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PII: S0011-2275(97)00035-0

Cryogenics 37 (1997) 479-486

0011-2275/97/$17.00

Heat load characteristics of new superconducting magnets for the Yamanashi test line*

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Received 6 August 1996; revised 16 January 1997

Superconducting magnets which are installed on a Maglev vehicle vibrate under the influence of various disturbances in running. The main disturbance is due to the harmonic ripples of electromagnetic flux generated by ground coils. To estimate the influence of the harmonic flux ripples, a facility called an electromagnetic vibration simulator was constructed. The heat load in some magnets made in the 1980s increased extremely in the high frequency region of the electromagnetic vibration test. We have investigated the cause of this phenomenon from various aspects, and made short superconducting magnet models containing a single superconducting coil and superconducting magnets with high rigidity having different internal structures for testing various ideas to reduce the heat load. As a result, we have obtained good results. We then started on production of the new superconducting magnets for the Yamanashi test line. This is an outline of the new magnets. © 1997 Elsevier Science Ltd.

Keywords: superconducting magnet; Maglev; heat load; electromagnetic vibration test

Since 1970, Japanese National Railways have continued to promote R&D of the superconducting Maglev system. The epoch-making event for this system came in 1990, when it gained the status of a national funded project in Japan. The government authorized construction of a new test line in Yamanashi prefecture, and R&D entered into a new phase. The project for the construction, in which the Railway Technical Research Institute, the Central Japan Railway Company and the Japan Railway Construction Public Company participated, was started. For the development of a superconducting magnet system, the Railway Technical Research Institute and the Central Japan Railway Company tied up closely with heavy electric industry makers in Japan, Hitachi Ltd, Toshiba Corporation and Mitsubishi Electric Corporation, in order to back up and push the development strongly.

In this project, the most important objective was to overcome the quenching of the superconducting magnet and to reduce the heat load within practical use in running. Since then, we have done our best to solve the problems and work out the design of the superconducting magnet system for the Yamanashi test line.

As for the countermeasure of quenching, we got good prospects in 1991. On the other hand, as to the countermeasure of heat load increase, we gained good prospects in 1992. Thus, the production of the superconducting magnets for the Yamanashi test line was started by the Toshiba Corporation and Mitsubishi Electric Corporation at the end of 1991, to be used in the Yamanashi test line practically. At the end of 1992, the first product came from each corporation. The first product by the Toshiba Corporation is named 'SCM1', and the second product by the Mitsubishi Electric Corporation is named 'SCM2' in this paper. As for Hitachi Ltd, according to the production and test results of superconducting magnets described in other papers, another trial production was made for the purpose of high performance and high reliability in 1992. This magnet is called the 'Prototype Superconducting Magnet'. First production in

*Originally published in *Teion Kogaku*, 1996, 29(10) (in Japanese)

Hitachi Ltd. started from the end of 1993 after all trials mentioned above.

Each superconducting magnet (SCM1, SCM2, and Prototype Superconducting Magnet) as a countermeasure for heat load increase for the Yamanashi test line is described in detail.

Basic ideas of the superconducting magnet for the Yamanashi test line and basic constitutions of SCM1 and SCM2

Basic ideas of the superconducting magnet

The superconducting magnet for the Yamanashi test line features the following points in addition to basic characteristics of the superconducting magnet for the Maglev vehicle: 'light and compact'.

1. To strengthen the countermeasure for the quenching of the magnet.
2. To reduce the heat load of the magnet to a low level which enables the magnet to operate continuously without additional liquid helium supplement when on-board refrigerator is operated.
3. To consider the exchangeability which enables one bogie to be switched to another bogie if any trouble occurs with the system.
4. To increase the reliability and durability of the total system.

Basic characteristics of both SCMs

The practical constitutions of both SCMs to realize the basic constitution mentioned above are as follows. At first, the countermeasure for the quenching of the superconducting magnet will be explained simply. Then the concrete countermeasures adopted to improve the characteristics of both superconducting magnets will be given.

1. To increase the sectional area of the superconducting (SC) coil. Hold a margin for quenching by decreasing the current density of superconducting wire by increasing the sectional area of the SC coil. This will increase the rigidity of bending and rolling of the SC coil and hence the stability of the magnet.
2. Set a buffer to prevent a rise in temperature in the innermost part and the outermost part of the SC coil exposed to the heat generated by friction, which is considered the main cause of the quenching and generated by mechanical slipping between superconducting coil and clamps.
3. To improve the structure of the support. Increase the span and number of columns supporting the SC coil, to make it difficult for the coil to twist and roll, and prevent the quenching of the magnet.
4. To improve the structure of the inner vessel. Increase the volume of holding liquid helium under severe restriction, which insures storage of liquid helium in various disturbances and improves the cooling performance.

