

Heating phenomena in the superconducting magnet of a maglev vehicle caused by electromagnetic vibration*

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The superconducting magnet which is installed on a maglev vehicle suffers a disturbance of magnetic fluctuation from the ground coils. This magnetic disturbance has a frequency ranging from zero to several hundred hertz and is proportional to the speed of the maglev vehicle. We constructed facilities which can simulate an actual electromagnetic disturbance on the magnet during running, and carried out electromagnetic vibrating tests. It was revealed that an extreme increase of heat load on the inner vessel of the energized magnet occurred at a particular frequency. The initial amount of the heat load surpassed the capacity of the refrigerator installed in the tank of the superconducting magnets. We have investigated the causes of these phenomena and performed an experiment for confirming the effect of an improvement in a new set-up. As a result, we could broadly identify three factors of heating and now there are good prospects of largely suppressing the heating by reducing the disturbance through the folded arrangement of the ground coils and structural improvement of the magnet. This paper describes the heating phenomena of a magnet under an electromagnetic disturbance and an improvement for suppressing them as well as the historical background of maglev development. © 1997 Elsevier Science Ltd.

Keywords: electromagnetic disturbance; heat load; inner vessel; superconducting magnet; magnet structure

The superconducting magnet on a maglev vehicle is different from those on ground facilities in that it is light in weight, receives various disturbances in high speed running and may be exposed to rain or wind. This paper describes heating phenomena in the superconducting magnet vibrated by the disturbance of magnetic fluctuation from the ground coils, and discusses countermeasures in connection with the history of the development of Japanese maglev.

Concepts of maglev and superconducting magnet

Figure 1 shows the concept of maglev. The propulsion (and guidance) coils and levitation coils are arranged on the guideway, and the superconducting magnets are installed on the maglev vehicle. The substation supplies alternating cur-

rent in three phases through the propulsion coils and propels the vehicle. Currents are induced in the levitation coils when the on-board superconducting magnet passes over them and repulsive forces are generated between them.

The superconducting magnet installed on a maglev vehicle suffers periodic magnetic fluctuations due to the induced currents in the ground coils which are arranged at intervals. This magnetic fluctuation has a frequency ranging from zero to several hundred hertz which is proportional to the speed of the maglev vehicle. These electromagnetic disturbances have various influences on the superconducting magnet.

The on-board superconducting magnet shown in Figure 2 comprises a cylindrical tank in the upper part which contains liquid helium and the coil units in the rectangular-shaped lower part. The superconducting coil is fixed inside the container, the inner vessel, and immersed in liquid helium holding the state of superconductivity. The radiation shield plate envelops the inner vessel and is maintained at the temperature of liquid nitrogen. The outer vessel houses all these structures in a vacuum. The on-board refrigerator

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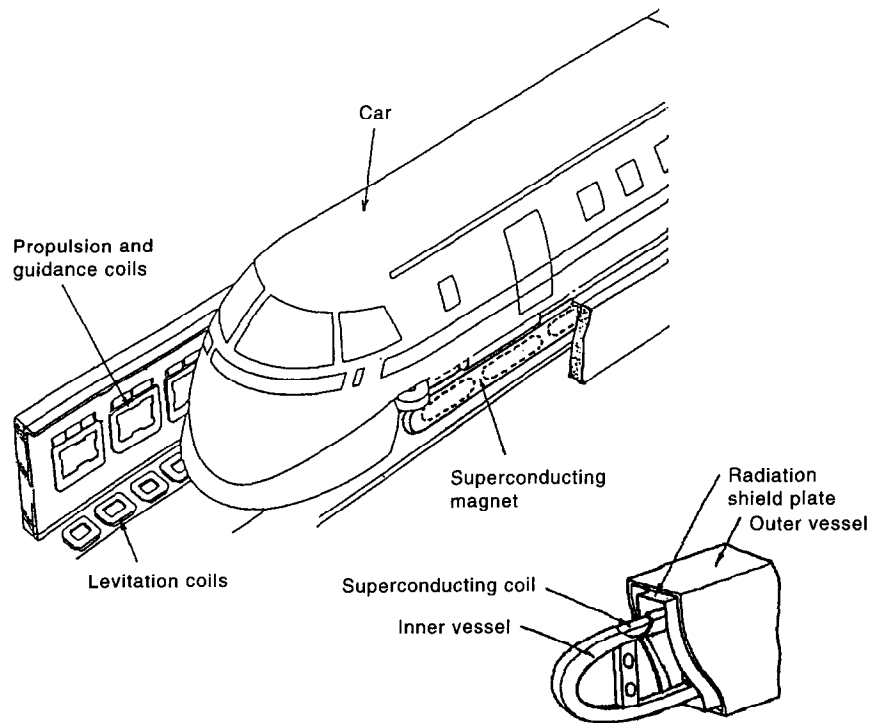


