EXPERIMENTAL STUDIES ON MAGNETICALLY SUSPENDED HIGH SPEED TRAINS USING LARGE SUPERCONDUCTING MAGNETS

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Abstract

In order to study the behaviour of a superconducting magnet used for a magnetically suspended high-speed train, large superconducting magnets of 0. 3 m x 1. 2 m were constructed. The maximum field was 27 kG at the designed operating current of 500 A. The cool-down characteristics and the field on and around the superconducting magnets were studied.

The electromagnetic forces acting on the superconducting magnets were determined using a "static levitation experiment" facility. In the static test, the rigidity of the cryostats against the lift and transverse forces acting on the superconducting coils inside the cryostats were tested. The superconducting magnet was levitated gradually from 3 cm to 6. 5 cm high above the ground coil by increasing current of the ground coil. The critical characteristics of the transverse stabilization was revealed in this experiment.

The dynamic tests using a disc track of 3. 1 m in diameter which had twelve sets of the ground coil and the stabilizer coil of 0. 3 m x 0. 6 m were also performed. The disc track rotated up to the rim speed of 120 km/hr to the fixed superconducting magnet. The lift and drag forces were simultaneously recorded on a two-pen recorder, and their perturbations due to the consecutive structure of the track and the suspension mechanism of the superconducting magnet were also studied. The induced currents in the track coils were measured and compared with the results from the theoretical study on a coil-track system. The sheet track of the aluminum sheets of 10 mm and 30 mm thick were also studied using the rotating disc.

1. Introduction

In order to study characteristics and behaviour of a superconducting magnet used for a magnetically suspended high-speed train, large superconducting magnets of 0. 3 m x 1. 2 m were constructed. The cross-sectional areas of the coils were 8 x 10 cm^2 and 5 x 8 cm^2, and the maximum field was 27 kG at the designed operating current of 500 A.

The cool-down characteristics and the field on and around the superconducting magnets were studied. The evaporation rate of liquid helium was 5 ~ 8 liters/hr in spite of the short height of the superconducting magnets, of 55 cm.

The electromagnetic forces acting on the superconducting magnets were determined using a "static levitation experiment" facility in which the superconducting magnet was set above the model ground coils involving a stabilizer coil. In the static test, the rigidity of the cryostats against the lift and transverse forces acting on the superconducting coils inside the cryostats were also tested. The superconducting magnet was levitated gradually from 3 cm to 6. 5 cm high above the ground coil by increasing current of the ground coil. The critical characteristics of the transverse stabilization was revealed in this experiment.

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The induced currents in the track coils were measured and compared with the results from the theoretical study on a coil-track system. The effects of the ac components of the field due to the discrete structure of the track on the thermal insulation of the cryostat and the superconductivity were studied using shielding plates of copper.

The sheet tracks of the aluminum sheets of 10 mm and 30 mm thick were also studied using the rotating disc.

2. Superconducting Magnets

2-1 Dimensions Chosen for a Model Superconducting Magnet

The net suspension height is assumed to be

7–10 cm at equilibrium vehicle position. The electric current of the superconducting magnet is the order of 10^5 A for levitating a 30 ton vehicle, for example. If the current of a superconductor is assumed to be 500– 1,000 A, the coil has some hundred turns of winding. For such a conductor, if the commercially available fine filamentary superconducting wire is used, the cross-sectional area of this coil will be the order of 10 cm^2.

If the characteristics length of the order of 1 m is chosen for a model superconducting magnet as compared with the real vehicle dimension, the dimension 7– 10 cm would be possible as a dimension between the center of the winding and the surface of the cryostat bottom which face to the ground coil array, containing the radiation shielding layers as the inner structure of the cryostat. The coil dimensions of 1. 2 m long and 0. 3 m wide measured to the center of the winding was chosen as a result of the coil configuration studies of the levitation characteristics.1)

2-2 Members for Transmitting Lift and Transverse Forces

The structure for transmitting forces from the superconducting coil in the liquid helium bath to the vehicle body of room temperature, has to support the weights of the passengers, the vehicle and other additional equipment. At the same time, it is necessary for the structure to have the dimensions through which the heat leak to the liquid helium bath has to be kept at a minimum.

Two requirements mentioned above contradict each others at the points of the rigid structure for supporting heavy weight and the small cross-section for minimizing heat transfer through the structural members. In the case of the magnet reported here as a way of transmitting forces from magnet windings to the part of room temperature, the electromagnetic force (lift) acting on the entire part of the windings was held with the coil former. And the force on the former was held and transmitted concentrically with the four columns to the part of room temperature.