The concrete constitution of the countermeasure for heat load increase will be described in the next section in detail. As for the refrigeration system, the capacity of the on-board refrigerator is over 8 W, the heat leakage of the superconducting magnet is under 5 W, thus the heat load margin of the system is over 3 W.

On the other hand, as the mean heat load increase of the superconducting magnet in running is suppressed under 8 W, it is obtained by electromagnetic vibration test simulating the running pattern for the Yamanashi test line.

Thus it is possible to make a perfect closed system which enables continuous operation without additional liquid helium supply.

As for the concrete constitution of exchangeability, all wiring and piping for control and measurement is unified in common items and the outer size of the magnet in relation to the body is also unified. A pair of superconducting magnets is constituted symmetrically with respect to the centre of the bogie, so each magnet can be set to either side of the bogie. The exchangeability between bogie and superconducting magnet makes it possible to set any bogie site in Yamanashi.

As for the increase in reliability and durability, design review is done at the design stage and any problem with regard to design is picked up. As for the on-board refrigeration system, a similar product is set in each magnet, to be confirmed in continuous operation over 10 000 h. Each piping of the superconducting magnet and on-board refrigerator is confirmed in part stages through vibration tests and so on. After the assembly of the total system, electromagnetic vibration tests and mechanical vibration tests are performed fully, then the vehicle load of the system is brought into the Yamanashi test line.

The basic items of both SCMs are shown in *Table 1*. *Figure 1* shows a schematic image of the superconducting magnet for the Yamanashi test line. *Figure 2* shows an outside view of the magnet.

The mechanism of heat load increase and ideas to reduce the heat load of SCM1 and SCM2

The cause of heat load increase

At present, it is thought that the following three phenomena are the main causes of the heat load increase.

1. Eddy current loss caused by the vibration between the superconducting coil contained in the inner vessel and

Table 1 Basic characteristics of the superconducting magnet

Item	Specification
Dimension of SCM	5.40 m (L) × 1.175 m (H)
Weight of SCM	Less than 1500 kg
Volume of LH_e tank	About 50 l
Volume of LN_2 tank	About 40 l
Superconducting coil	
Magnetomotive force	700 kA (1400 turns)
Shape of SC coil	Race track
Copper ratio of SC wire	1.0–1.5
Dimension of SC wire	1.1 × 2.5 mm
Heat leakage to inner vessel	4 W
Levitative force per magnet	98 kN
On-board refrigerator	Built-in type
Refrigeration capacity	More than 8 W at 4.4 K