Figure 1 Concept of maglev

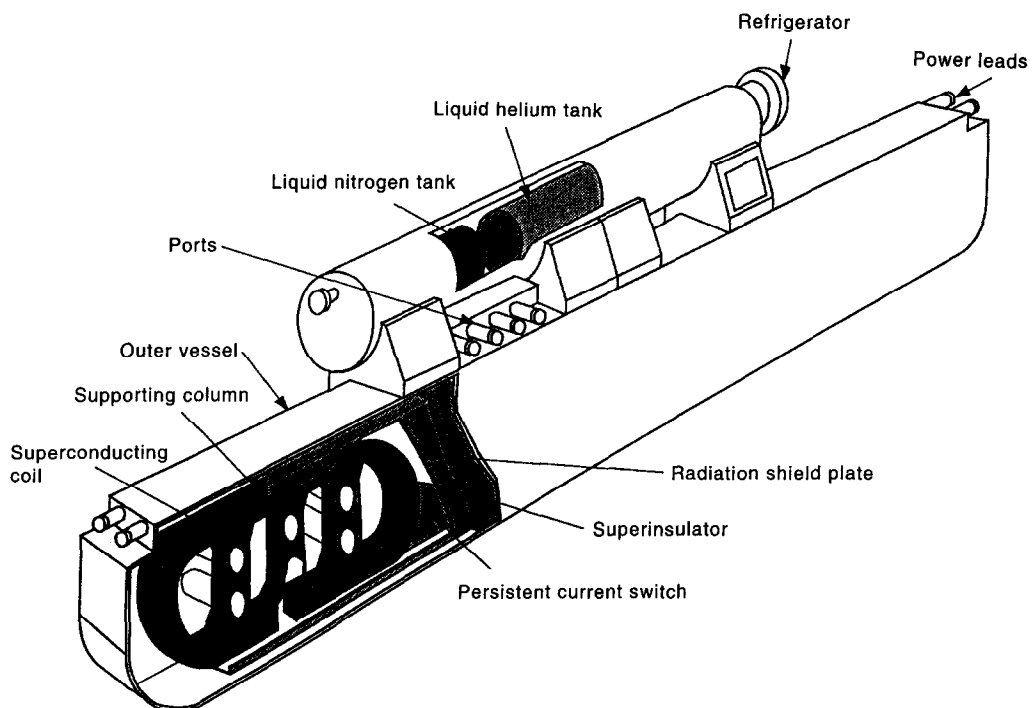


Figure 2 Schematic structure of superconducting magnet

is installed at the end of the liquid helium tank and plays the role of re-liquefying the evaporated gas in the magnet.

Concept of electromagnetic vibration test

Electromagnetic vibration simulator

The influence which the above-mentioned electromagnetic disturbances have on the superconducting magnet has been discussed from the initial stages of the development of maglev. The facilities which can simulate these real disturb-

ances on the magnet while running are called the 'electromagnetic vibration simulator', an unfamiliar name. The exciting coils which simulate the real ground coils are set opposite to the superconducting magnets mounted on both sides of a truck.

The exciting coils are arranged at one-third of a pole pitch in the superconducting magnet when the real propulsion ground coils are in single arrangement, as shown in Figure 3 (this arrangement forms the second wave configuration in space). In reality the arrangement of exciting coils is more complicated because of the folded arrange-

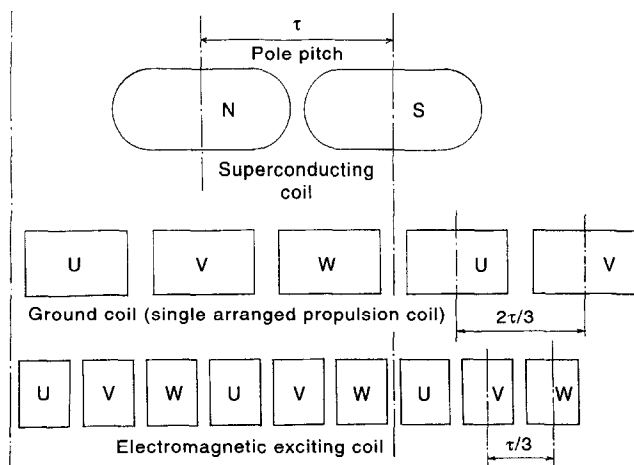


Figure 3 Arrangement of exciting coils

ment of the propulsion coils adopted in order to reduce the fluctuation on the magnet (this arrangement forms the fifth wave configuration in space). The magnetic variation in high harmonics is discussed in Appendix A.

History of the electromagnetic vibration tests

Table 1 gives a brief history of the electromagnetic vibration tests. The first vibration test was executed in 1981 using the magnet for the Miyazaki Test Track with a pole pitch of 2.1 m. We have never executed the test in detail before 1985 and have only estimated the heat loss on a stationary inner vessel due to the eddy current induced by the simple alternating magnetic field. This loss due to the eddy current induced by the magnetic fluctuation on the

inner vessel, whose penetration the outer vessel and aluminium radiation shield plate could not prevent, is reduced at higher frequencies. We have considered that the heat loss in the energized superconducting magnet is the same quantity as the AC loss in the de-energized state.