The columns had the basically same structures as the upper part of a cylindrical dewar for experiments of physics, and served as the access funnels, through which piping for introducing liquid helium and outlet pipes of vaporized gas helium, lead wires for sending temperature and magnetic flux around the windings, and the current leads etc. were introduced into the helium bath. The structure of one of the four columns is shown in Figure 1. As can be seen in this figure, the force transmitting member was the metal cylinder penetrating directly from the region of 4. 2°K to the room temperature region. The distribution of various pipings, as described afterwards, was determined after considerations of design of the cool-down process. In our model superconducting magnet, the lift was transmitted to the upper flange of the outer vacuum vessel. In other words, the superconducting coil was hung from the upper flange when no electromagnetic force acted. For the horizontal components of the force: the transverse or driving forces, the coil was fixed with the thin rods of stainless steel, to the side wall of the outer vessel. This way of fixing the superconducting coil was already tested and reported when the 10 kVA disc type homopolar superconducting generator was developed.

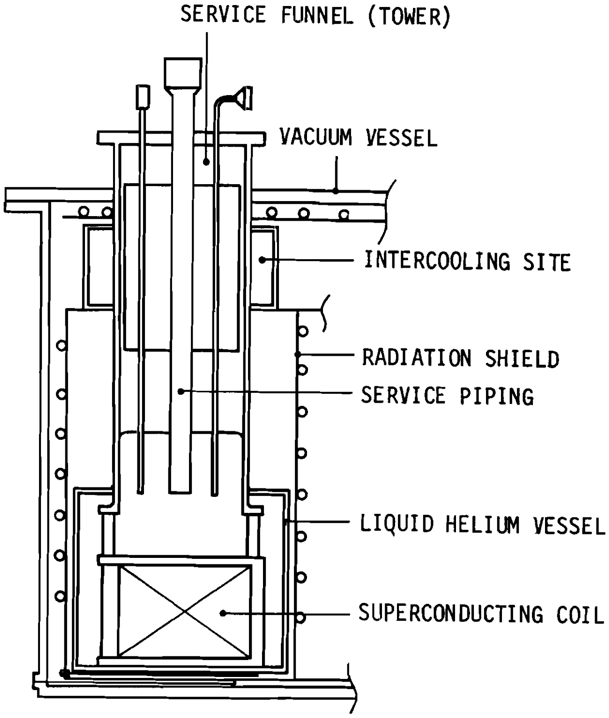

Fig. 1

2-3 Heat Leak and Heat Insulation

Sources of the heat leak into the liquid helium bath are divided into two groups:

(1) One due to the structure of the cryostat.
(2) One due to the performance suspending the vehicle.

The second contains, for examples, eddy current losses in the various layers of the cryostat, and ac loss of the superconductor etc.

As one of the guiding philosophies of this project, to minimize the heat leak due to the cryostat structure was chosen. And using the superconducting magnet developed, the contribution of the suspended characteristics to the heat leak was studied.

The three layered structure was used as a basic cryostat structure: the outer vessel as the vacuum jacket, the radiation shield of copper of the liquid nitrogen temperature, and the inner liquid helium vessel which contained the superconducting coil.

There were many penetrations in the cryostat for supporting the superconducting coil and the liquid helium vessel. Therefore, for simplicity, the multilayered radiation shield was not used in this model. In order to minimize heat leak through the penetrations, especially through the four columns, various piping and the current leads, liquid nitrogen which circulated over the radiation shield was used, so that the temperature of the heat source to the helium bath was fixed to 77°K of liquid nitrogen. Additionally, the cold helium gas vaporized was also utilized by designing paths of vaporizing gas with good contact with the penetration surfaces, as the method of designing large current leads. The resulting structure is shown schematically in Figure 2.

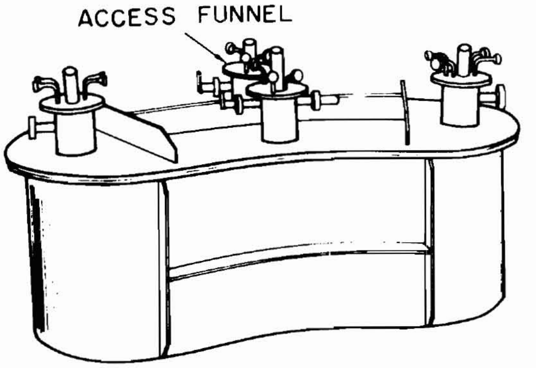

Fig. 2

2-4 The Shape and the Weights of the Model Superconducting Magnets

In the last stage of the design, the method of experiments was taken into the considerations, in which a rotating disc track was used for studying performances of the model superconducting magnets. The twelve track coils and the stabilizer coils were arranged around the rim of the disc, and the model superconducting magnet was fixed over the track, as shown in Figure 3. The maximum rim speed was 120 km/hr, and it was planned for study to be extended to the region where the asymptotic trend in the lift- and drag-velocity characteristics already appeared. The diameter of 3.1 m of the rotating disc was chosen as a largest one which could be made from ERP at the maximum rim speed. The maximum speed was 100 km/hr at the center of the track.