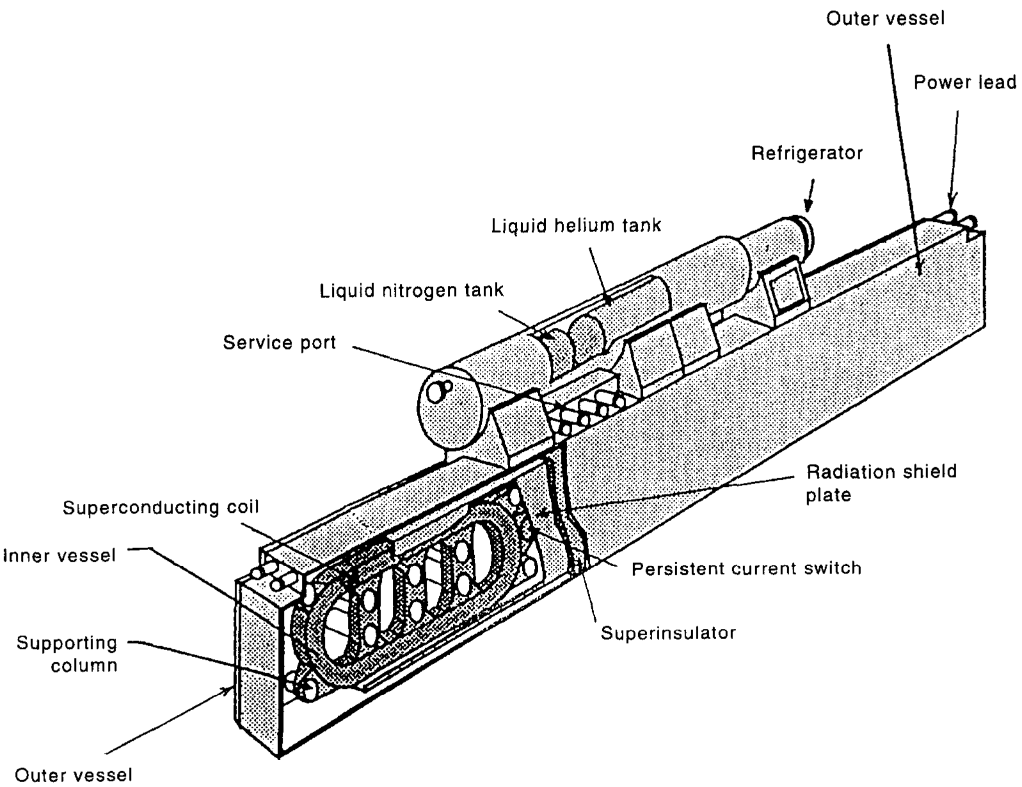

Figure 1 Illustration of the superconducting magnet

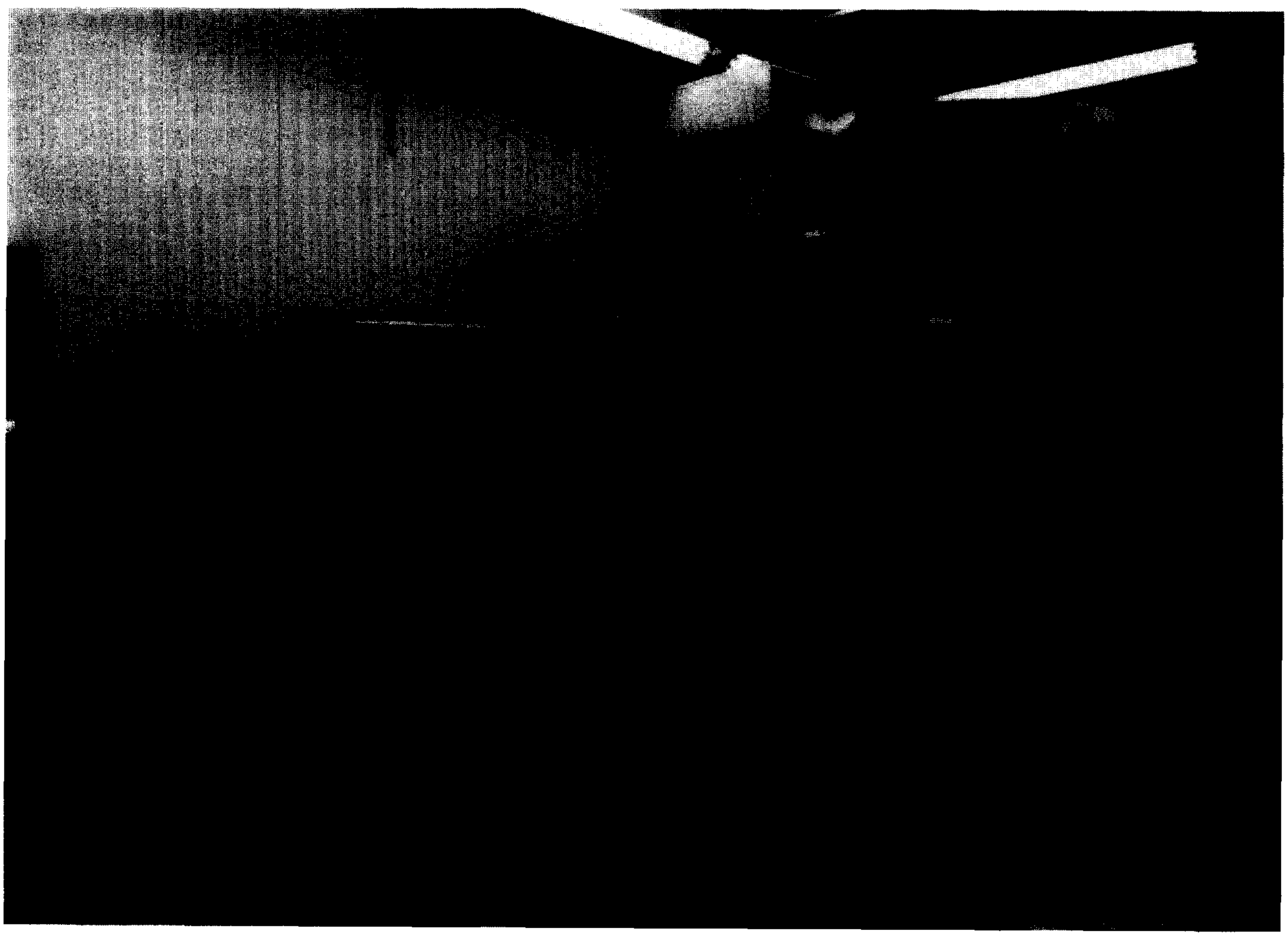

Figure 2 Outside view of the superconducting magnet

the other structural components of the radiation shield and the outer vessel at the resonance frequencies.
2. Eddy current loss caused by the penetrating harmonic ripples of the electromagnetic field due to the ground coils, which will not be shielded by the outer vessel and the radiation shield.
3. Mechanical loss caused by the relative displacement or slip between the inner vessel, clamps and the superconducting coil, in connection with the deformation of the superconducting coil and the inner vessel.

Initially, the heat load increase described in (1) above was considered to be the main cause, and the countermeasure against this seemed to solve the problem. But after the heat load increase due to the mutual vibration of the major components was made less, it was made clear that the heat load of (2) and (3) could not be neglected, especially after employing high resistivity materials as the radiation shield, and thus the overall research and development were required.

The reduction of the heat load increase in SCM1 and SCM2

The reduction of the heat load increase has to be taken into account from many aspects, since the superconducting magnet for the Maglev vehicle must be designed under the limitation of severely narrow space and light weight.

The methods employed to solve this problem are as follows.

1. Originally, a superconducting coil contained in the inner vessel was supported at four inner corners, by supporting columns bridged to the outer vessel. Four support columns were added at the outer corners of the inner vessel in order to make the magnet more rigid, and thereby to reduce the vibration. This reinforcement could reduce the relative displacement of the superconducting coil contained in the inner vessel against the radiation shield and the outer vessel, and accordingly a reduction of the eddy current loss was achieved. This also made both the inner and the outer vessel more rigid, and could decrease the mechanical loss too, owing to less structural deformation.
2. The outer vessel plate facing the bogie frame was designed in a honeycomb structure, to increase the equivalent thickness to meet the requirement of minimum weight increase. This kind of structure could increase the overall rigidity of the superconducting magnet, and thereby the vibrations of the inner vessel were able to be reduced.