In the second half of the 1980s the superconducting magnet often quenched in running at the Miyazaki Test Track. So in 1986 and 1987 we performed the electromagnetic vibration tests in order to investigate the causes of quenching and to estimate how much the vibrating magnet suffers heat loss in long-term service. We could not see any noticeable evaporation of liquid helium because of the lower exciting frequency and the restriction of the test time due to a temperature rise of the exciting ground coils. We expected to be able to easily decrease the vibration of the magnet by reinforcing the frame of the truck and did not regard the heating phenomena in the vibrating magnet as a serious matter.

Heating phenomena in the electromagnetic vibration test

We planned to produce a new magnet having a long pole pitch of 2.7 m and so reinforced the electromagnetic vibration simulator, the exciting ground coils and ground facilities for the power supply with regard to this new magnet. Utilizing these facilities we started regular electromagnetic vibration tests in 1988. This simulator is shown in Figure 4. The maximum frequency of an inverter supplying the current to the exciting ground coils is 170 Hz because a velocity of 500 km h⁻¹ corresponds to a frequency of 154 Hz.

We measured the outgoing evaporated volume of helium gas through the flow meter and estimated the increase of

Table 1 History of electromagnetic vibration test for superconducting magnet

Years	1981 Showa 56	82 57	85 60	86 61	87 62	88 63	89 Heisei 1	90 2	91 3	92 4	93 5
System of Maglev	Corresponding Miyazaki test track conventional arrangement of levitation coil cycloconverter (power supply)						Corresponding Yamanashi test track new arrangement of levitation coils inverter (power supply)				
Vibration simulator	Primary test drive		Stationary test at Miyazaki			Improving the simulator		RTRI			
								Three electric makers			
								JR Central (testing magnet having a single coil)			
Magnet for test				SCM having pole pitch 2.1 m corresponding Miyazaki track			SCM having pole pitch 1.35 m corresponding Yamanashi test track				
							SCM having pole pitch 2.7 m				
Exciting frequency	0~100 Hz		0~100 Hz			13.2~33.1 Hz			Simulator in RTRI 0~170 Hz		0~400 Hz
									Simulator in electric makers 0~400 Hz		

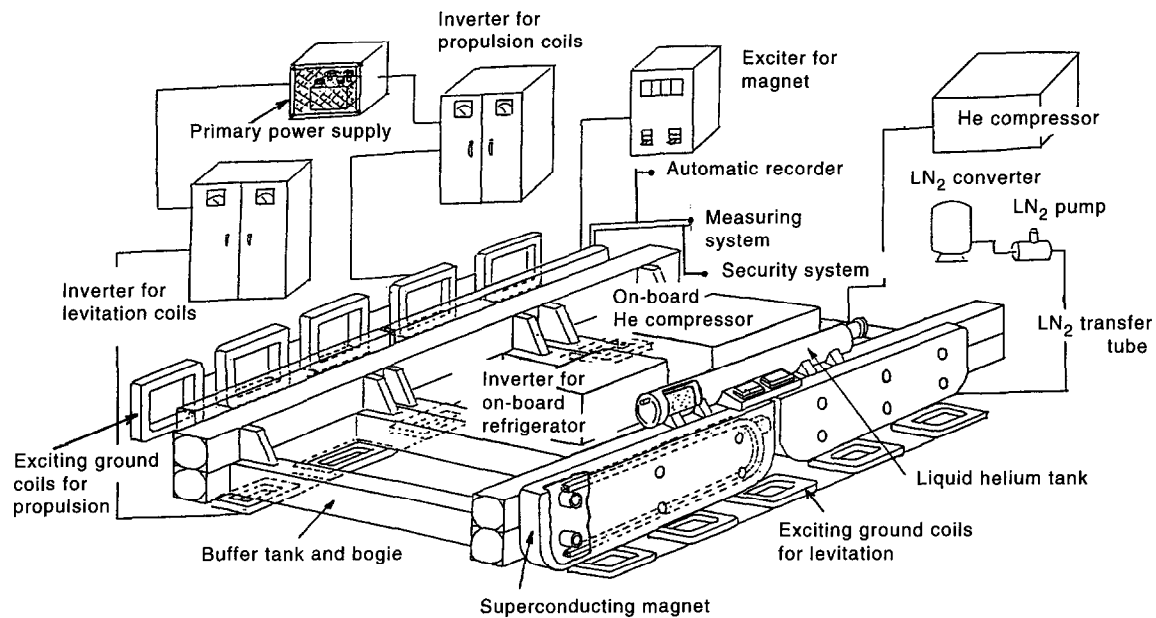


Figure 4 Electromagnetic vibration simulator

heat loss in the superconducting magnet by investigating the difference of evaporation under electromagnetic vibration and in a static state.