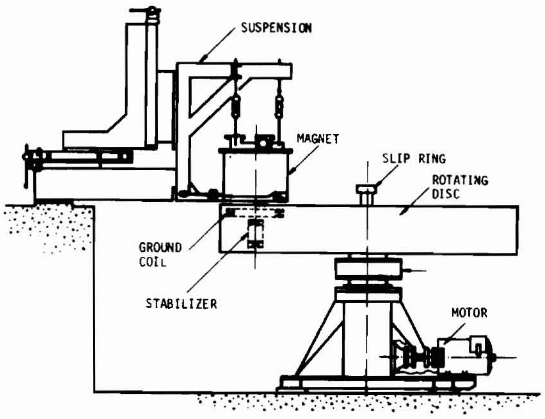

Fig. 3

The superconducting coil had a modified race-track shape in order to fit the motion of the track coils, and a curvature of 1.25 m at the center of the coil. One of the problems for designing the model superconducting magnet was to minimize the distance between the superconducting coil and the track coils in the disc, therefore the distances between the surfaces of the bottom or the sidewall of the outer vessel and the superconducting winding must be as thin as possible. This resulted in the flat bottom and the arced shape of the outer vessel as shown in Figure 4. The large flat metal plate of the bottom must be thick and heavy in order to suffer

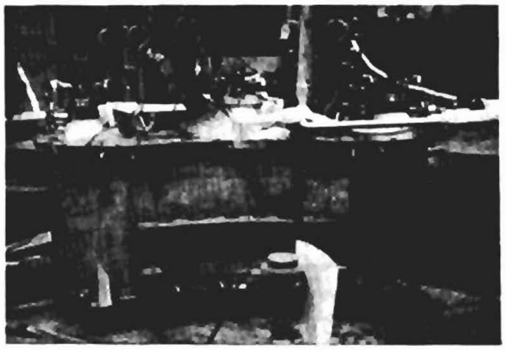

Fig. 4

atmospheric pressure, resulting in the heavy superconducting magnet. This difficulty was avoided by using a reinforcing ribs and the weights of the superconducting magnets realized were 748 and 675 kg with the stainless steel outer vessels and 625 and 555 kg with the aluminum alloy outer vessels. Afterwards, the waved side wall as shown in Figure 5 was tested to be useful in decreasing weight of the magnets. As shown in Table 1, the large part of the weight of the magnet was occupied by the weight of the outer vessel. This was due to the designing philosophy which intended that the outer vessel must suffer inside pressure which might develop when the quench of the magnet might result in breakdown of the liquid helium vessel. If releasing this requirement, the outer vessel would be much lighter. The superconducting magnet for a null flux suspension vehicle is now under construction along this line. The difference of the weights of the model superconducting magnets was due to the choice of the superconducting wires. As already mentioned in the previous report,2) the superconducting wires were the CST-8 and the multifilamentary wire IMI FM C 361/142. The copper ratios were 12: 1 and 2: 1, respectively.

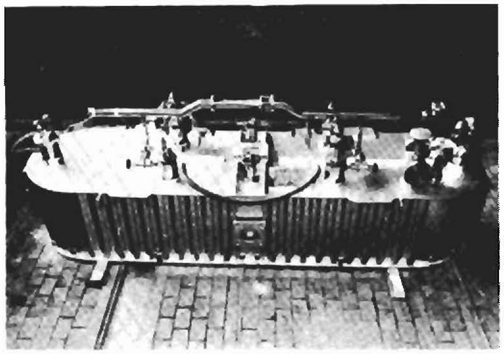

Fig. 5

Table 1

Vacuum Vessel	340 kg (SUS)
	215 kg (Al)
Radiation Shield	80 kg
Liquid Helium Bath	70 kg
Former	45 kg (IMI wire)
	56 kg (CST-8)
Wire and others	140 kg (IMI wire)
	192 kg (CST-8)
Total	675 kg (IMI wire)
	748 kg (CST-8)

2-5 Cool-down System and the Towers

The cool-down process and the injection of liquid helium to the short height, expanded type cryostat such as a vehicle suspension magnet necessitate the different procedure from ones for the usual cylindrical dewar. As a matter of fact, for immersing the superconducting coil with liquid helium which is delivered from the outlet as small as 10 mm in diameter of the transfer tube into the liquid helium vessel, a deep consideration for designing a cool-down process and utilizing vaporized cold helium gas must be needed. This problem was solved by proper design of distribution of the service pipings to the four towers situated at the positions shown in Figure 2.