3. To reduce the eddy current loss caused by the interaction between the superconducting coil contained in the inner vessel and the radiation shield, the radiation shield was made of high resistivity material. Almost no eddy current flows in the radiation shield adopting this material, namely, no loss due to the above effect.
4. To reduce the eddy current loss on the surface of the inner vessel, the surface of the inner vessel was plated with copper for the achievement of diminished electrical resistance.
5. To reduce the eddy current loss caused by the penetrating harmonic ripples of the electromagnetic field by the ground coils, the material of the outer vessel plate facing the ground coils was changed from alloy to pure aluminium, and further its thickness was increased in order to shield the harmonic field.

The construction of the Prototype Superconducting Magnet was different from that of SCM1 and SCM2, in particular with respect to (3) mentioned above. With regard to the radiation shield, the former is made of high resistivity material, whereas the latter is made of pure aluminium plate, where the plate has a shell-type configuration, and is supported at more points, so that the rigidity of the radiation shield can be increased. By means of these improvements, the eddy current loss caused by the relative motion was conspicuously reduced.

Results of electromagnetic vibration tests of SCM1 and SCM2

Test results for SCM1

Figure 3 shows the increase in heat load resulting from the electromagnetic vibration test, simulating the harmonic ripples of an electromagnetic field generated by levitation ground coils. *Figure 4* shows the acceleration of two coils, located at the end of SCM1, as obtained by the vibration test in the case of energized SCM. In this case, the peaks of the increase in heat load appeared at frequencies around 120, 200 and 320 Hz. It was confirmed that the acceleration of two coils increased at the same frequency. This agreement indicates the correlation of both phenomena.

The heat load in an unenergized SCM decreases exponentially with the increase of the frequency. In this case, it is inferred that the vibration of the magnet is quite small, and therefore most of the heat loss is due to the eddy current loss caused by the penetrating harmonic ripples of the electromagnetic field of the ground coils through the outer vessel, since the resistivity of the radiation shield is pretty high.

The heat generation is quite different according to the condition of whether the SCM is energized or not. This suggests that there still remain a lot of eddy current losses caused by the relative motion of the superconducting coil contained in the inner vessel against the outer vessel, and the mechanical loss caused by the slip or friction in the coil structure.