Results of testing. Figure 5 shows the results of electromagnetic vibration tests by supplying the current to the exciting ground coils for propulsion. A sharp peak of evaporation is recognized at a particular frequency even under a current of 20 A, one-seventh of the exciting current that causes the magnetic fluctuation on the magnet in actual running. We could not see any remarkable variation in the heat loss on the radiation shield plate.

Figure 6 shows the dynamic characteristics of the magnet at resonance (75 Hz) in relation to magnetomotive force. As shown in this figure, increment of heat load in the inner vessel varies with about the square of the mag-

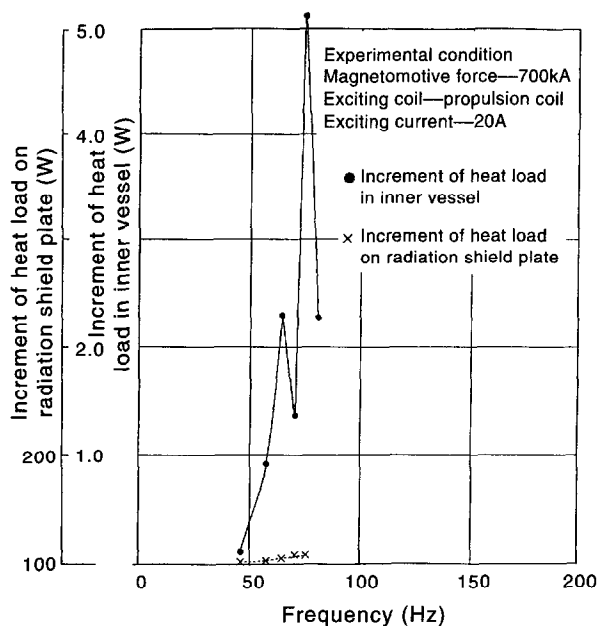


Figure 5 Characteristics of the increment of heat load versus frequency (excited by propulsion coils)

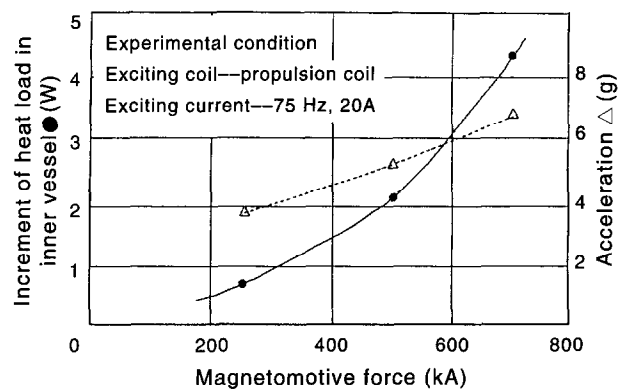


Figure 6 Increment of heat load versus magnetic force: ●, increase of evaporation; △, magnitude of vibration at the point of the load supporter column

netomotive force but the acceleration varies linearly with the force. This suggests that these phenomena depend not only upon the mechanical vibration but also upon electromagnetic factors. Investigation into the increments of heat load in the inner vessel and the radiation shield plate relating to the exciting current revealed that the heat load increases in proportion to the square of the exciting current. On the other hand, the load in the de-energized state has the tendency to decrease in higher frequency regions in both exciting cases of levitation coils and propulsion coils. It proved that the increment of the heat load in the energized state is still large compared with the one in the de-energized state.

Problem of heat occurrence. An extreme increase of heat load on the inner vessel is caused by the fluctuation of the magnetic field at a particular frequency under utilization of these facilities. These phenomena posed so serious a problem that the heat load overwhelmed the capacity (5–8 W) of the refrigerator and we could not constitute a system reliequifying the evaporated helium gas by a refrigerator.

If the increment of heat load varies with the square of

the magnitude of the exciting current, the increment will be 100–200 W in actual running. Besides, we recognized this phenomenon only in the energized state and the magnitudes of vibration at each point of the magnet became large at this particular resonant frequency.

Investigation into the cause of heating and improvement of the ground coils

Investigation into the heating phenomenon

The heating phenomenon is supposed to arise from the whole mechanical vibration of an energized superconducting magnet induced by the magnetic fluctuation from the outside because this heat load is less in the de-energized state of a magnet. Besides there is a possibility that electromagnetic factors play an important part in this phenomenon. A convincing interpretation is heat generation due to eddy currents induced by the relative displacement.

As shown in Figure 7, the relative displacement occurs between the superconducting coil and conductors such as the outer vessel or radiation shield plate when the superconducting magnet vibrates mechanically. The eddy current on the conductors causes a magnetic fluctuation on the inner vessel housing the superconducting coil and an eddy current is induced on the inner vessel. The heat occurs due to this eddy current and evaporates the liquid helium in the inner vessel. However, we could not experimentally verify this at that time.

