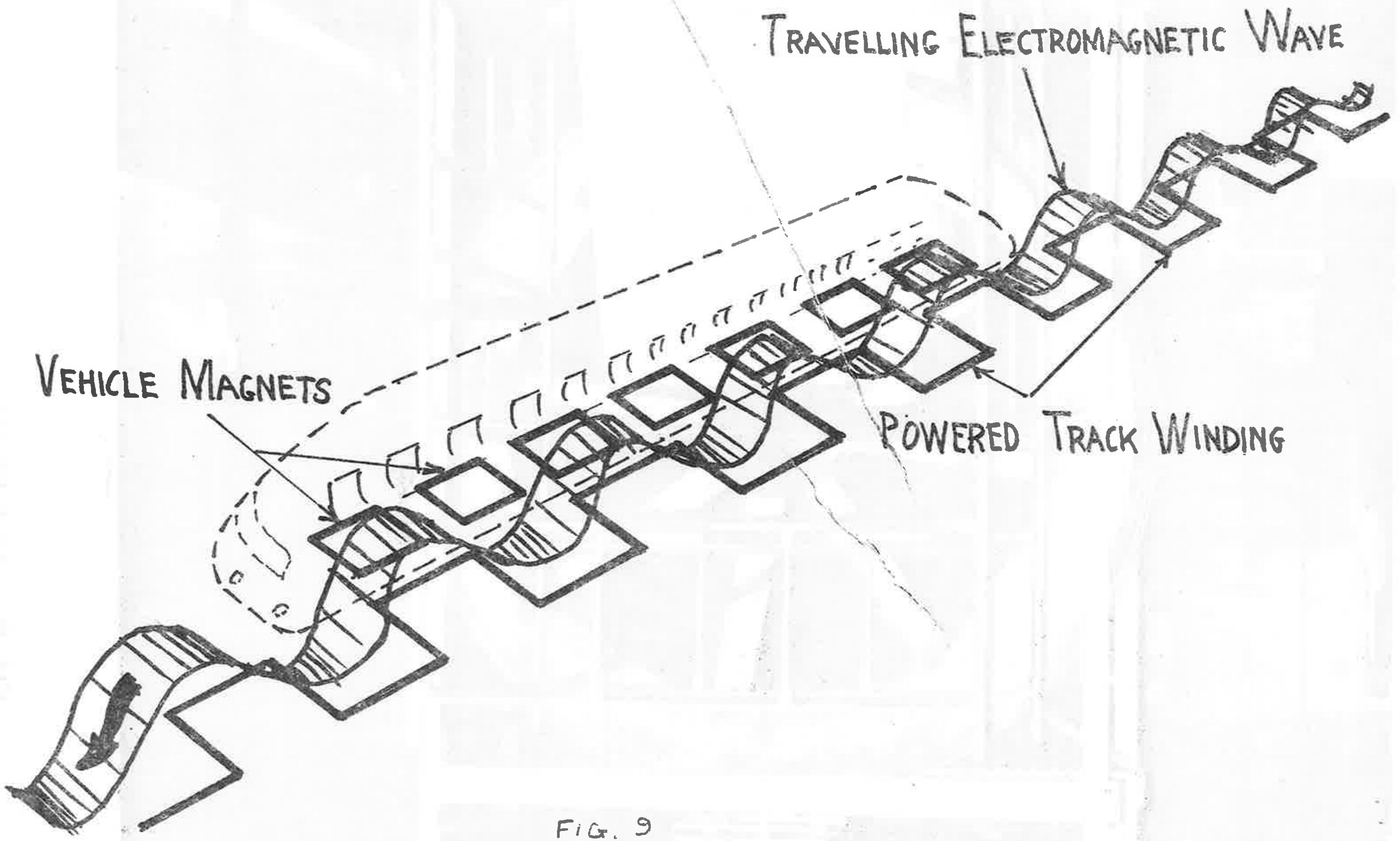


FIG. 9

LINEAR SYNCHRONOUS MOTOR

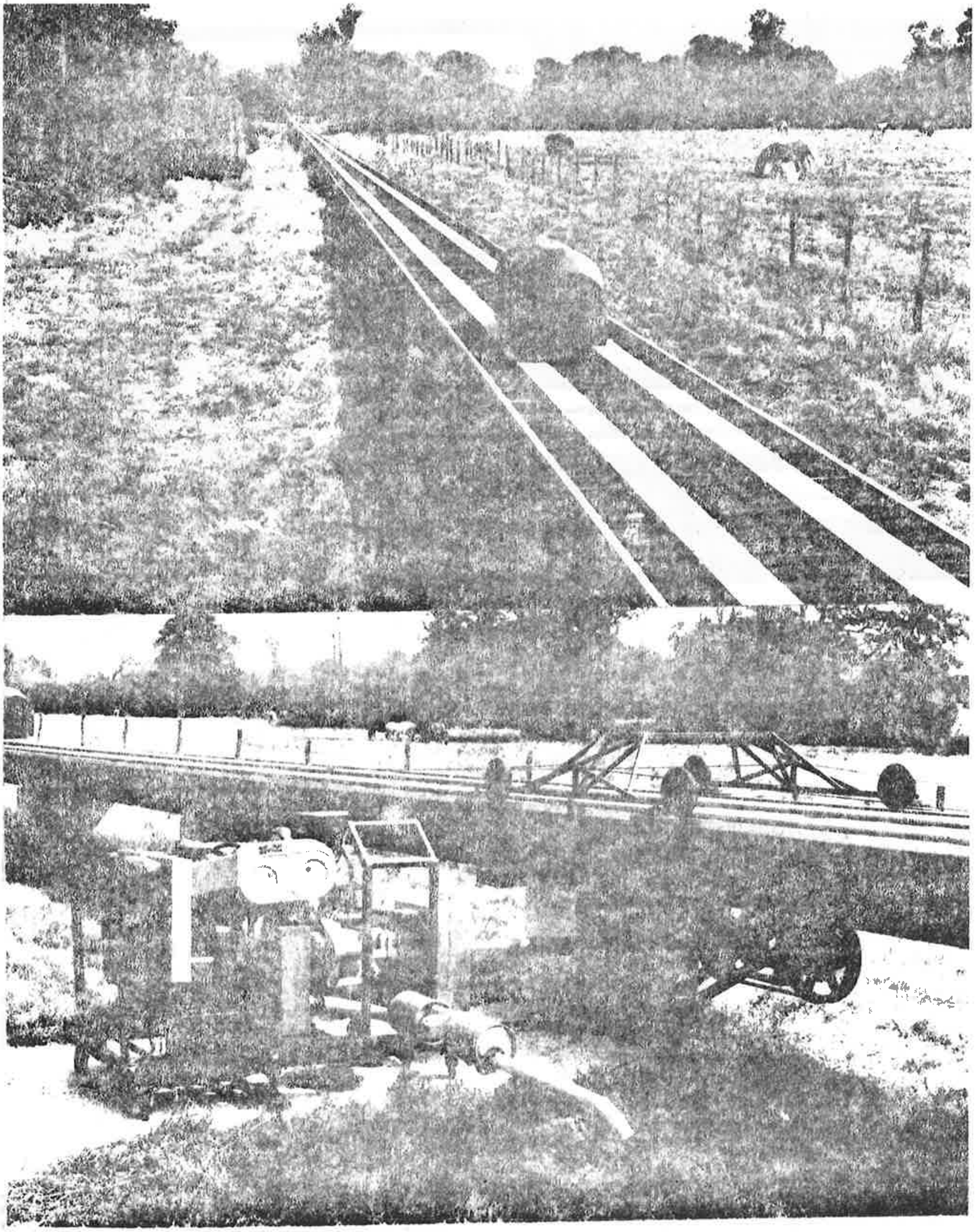


FIG. 10 TEST TRACK

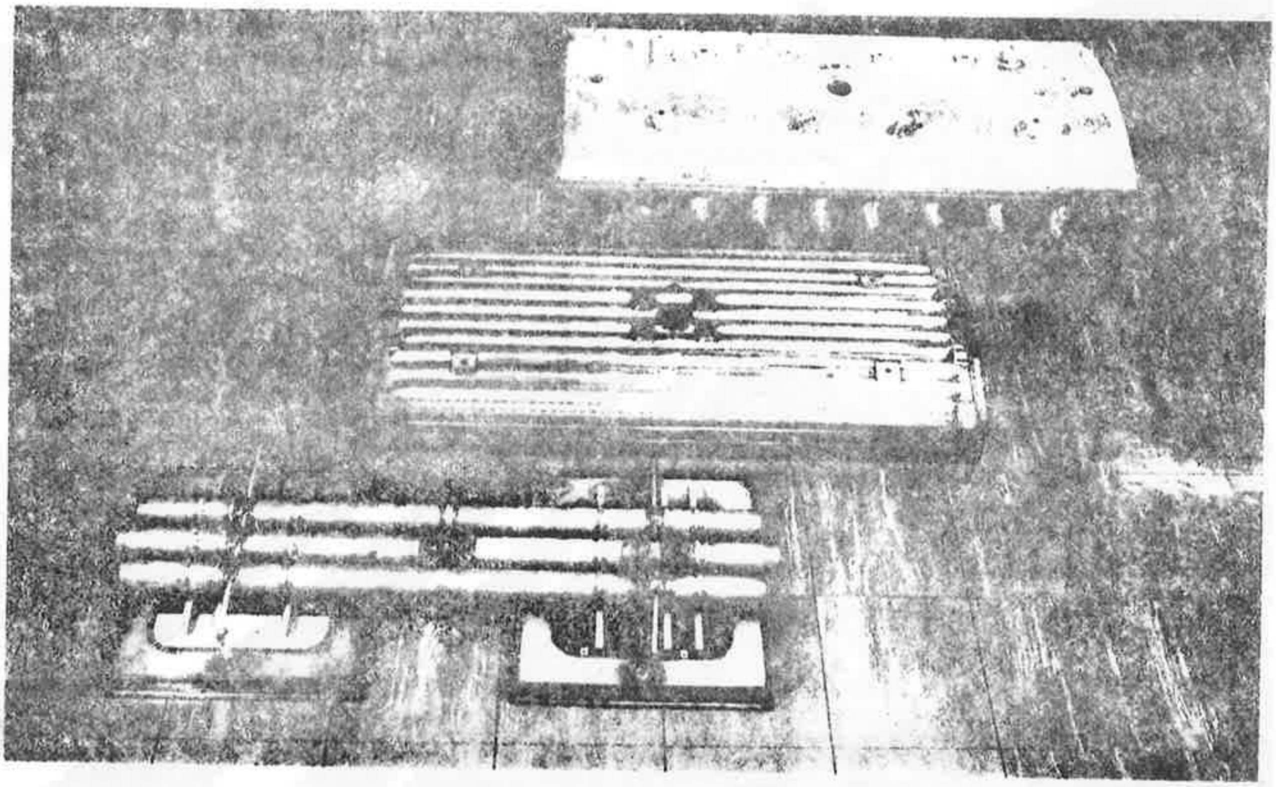


FIG. 11. Cryostat Assembly.

Table 1 Preliminary Guideway Designs

	'Infinite' Sheet	Channel'	Canadian 'Null Flux' Guidance	'Split' Guideway	
Conductor Thickness	15	15	10	15	mm
Levitation Height	300	300	220	300	mm
Coil Width:	0.5	0.5	0.3	–	m
Length:	3.0	3.0	1.0	1.5	m
Track Conductor Width (each, of two)	1100	1200	800	550	mm
Channel depth	–	600	–	–	mm
lateral gap	–	300	–	–	mm
Split Track Gap	–	–	–	1250	mm
Lift/Drag at 300 mph (allows for edge effects)	38	24	~ 22	~ 20	
Guidance/Lift at 30 mm lateral displacement	0	0.23	0.1	0.1–0.2	
Total Conductor Mass	89	145	54	45	tonne/km