The electromagnetic vibration test of the SCM was performed by the simulation of the running pattern in a long-term confirmation test for the Yamanashi test line. The average heat loss obtained from this simulation test, which

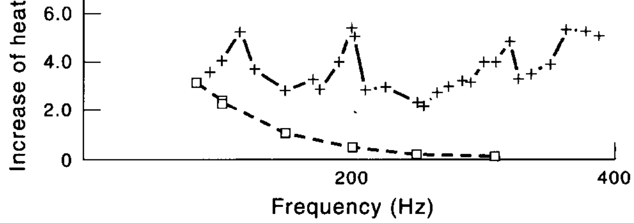

Figure 3 Increase in heat load resulting from the vibration test (SCM1)

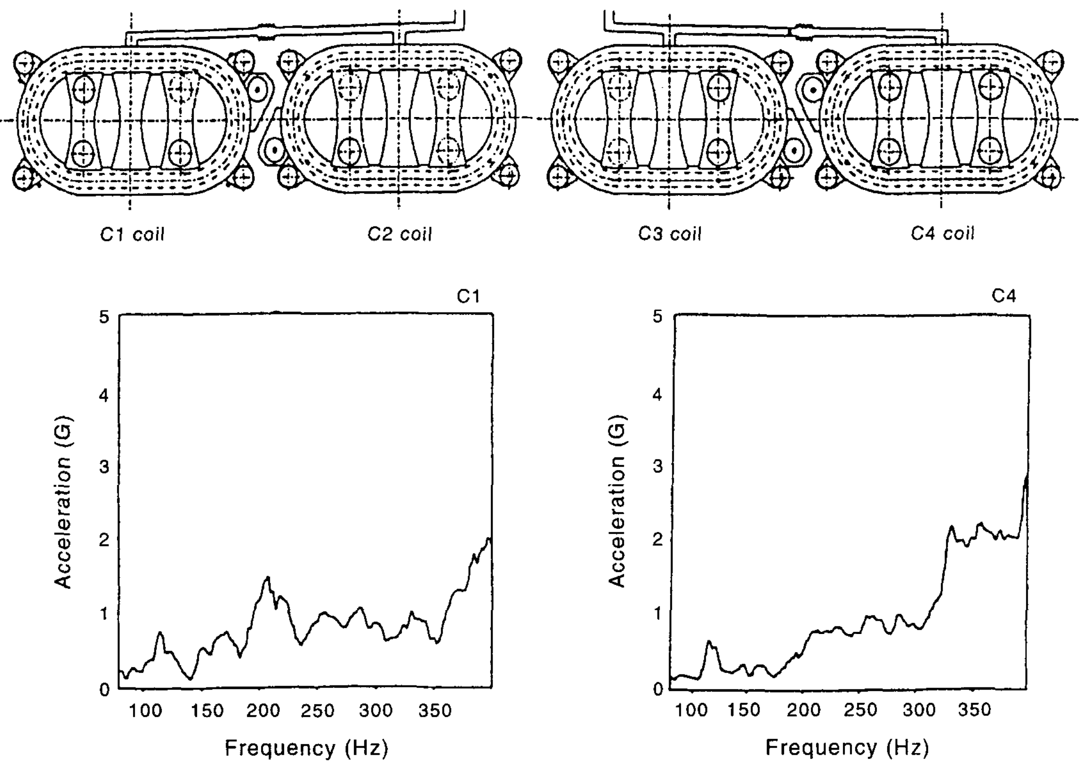

Figure 4 Acceleration in SCM1 resulting from the vibration test

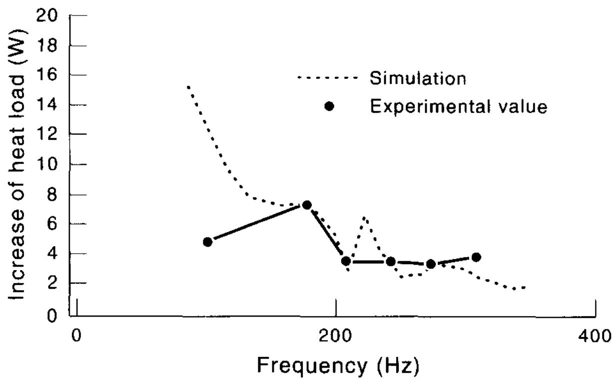

Figure 5 Increase in heat load resulting from the vibration test (SCM2)

is in particular an important one for the helium refrigeration system, was 8.5 W.