Prevention of heating by a change in arrangement of the propulsion ground coils

We devised a means to decrease the fluctuating amplitude of the magnetic field from the ground coils as much as possible, in order to decrease the heat loss together with investigating the heating mechanism inside of the magnet. We tried to eliminate the force on the inner vessel itself by shortening the wavelength of the actuating force and improving the arrangement of the ground coils in addition to a trial to reduce the amplitude of original actuating elec-

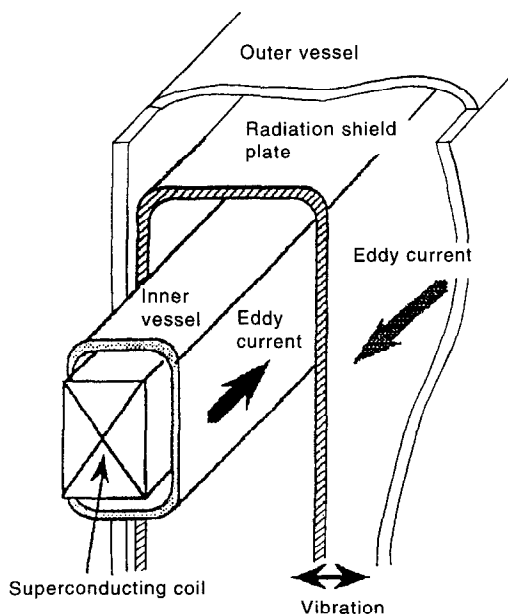


Figure 7 Occurrence of eddy current due to relative vibration

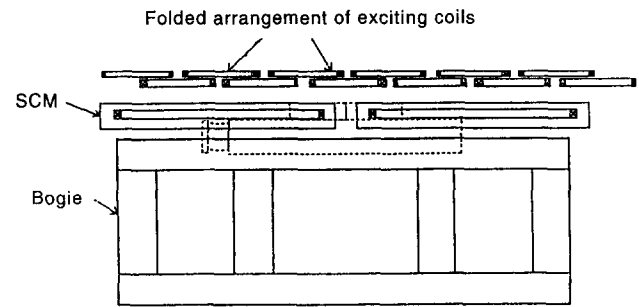


Figure 8 Arrangement of coils in electromagnetic vibration test

tromagnetic force. The fluctuating magnetic field can be reduced cancelling the third harmonics of the fluctuating ripples by changing the arrangement of the propulsion ground coils into the folded type, rather than the conventional single type arrangement.

Figure 8 shows the arrangement of coils in the electromagnetic vibration test performed for the purpose of investigating the heat loss as influenced by the folded type of the exciting ground coils as mentioned above. Figure 9 shows the results of the experiment. In this diagram the horizontal axis indicates the ratio of load to that in actual running and the vertical axis indicates the increment of heat load. From this diagram we see that a considerable heat load occurs at 20% level in the case of the single arrangement of ground coils but the heat load is reduced at 100% level in the case of the folded arrangement of ground coils. For these reasons, we intend to adopt fundamentally the folded arrangement of the propulsion coils in the construction of maglev system. By adopting this construction, the influence on the heat load due to the actuating disturbance from the propulsion coils can be decreased to a negligible level.

Constitution of new maglev system

This problem was considered to be solvable by the improvement of the arrangement of the propulsion coils. In fact it was not so simple, since we were at that time considering the necessity of constructing a new system for future maglev taking into consideration the technical progress.

A feature of this new maglev system is the new levitation

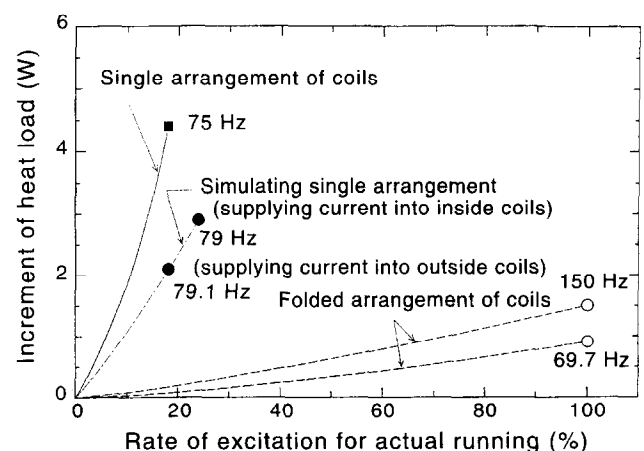


Figure 9 Increment of heat load versus rate of excitation for actual running

system shown in *Figure 10* with the articulated bogie system which has each bogie with superconducting magnets mounted between cars. The ground coils for levitation are arranged on the base of the guideway in the conventional system; however, eight-figured ground coils are arranged on the sidewall of the guideway in the new levitation system.

This method has the advantages that the magnetic drag in running is reduced and the recovering force in lateral motion of the car is stabilized. Adoption of the new levitation and articulated bogie system with fewer bogies makes it necessary in future to study the influence from the levitation coils under electromagnetic vibration which we have neglected in the conventional levitation system.

We adopted an inverter instead of the conventional cycloconverter as the electric power supply for the ground coils. This is another improved feature in this system. As a result, with no restriction on the upper limit of the frequency of the power supply, we have shortened the length of pole pitch of the magnet from various viewpoints. Hence, the superconducting magnet for the Yamanashi Test Line will have four coils with a pole pitch of 1.35 m. With this length, the pitch of the ground coils is shortened. *Figure 11* shows the arrangement of ground coils on the commercial line and eight-figured levitation coils attached on the sidewall of the guideway.