The penetrations to cool-down and operate the superconducting magnets, and for measurement, are as followings:

(1) Inlets of cold gas for cool-down,
(2) Outlets of gas used for cool-down,
(3) Inlets for injection of liquid helium,
(4) Outlets for vaporized helium gas,
(5) Pipes for guiding the liquid level sensors and the lead wires from the temperature and magnetic flux sensors,
(6) Current leads for energizing the superconducting coil,
(7) Operation levers or leads of a persistent current switch,
(8) Piping for pressure gauges and for rupture discs,
(9) Piping for controlling pressures at various positions of an expanded vessel, and
(10) Piping or openings on pipes for avoiding undesirable thermal oscillation which causes anomalous heat leak to liquid helium.

A piping can share other functions at the same time. Distribution of the functional pipings on the towers of the model superconducting magnet is shown schematically in Figure 6.

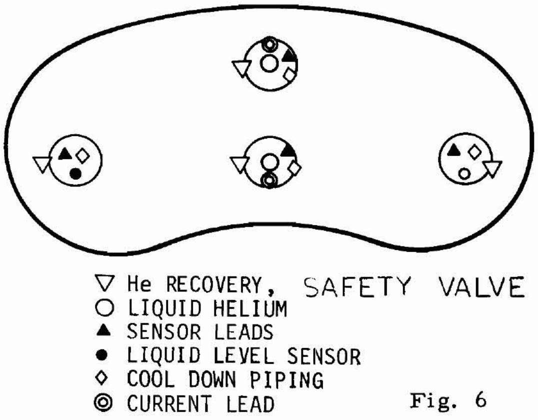

Fig. 6

Operation of opening or shutting the valves of the helium gas recovery pipes and the releasing pipes were done so that the cool-down process progressed effectively, observing the elapses of temperatures of the various parts of the coil and vessel. When the current leads were used, the flow rate of the helium gas through the current leads were increased intentionally by operation of valves.

2-6 The Superconducting Wires, Coils and the Persistent Current Switch

The superconducting wires used were a multistrand cable CST-8 which was manufactured by Toshiba, and Showa wire and Cable Co. and IMI FM C361/142 multifilamentary strand cable. Their operating currents were both 500 A at about 3T. The number of windings were both 400 turns and an example of the cross-section is given in Figure 7. The solenoid winding had the vertical channel of 1 mm for cooling. In order to prevent catastrophic quenching of the superconductor due to small slip and motion of the winding, the precaution was taken in the design and winding of the modified race-track coil which contained concaved part in the winding. To form coil, especially with IMI wire of the round cross-section, was difficult due to this concave part where the tensile force given on the wire became negative. The coil is shown in Figure 8, in which the heater on-off type persistent current switch of a capacity of 700 A can be seen.

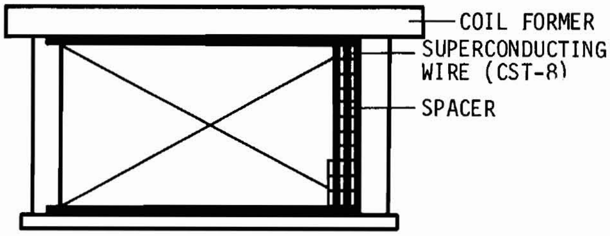

Fig. 7

Fig. 8

3. Experimental Apparatus

3-1 Cool-down System

Cool-down of the magnets was done with the No. 2 refrigerator of Toshiba Research and Development Center. From the results of experiments, it was concluded that the cool-down of the model superconducting magnet would be done easily with the system as shown in Figure 9. Therefore, the experiments hereafter were done with this system and the superconducting magnets fixed in the static or dynamic performance test facilities. In this system, the cold helium gas cooled at the liquid nitrogen temperature circulated through the liquid helium vessel to cool-down the coil to temperature 100°K. In the next stage, the superconducting coil was cooled down to 4.2°K with direct injection of liquid helium. The quantity of liquid helium for cooling-down the coil to 4.2°K was about 30 liters in the case of the CST-8 coil. An example of the temperature variations in the cool-down process is shown in Figure 10.