Test results for SCM2

Figure 5 shows characteristics of the heat load increase obtained from the electromagnetic vibration test which simulated the disturbance arising from the ground coil for levitation. *Figure 6* shows the average acceleration of eight points along the inner vessel of the coil located at one end of four coils in the SCM obtained from the electromagnetic vibration test. The peak of the heat load increase appears around 180 Hz, and the average acceleration of eight points along the end-coil's inner vessel increases around the same frequency. The simulated values indicated by the dotted line were obtained in the following way.

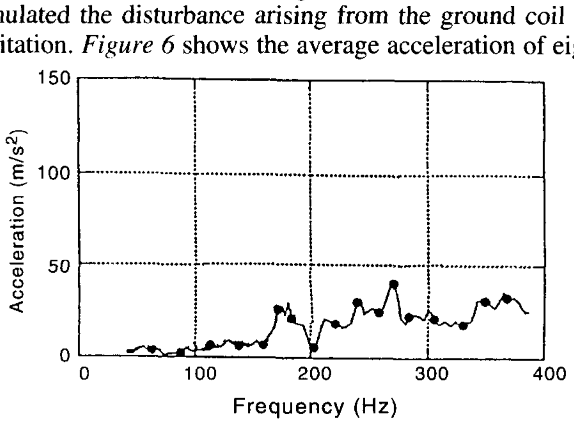

Figure 6 Acceleration in SCM2 resulting from the vibration test

1. The changes in eddy current loss generated in the copper plating of inner vessels, which was carried out on the one coil model SCM to modify it to SCM2, were calculated using the eddy current analysis simulation model.
2. The mechanical losses in the heat load increases exhibited in the electromagnetic vibration test of the one coil model SCM were obtained by subtracting the test results of a vibration test without energization from those of a vibration test with energization.
3. The values obtained in (1) were subtracted from four times the values calculated in (2). *Figure 5* shows that the measured heat load increases agree well with these simulated values.

The electromagnetic vibration test simulating the running pattern used for continuous endurance tests on the Yamanashi test line revealed that the average heat load was about 8.7 W.

Results of other tests

In energization and de-energization of both SCMs with active on-board refrigeration systems, the internal pressure of the inner vessel in the liquid helium tank could be suppressed below the blow-out pressure of the safety valve, 0.4 atg or less, and the amount of evaporated liquid helium in energization and de-energization was less than 3 l.

SCM1 is fitted with a GM cycle refrigeration system and

SCM2 with a Stirling cycle refrigeration system which has higher efficiency. It was established that they had refrigerating capacities of 8 W or more and 10 W or more respectively. In addition, tests show that, when combined with an SCM, each refrigeration system provides more than enough refrigerating capacity. Both SCMs exhibit an average heat load of about 8 W in a vibration test simulating the running pattern used for continuous endurance tests on the Yamanashi test line.

Thus it is almost certain that they can be operated continuously while operating the on-board refrigeration systems without additional supply of liquid helium. Here we do not go into details about the effects of the countermeasure against quenching.

To sum up the effects briefly, it has been established that, thanks to the countermeasure described earlier, in both SCMs the superconducting coils are not quenched up to about 80**g** of bending and twisting mode acceleration at the resonance points. This represents a significant progress from conventional SCMs.

Results of prototype test on demonstration SCM

Objective of demonstration SCM prototype

On the basis of the results of technical developments obtained so far, including the improvement in anti-quenching performance, reduction of heat load increase with electromagnetic excitation, improvement in on-board refrigerator performance, etc., the demonstration SCM was further improved in performance. Aiming to demonstrate the feasibility of the superconducting magnet performance required in the Yamanashi test line by manufacturing a full size superconducting magnet equivalent to an actual machine for the Yamanashi test line to further improve the performance, the prototype test was made from the fiscal year 1992 through the fiscal year 1993 in a joint work of the Central Japan Railway Company and Hitachi Ltd.

The concept of the specification of the prototype superconducting magnet

In order to achieve the above purpose, the basic specification of the superconducting magnet was set as follows.