Suppression of heat generation in the new system

Electromagnetic vibration test using new magnets

In order to confirm the reliability and durability of the new magnet system, we constructed the facilities of an electromagnetic vibration simulator on special funding from JR at each factory of Hitachi Works, Toshiba Corp. and Mitsubishi Electric Corp., which are the makers of the supercon-

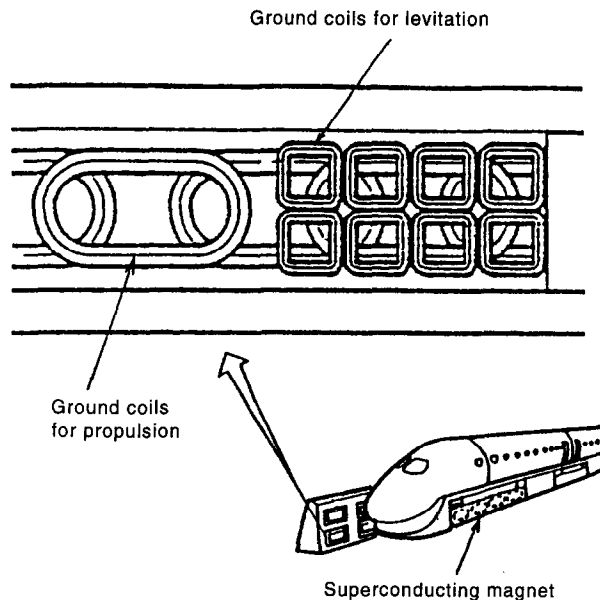


Figure 11 Arrangement of ground coils on the commercial line

ducting magnet, under the supervision of the Railway Technical Research Institute (RTRI). We tested magnets with different structures under various conditions. The actuating frequency of the electromagnetic vibration tests ranged from 0 to 308 Hz corresponding to a speed of 500 km h⁻¹.

Although we omit here the details of the results of these tests, we note the difference in heating due to that in the structures of the magnets. And naturally a serious increment of heat loss still occurs at the frequencies over 300 Hz in a particular superconducting magnet. We suspect that this large heat generation has something to do with the relative displacement between the inner vessel and the radiation shield plate and that the deformation of the superconducting coil itself in resonance is also related to this heating.

Establishment of countermeasures for heat generation

On the basis of these results, the agencies concerned with the development of superconducting magnets for maglev, i.e. Central Japan Railway Company, the manufacturers mentioned above and RTRI, organized means for resolving these problems and have made investigations into the cause of these phenomena, tried improvements and tested for confirmation of the results of improvements.

We carried out both electromagnetic vibration tests at the facility which contains a single superconducting magnet and ones using the actual superconducting magnet with four superconducting coils as a means for resolving this problem. The former contributes to changing the outside and inside parts of the structure in the magnet. The results of tests using these facilities are reported elsewhere¹⁻³.

Analysis of the factors of heating phenomena

Table 2 summarizes the improvement efforts for the reduction of excessive heating induced by electromagnetic vibration. The factors causing heat generation are mainly divided into three items. They are: (1) eddy current induced by the relative displacement between the elements in a

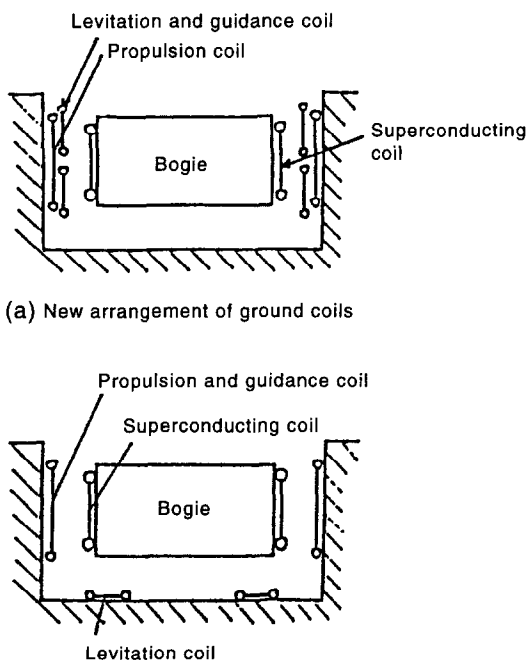


Figure 10 Levitation system and coil arrangement

Table 2 Improvement in reduction of excessive heating induced by electromagnetic vibration