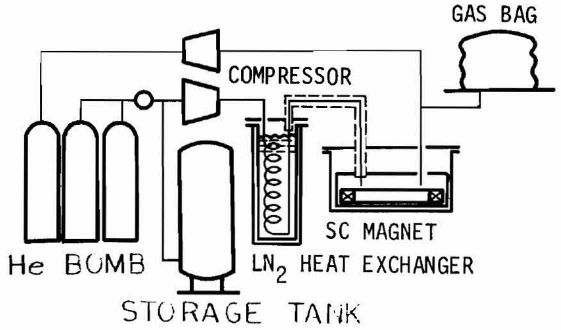

Fig. 9

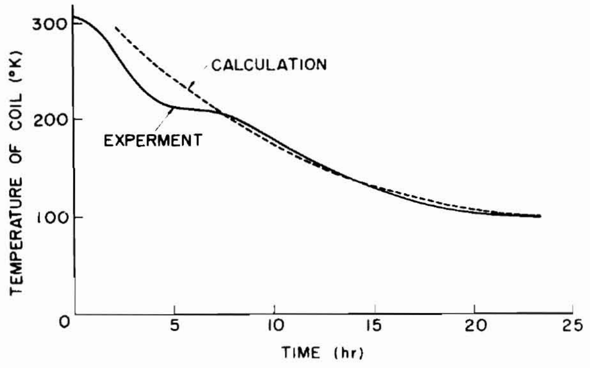

Fig. 10

The superconducting magnet was energized with current increase rates up to 10 A/sec. The helium evaporation rates in the experiments were measured to be 5 ~ 8 liters/hr according to the liquid helium levels in the helium vessel.

3-2 The Static Test Facility

In order to study effects of the static electromagnetic forces on the superconductivity, and characteristics of lift and transverse forces when the displacements were given between the centers of the superconducting coil and the model track coils, a system of the coils of the normal conductor cooled with water was constructed as shown in Figure 11, over which the test superconducting magnet was hung by ten suspending wires.

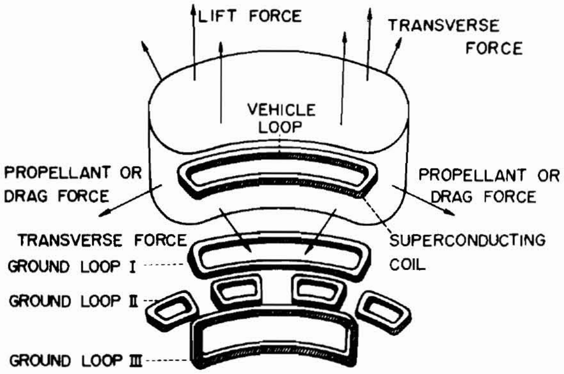

Fig. 11

The coil 1 had the same shape and dimensions as the superconducting coil and the coil 2 had the half-length of the coil 1 and the same width. The coil 3 situated vertically at the center of the coil 1 to act as a stabilizer when the transverse displacement occurred between vehicle and track. These coils all were designed to have current capacities up to one tenth of the superconducting current and the coils 1 and 2 could exert forces up to 800 kg at the designed magnet positions to the superconducting magnet.

3-3 The Dynamic Test Facility

The rotating disc track already described is shown in Figure 12 in which the track coils consisting of the horizontally and vertically situated ones. The latter was used for studying the effect of the passive stabilizer coil. When studying the sheet track, the aluminum sheets of 10 and 30 mm thick and diameters of 3. 0 m were placed on the disc. The representative values of the track coils and sheets are given in Table 2.

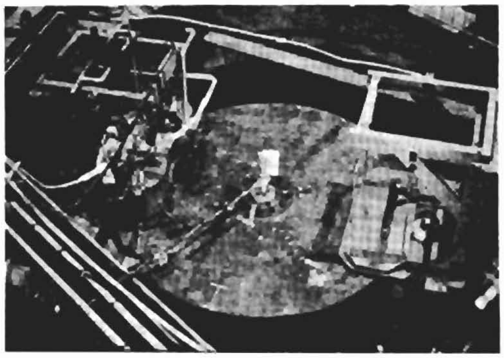

Fig. 12

Table 2

(a) Track Coil	
Size	0. 3 m width x 0. 55 m
Coil Pitch	0. 65 m
Winding	19 turns x 6 layers
Cross-section	0. 1 m x 0. 06 m high
Material	Copper (Hollow Conductor)
Inductance	7. 32 mH
Resistance	0. 1 Ω
(b) Sheet	
Size	3. 0 mφ 30 or 10 mm thick
Material	Al

3-4 Measurements

Forces such as lift, drag and transverse force, the magnetic flux on and around the magnet, induced currents in the track coils, the vaporization rate of liquid helium and the temperatures at various point in the magnet were measured.

Forces. The lift, drag and transverse forces were measured by the load-cells which were set with ten suspension wires. The outputs were provided to the y-axis of an x-y recorder through the dc amplifiers as well as to voltmeters for direct reading of the average values. One of the voltmeters showed the total lift by coupling the outputs from the four vertically suspending wires.