1. Weight. A simple body weighing 1400 kg (including the weight of an on-board refrigerator but excluding the weights of a compressor unit for a refrigerator and a superconducting magnet protective circuit, etc.) specified for the superconducting magnet for the Yamanashi test line is to be realized.
2. Total heat load performance. With the total heat load including the quantity of static heat penetrated and the heat load increment by electromagnetic vibration test being 8 W or less, the heat load balance under an operating on-board refrigerator (refrigerating capacity 8 W or over) is to be realized.
3. Policy to improve the anti-quenching performance. In order to reduce the mechanical loss (minute slip friction calorification) between the inner vessel and the superconducting coil as a main factor of coil quenching owing to the electromagnetic disturbance while the vehicle is running, the inner vessel rigidity relative to the structure is optimized and the force of constraint of the superconducting coil by the inner vessel is enlarged as much as possible. For the superconducting wire material the copper ratio of 1 is selected with a view to securing the light weight and temperature margin.
4. Policy of reducing calorification when electromagnetically exciting. The relative displacement is minimized to restrain the electromagnetic loss (eddy current calorification) accompanying the vibration in the superconducting magnet by making the radiation shield plate using aluminium material, to be constructed as the shell along with the inner vessel, and increasing the mechanical rigidity by arranging them in the vicinity of each other. The electromagnetic loss is restrained by adhering aluminium materials with little electromagnetic resistance effect onto the surface of the inner vessel. By adopting a honeycomb structure of the bogie frame side outer vessel, the improvement of the cryostat rigidity and the reduction of the weight are reconciled. For the outer vessel material for the ground coil side, the plate thickness is secured and the plate material clad with low electric resistance aluminium (A1070 material) on the A5083 material adopted to improve the electric shield performance. Local deformation in the inner vessel is restrained and the oscillation frequency natural to the inner vessel is improved in a functional arrangement by spreading the inner vessel load supporting materials.
5. On-board refrigerator. An 8 W class GM cycle refrigerator developed for the vehicle is included in the magnet.
6. Policy to improve reliability and durability. Though conditions of actual load on the superconducting magnet in the Yamanashi test line are still indefinite at the present stage, designing and manufacturing are advanced to secure the reliability endurance levels required at the commercial line stage. For instance, the Persistent Current Switch (PCS) is subjected to the single body mechanical excitation test in advance and incorporated in the superconducting magnet after confirming vibration resistance, stability, etc. Also, the oscillation frequency natural to components in the cryostat is designed to be maintained over the actual service area as high as possible, to be verified by all the elements.

Results of performance test on prototype superconducting magnet

Results of measuring the weight. *Figure 7* shows a general view of the prototype superconducting magnet. The measured weight of the independent body was 1392 kg, which satisfied the specification.

PCS mechanical excitation characteristics. The mechanical excitation test on the PCS was conducted. We confirmed that it withstood vibration acceleration of 10**g** or over under the following conditions, and in addition was free from problems in the stability:

supply field: 1 T;
PCS current: equivalent to superconducting coil mag-

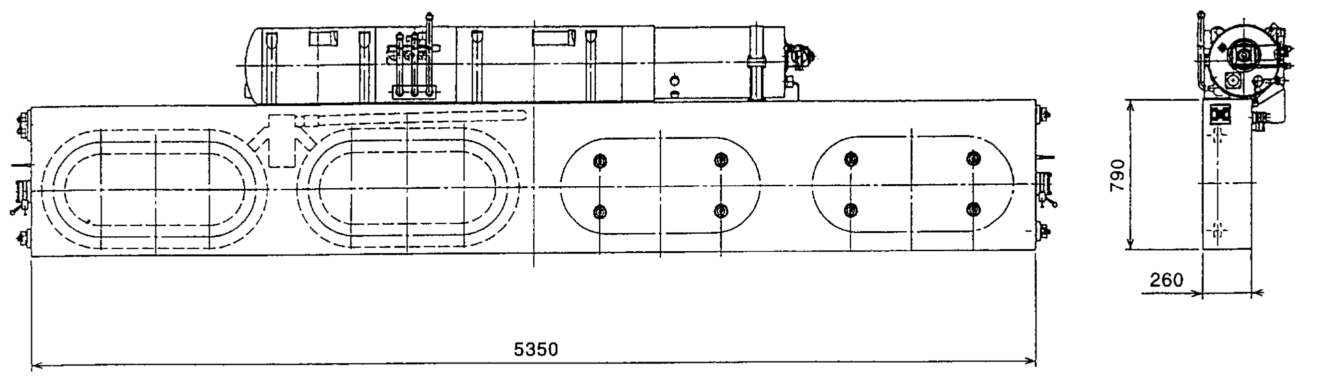

Figure 7 Illustration of the prototype superconducting magnet

netomotive force 800 kA (rated magnetomotive force 700 kA);
excitation frequency: 50–400 Hz.