Table 2 3m Test Wheel Parameters

Diameter	3 m
Rim Width	305 mm
Max. Rotational Speed	287 r.p.m.
Max. Peripheral Speed	45 m/s
Max. Peripheral Acceleration	0.4 g
Max. Power	65 kW
Wheel Mass	500 kg
Moment of Inertia	1100 kg m^2
Max. Kinetic Energy	495 kJ

Table 3 Characteristics of the Superconducting Coil

Conductor	
Type	Multifilamentary core wire
Material	Nb-Ti-IMI Niomax FMA61/33
Filament diameter	.028 mm
Wire diameter	0.33 mm
Copper/superconductor ratio	1.35:1
Coil	
Number	1
Dimension (square)	130 mm
Cross section	15 x 15 mm
Excitation mode	Persistent current
Short sample current	90A
Quench current	50A
Operating current	35A
Excitation	3.7×10^4 A-turns
Overall current density	160 A mm^{-2}
Field	
Centre	10.43 mT/A
79 mm below centre	3.37 mT/A
Winding resistance at 20°C	157 Ω
Inductance	132 mh
Stored energy	80 J

Table 4 Characteristics of the Superconducting Coils

Conductor:	
Type	Simple core wire
Material	Nb-Ti-IMI Niomax S20/40
Core diameter	0.20 mm
Wire diameter	0.40 mm
Copper/Superconductor ratio	3:1
Coils:	
Number	2
Separation (centre to centre)	790 mm
Dimensions (square)	395 mm
Cross-section	25 x 55 mm
Excitation mode	persistent current (5.2.3)
Minimum propagating current (estimated)	49A
Current	36.2A
Excitation per coil	2×10^5 A-turns
Overall current density	140 A mm^{-2}
Field:	
Centre	0.58 T
80 mm below centre	0.47 T
Change due to presence of second coil	$\pm$ 0.025 T
Maximum at winding	2.1 T
Winding resistance at 20^oC	1420 Ω
Inductance, per coil	23 H
Stored energy, per coil	15 kJ

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