- | |
|---|
| <p>(1) Diminishing vibration to decrease the deformation of superconducting coil and the relative displacement or slip between the elements in a magnet</p> <ul style="list-style-type: none"> • suppressing the disturbance (folded arrangement of ground coils) • increase in number of supporting columns • increase in the rigidity of magnet (for outer vessel and radiation shield plate) <p>(2) Diminishing the heat load generated by eddy current</p> <ul style="list-style-type: none"> • treatment for diminishing the electrical resistance on the surface of the inner vessel (ex. copper plating) • selection of a radiation shield plate with high electrical resistance <p>(3) Shielding the penetration of the fluctuating magnetic field</p> <ul style="list-style-type: none"> • adoption of pure aluminium as the material for the outside of outer vessel • increase in thickness of the outer vessel |
|---|

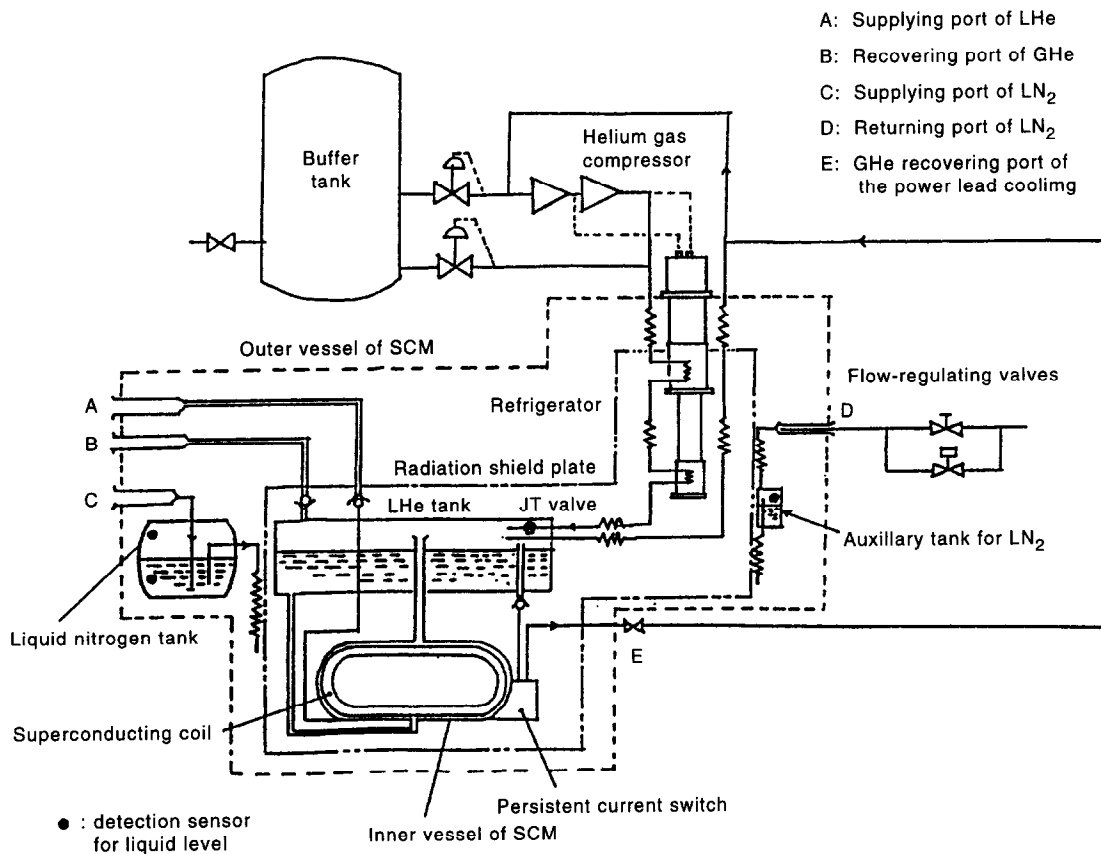


Figure 12 Cooling flow diagram of superconducting magnet

magnet; (2) eddy current induced by the penetration of the fluctuating magnetic field; and (3) frictional heat loss through deformation of the superconducting coil. At present, we have good prospects of decreasing greatly the internal heat generation by these countermeasures.

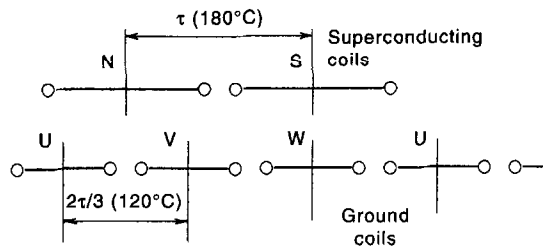
The problems still unsolved are the establishment of effective means for further reduction of heating and an exact grasp of the ratios of electrical and mechanical factors responsible for heat generation. We also performed tests which cause the vibrating deformation of a single superconducting coil by pure mechanical means; the results of these tests are reported elsewhere³.