Mechanical loss characteristics between the inner vessel and the superconducting coil. We verified that the mechanical loss calorification was almost proportional to the square of the vibration speed.

Results of the measurement of the quantity of static heat penetrated. The measured quantity of heat penetrated in a static state was 4.6 W.

Heat load characteristics in the electromagnetic vibration test. In conducting the electromagnetic vibration test, we simulated bogie frame rigidity in three stages by varying the spring coefficient of the fixture to be inserted in the mounting part of the superconducting magnet of the bogie frame to see the influence of the bogie frame rigidity in mounting the superconducting magnet on the heat load characteristics. *Figure 8* shows the heat load increment characteristics obtained by the test. From the excitation frequency around 100 to 350 Hz, various superconducting magnet vibration modes exist and the heat load peak corresponding to the resonance occurs. Whole frequency characteristics are similar irrespective of bogie frame rigidity parameters, but for the heat load peak appearing in the vicinity of 240–260 Hz, the correlation is recognized to the bogie frame rigidity. This peak is generated in the same vibration mode, in which the vibration resonance frequency drops as the simulated bogie frame rigidity is minimized, while the peak value tends to become larger.

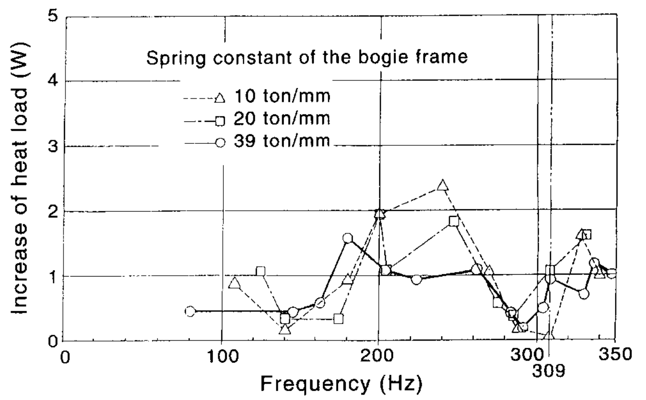

Figure 8 Increase in heat load under the vibration test of the prototype superconducting magnet

Judging from the relation to the quantity of vibration, the correlation between the inner vessel vibration speed and the heat load increment is so high that the mechanical loss caused between the inner vessel and the superconducting coil seems to constitute most of the factors for the heat load increment. From this test result, the total heat load summed up with the quantity of static heat penetrated, 4.6 W, and the heat load increment attained while electromagnetically exciting was 6–7 W, which we could set within 8 W of the on-board refrigerating capacity.

Refrigerator balanced operation characteristics. With the helium cooling system within the superconducting magnet sealed off and the on-board refrigerator operating, we conducted the frequency sweep electromagnetic vibration test simulating the running conditions in the Yamanashi test line. Without a change in the internal pressure and the quantity of liquid in the helium cooling system, we confirmed the stable heat load balance operation.

Future subjects

The heat load performance required for the Yamanashi test line is achieved for the first time by the prototype test in the demonstration, in which the heat load balanced operation by the on-board refrigerator under electromagnetic excitation was demonstrated. We obtained good prospects of the smooth operation of the superconducting magnet in the Yamanashi test line.

Henceforth, bearing the commercial line stages in mind, we expect to demonstrate by the durability-verifying tests that the functions of various components of the superconducting magnet are without any problems over a long period of time and, therefore, the superconducting stability is maintained. From the viewpoint of reducing the construction cost by simplifying the ground coil components for reliability and durability, our object is to consider the development of the superconducting magnet enduring larger electromagnetic disturbance and the design and manufacturing methods of superconducting magnets coping with mass production with little scattering in performance and of reducing the manufacturing cost.

Conclusions

Heat load in some magnets made in the 1980s increased extremely in the high frequency region of the electromagnetic vibration test. This situation was found serious in producing superconducting magnets for the Yamanashi test line. We analysed the cause and investigated from various points and proceeded with many model tests which include the countermeasure to improve characteristics of heat load increase. Thus we succeeded in producing the new superconducting magnets with high performance in heat load increase which endure the daily operation of the Yamanashi test line without additional supplement of liquid helium. Hereafter, we will continue to produce all the magnets provided on the first set of Maglev vehicles by the middle of 1995.

Acknowledgements

The development and production of the superconducting magnets for the Yamanashi test line is subsidized by the Ministry of Transport of Japan. Part of the R&D is supported by the Central Japan Railway Company.

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