In the measurements, when the large forces were occurred, the coupling through the wires between the vertical and horizontal components of the forces became important and the independence of the two output readings should not be expected. To avoid such difficulties, the displacement must be restricted in a certain narrow range, or the lifts were measured without the side suspension wires. Due to the inhomogeneous distribution of the weight in the magnet and due to the improper choice of the points of the suspension wires, the precise quantitative discussions would be restricted. The drags were determined also from the input power to the disc driving motor.

Magnetic Flux. The magnetic flux on and around the superconducting coil was measured by the magnetostriction elements and the Hall elements which were set on the coil former.

The effects of the field from the track coils were studied using the search coils which were placed on the bottom of the outer vessel and on the surface of the rotating disc. The magnetic flux distributions around the superconducting magnet were also determined using a flux meter.2)

Currents Induced in the Track Coils. The currents induced in the one of the track coils were measured from voltage drops on a shunt, the output of which was extracted using a slip ring from the rotating disc. The currents induced in the stabilizer were recorded by the same method.

Temperature of the Track Coil and the Sheet. The temperature rises of the track coil and the sheet were measured by using the copper-constantan thermocouples and determined from the outlet temperature of the cooling water in the case of the coil track, of which temperature rise was ~ 1°C through experiments. The maximum temperature rise on the sheet track was ~ 50°C with 10 mm thick aluminum sheet.

4. Experimental Results

4-1 Static Tests

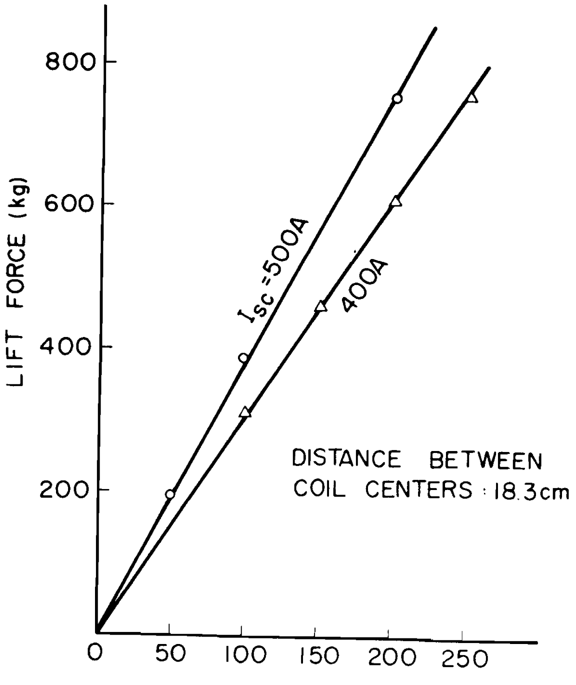

Fig. 13

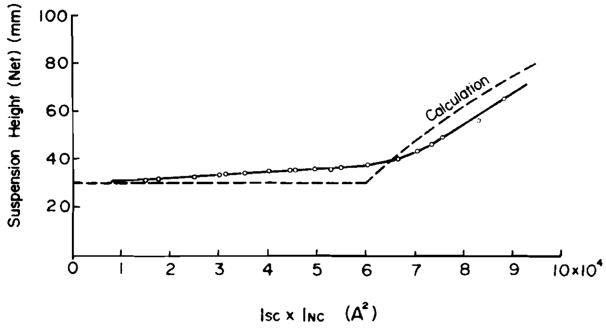

Fig. 14

Keeping the distance between the superconducting magnet of fixed current and the track coils, the current of the track coils was increased gradually, the lift was measured in the range where the lift did not exceed the weight of the superconducting magnet. In Figure 13, the lifts with the superconducting currents 400 and 500 A are shown. In this figure, the centers of the model magnet and the track were coincided. The variations of the height of the superconducting magnet were shown in Figure 14, when the current of the superconducting magnet was fixed and the current of the track coil was increased. In these experiments, in order to avoid the accident such as a magnet upset, the four counterbalances of 50 kg each through the wires were used. The suspended heights were the average values at the positions of the four counterbalances. Because the centering of the magnet and the track coil was very difficult, the magnet shifted transversely, therefore the virtual levitation of the superconducting magnet began a little earlier.

The main objects of these series of the test were to prove the stability of the superconductivity to the electromagnetic force, the rigidity of the interstructure of the superconducting magnet to the electromagnetic force which corresponded to the lift force which suspended the superconducting magnet, and to show real levitating performance. It was concluded that the experiments revealed the satisfactory results.