On-board refrigerating system

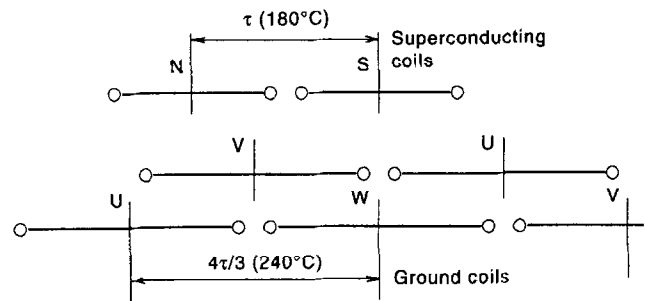
It is necessary to investigate the behaviour of the on-board refrigerator under the increment of heat load due to the electromagnetic vibration. The refrigerator has a refrigerating capacity (8–10 W) which can deal with the heat load

(3–5 W) in the static state, but a temporary heat load under the electromagnetic vibration overwhelming this capacity will burden the refrigerator.

We adopt a direct cooling system, shown in *Figure 12*, as the on-board refrigeration system of the magnet. The mist of helium gas in the refrigerator is blown into the liquid helium tank of the magnet and the evaporated helium gas comes back into the refrigerator. Because part of the evaporated helium goes out via the heat exchanger of the refrigerator and cools the gas in a high pressure line, the net decrease rate of the liquid helium in the tests turns out to be below half the volume converted from the difference between the excessive temporary heat load and the refrigerator capacity. Considering this result and the occurrence of most of the heat generation only at a particular frequency in resonance, this system has such good characteristics that it does not cease to function even if the heat surpassing the capacity of the refrigerator is generated temporarily in actual running.



Scheme 1 Single arrangement of ground coils



Scheme 2 Folded arrangement of ground coils

Conclusions

The phenomenon in which the heat loss in the superconducting magnet increases under the fluctuating electromagnetic disturbances on the magnet is an extremely important problem for the refrigerating system of maglev. This subject is interesting but hard to analyse because electromagnetism and mechanical vibration are involved deeply from an academic point of view. The understanding and analysis of this phenomenon have been accomplished through investigations carried out, but we are aware that the means for improvement still exist.

We intend to confirm the effect of these improvements using the magnets incorporated with the various countermeasures described in this paper, and we plan to continue the development of a better superconducting magnet. We hope that this article will be useful in providing preliminary knowledge: for further information the reader is referred elsewhere⁴⁻⁸.

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Appendix A Explanation of varying magnetic field having high harmonics from the ground coils

Actuating frequency of magnetic field from ground coils that the superconducting magnet suffers

In general, taking the pole pitch of the superconducting magnet (the distance between the north and south poles) as τ (m), and the running speed as v (m s^{-1}), we can obtain the fundamental frequency f_0 (Hz) of the current from the power feeding facility as $f_0 = v/(2\tau)$.

Scheme 1 shows the fundamental arrangement of the

ground coils for propulsion. A group of these coils having the distance of the electrical angle 120° between them are arranged in a single layer and the phases of *U*, *V* and *W* are connected to form a pattern with the same pole each at an electrical angle of 360° . We call this array of the coils a single arrangement. *Scheme 2* shows the arrangement of a group of ground coils having the distance of the electrical angle 240° between them and we call this array a folded arrangement.

Observing the wave of magnetic flux on the on-board superconducting magnet varying by the current with fundamental harmonics from the ground coils, we can see that the wave has the harmonics of $(3n \pm 1)$ th in space and $(3n)$ th in time in the case of *Scheme 1* and $(6n \pm 1)$ th in space and $(6n)$ th in time in the case of *Scheme 2*. In the fundamental case of $n = 1$, the on-board superconducting magnet suffers electromagnetic disturbances having the high harmonics of 5th and 7th in space and 6th in time. In a concrete case of $\tau = 1.35$ m and running speed = 500 km h^{-1} in *Scheme 2*, the actuating frequency is calculated as $6 \times 51.4 = 308.4$ Hz because $f_0 = 51.4$ Hz and the pitch of each coil arranged in the folded arrangement is calculated as $4\tau/3 = 1.8$ m.

Because the levitation ground coil, which forms the independent closed loop, has half the length of the propulsion coil and takes the arrangement as in *Scheme 1*, the pitch of the levitation coils is calculated as $\tau/3 = 0.45$ m. The fundamental harmonic from these levitation coils becomes the 6th one and the frequency is 308.4 Hz in the case of a running speed of 500 km h^{-1} .

Arrangement of the exciting coils in the electromagnetic vibration simulator

The length of the pitch of the exciting coils for propulsion in this simulator as shown in *Scheme 2*, is selected in order to impose a magnetic disturbance having 5th harmonics in space upon the magnet. The length of the pitch of the exciting coils for propulsion supplying the current in three phases is calculated as $0.54 \text{ m}/3 = 0.18$ m because the length $(2\tau/5)$ corresponding to the electric angle of 360° equals 0.54 m when τ is 1.35 m.

Because the arrangement of the exciting coils for levitation is the same as in *Scheme 1*, the length of the pitch of these exciting coils equals 1.8 m, i.e. the same as in the case of the exciting coils for propulsion. But we can occasionally take the arrangement of the exciting coils as the folded one having a coil pitch of 0.36 m under the restraint in producing the actual exciting coils.