4-2 Dynamic Tests with the Rotating Disc Track (Coil Track)

In the dynamic tests the gap between the superconducting magnet and the disc, and the currents of the superconducting coil were initially set, then the speed of the rotating disc was increased to 100 km/hr, in the course of the speed-up the measurements of the lift and drag were done. Especially, at the speed 10, 20, 40, 60, 80 and 100 km/hr precise reading of the outputs from the various sensors were recorded. Examples of the resulting curves are given in Figure 15. Fluctuations of the forces due to the consecutive structure of the array of discrete loop of the track were also recorded. Figure 16 shows the fluctuations in the lift and drag. In this figure, the fluctuations are prominent in the lower speed region, which may be due to the resonance of the suspensions and piping for helium recovery. Afterwards these resonances were studied by exciting the resonance modes of all the structure of the experimental facility. The origin of the resonance, of course, was the consecutive structure of the track coils, in which the current as shown in Figure 17 was induced and the superposition of the contribution from the each coil resulted in the fluctuation in the lift and drag.

When the transverse displacement was given between centers of the superconducting magnet and the track coils, the transverse forces which repelled each other developed as shown in Figure 18. In this figure the results were compared when the stabilizers were open-circuited or short-circuited. Conclusively from this figure, the effects of the stabilizers were effective only at so large displacement which should not happen in the actual train.

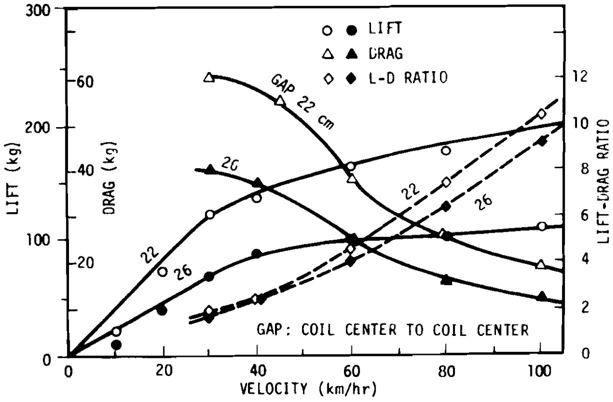

Fig. 15

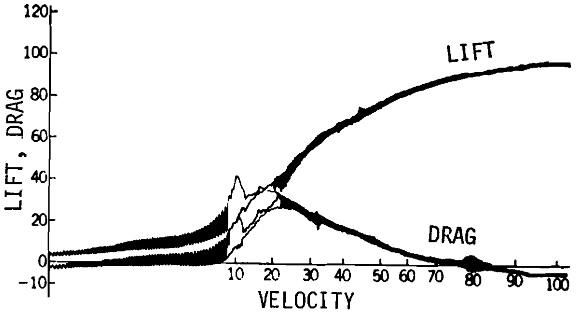

Fig. 16

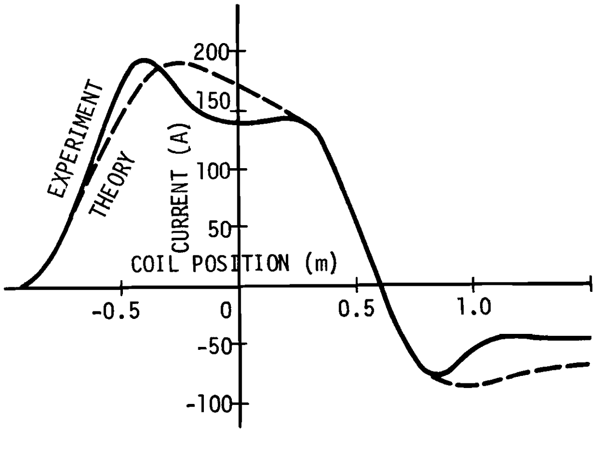

Fig. 17

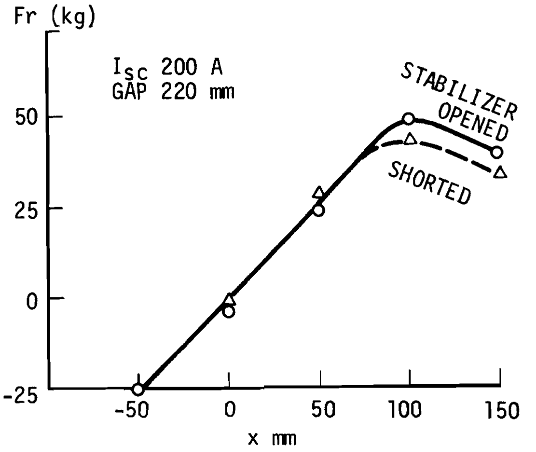

Fig. 18

4-3 Dynamic Tests (Sheet Track)

The sheets were of aluminum and 30 and 10 mm thick, and 3.0 m in diameter. The sheet placed on the rotating disc was rotated with the track coils in the disc. The experimental procedure was as same as the case of the coil track. Because this facility was designed for tests of the coil track, the driving power of the sheet disc was insufficient for the drag with the sheet track, therefore the height and the current of the superconducting coil in the sheet experiments had to be higher and smaller than in the coil track experiments. Examples of the measured lift and drag characteristics are given in Figures 19 and 20. The recorded lift and drag on the x-y recorder are shown in Figure 21.

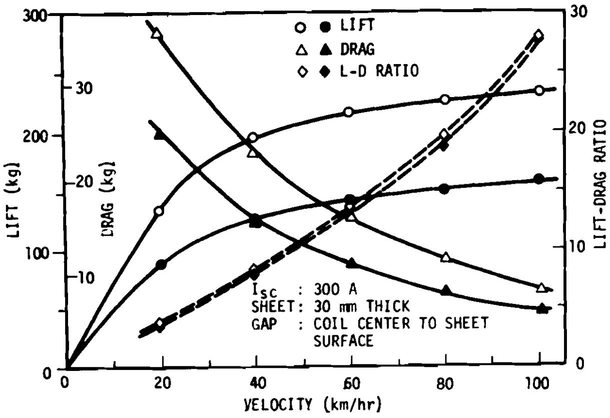

Fig. 19

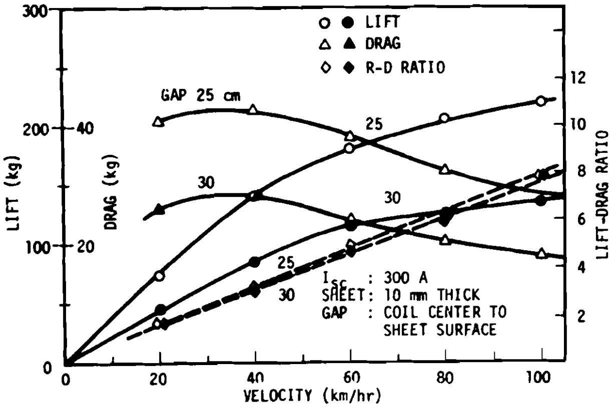

Fig. 20

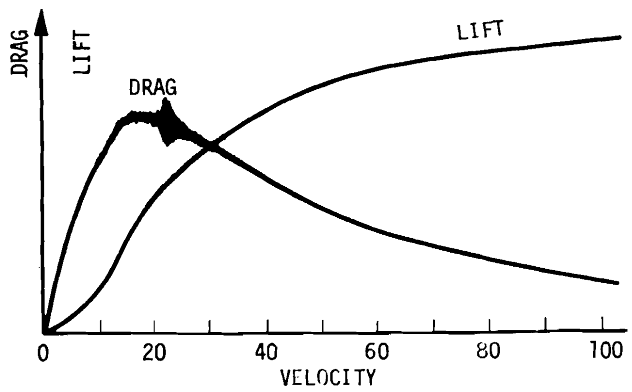

Fig. 21

It was found, in the course of the sheet experiments, that the fluctuation or the resonance oscillation of the suspension system of the superconducting magnet could not be experienced, especially with the 30 mm thick sheet. In Figure 21, however, the lift and drag have the fluctuational components, presumably due to the effects of the coils under the sheet.

5. Discussions on the Dynamic Experiments

5-1 Lift and Drag

The calculations of the levitation characteristics were done by Takano et al.[3] Their theory was based on the variation of the mutual inductance when the two rectangular coils approached and separated each other. The significance of this theory was that the theory contained always the effects of the short arrays of the vehicle superconducting magnets, and could study the edge effect of the top superconducting magnet. The results of the calculations are plotted in Figures 14 and 15. The calculated induced current in a track coil is in Figure 18, comparatively. It can be said the theory and the experiments were well coincide. The cause of the fluctuation in the experimental results in Figure 18 has not yet been clarified. The lift and drag with the sheet were calculated using the theory by Reitz et al. The calculated values always exceeded the experimental results, therefore, the theory only explains the trends of the experiments. The coils embedded in the disc affected the characteristics. The variation of the current induced in the coils in the disc were shielded by the sheet, and the shielding current in the sheet flows the opposite direction to the current induced by the flux of the superconducting magnet.

5-2 Comparison of the Coil and Sheet Tracks

Comparison of the two tracks was done using the lift-drag ratios as can be seen in Figures 15, 19 and 20. According to those figures it can be said that the difference of two system is very small.

5-3 The Transverse Force, Stability and Guidance

As can be seen in Figure 18. increasing the transverse displacement between track and the superconducting magnet, the lift decreases and the transverse force increases. The increase of the transverse force is so rapid that the lift and the transverse force become equal in the small displacement as the half width of the coils. To give the stability and guidanceability to the system, the way other than the

Powell-Danby's stabilizer must be added. The guide way in which the levitation vehicle coil play the lift and guide magnets has already been proposed.[4)]

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