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Heat load tests of superconducting magnets vibrated electromagnetically for the Maglev train*

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Superconducting magnets on Maglev trains vibrate due to harmonic ripples of electromagnetic flux generated by ground coils. Heat load caused by vibration in the magnet amounted to several tens of watts in the electromagnetic vibration test. This was mainly because a.c. loss was induced in the helium vessel housing the superconducting coil, due to relative vibration between the aluminium thermal shield and the coil. The heat load caused by vibration should be strictly restricted to less than 4 W due to limited cryogenic refrigeration capacity. The heat load was tested using electromagnetic flux ripples for a superconducting magnet model of one coil which corresponds to 1/4 of an actual magnet. The flux ripples simulated the 6th harmonic of the actual ground levitation coil. Some ideas to reduce the heat load were tried for the magnet model, such as applying high resistance thermal radiation shielding, increasing rigidity of the vacuum vessel, and using high purity copper plating on the helium vessel. These ideas proved effective, and the maximum heat load due to vibration was held to less than 4 W per magnet for the one coil magnet model. © 1997 Elsevier Science Ltd.

A superconducting magnet system is in the process of being developed for the Japan Railway (JR) Maglev project. These magnets require improved weight and reliability characteristics, and are cooled in a pool of liquid helium. The pool is maintained by a cryogenic refrigerator of 8–10 W capacity. The heat load on the cryogenic systems must be restricted to less than this capacity.

Heat loads are of two kinds. One is a steady heat load such as thermal radiation and conduction along coil supports. The other is a variable heat load caused by vibration of the magnet under system operation. The magnet vibrates due to harmonic ripples of electromagnetic flux generated by ground coils. Because of the flux ripples, induced currents flow within the aluminium wall of the vacuum vessel housing coils. This generates electromagnetic force due to the effect of the superconducting magnet field. Steady heat load is estimated to be about 4 W for a magnet consisting of four coils of the latest design. Thus the margin for the variable heat load due to vibration is 4 W for continuous magnet system operation.

Heat load caused by vibration in the magnet made in 1990 amounted to several tens of watts in the electromagnetic vibration tests which simulated the 6th harmonic of the ground levitation coils[1]. It was concluded that the harmonic ripples caused eddy current in the outer vessel of a magnet, which vibrated due to the electromagnetic force acting on the eddy current in the magnetic field of the superconducting coils. Especially, eddy current (a.c.) loss was induced in the inner helium vessel housing the superconducting coil due to relative vibration between the aluminium thermal shield and the coil[2].

Heat load tests have been performed using electromagnetic flux ripples for a superconducting magnet model of one coil which corresponds to 1/4 of an actual magnet. The flux ripples simulate the 6th harmonic of the actual ground levitation coil, and the frequencies of vibration from 60 to 340 Hz correspond to vehicle speeds of 100 to 550 km h^{-1}, respectively. The amplitude of coil vibration increased extremely at some resonance frequencies, however, the maximum heat load due to vibration was restrained to less than 4 W for a one coil magnet model by taking measures to reduce the heat load.

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Production of one coil model of superconducting magnet[3]

Structure of the superconducting magnet model

The structure of the superconducting magnet model is shown in *Figure 1*. The magnet model has one coil which consists of a race-track shaped structure embedded in epoxy. Thermal shields are placed around an inner helium vessel to shield the thermal radiation from an outer vacuum vessel. The outer vacuum vessel, made of aluminium, shields the coil from flux ripples generated by ground coils. The coil and the thermal shield are connected with the outer vacuum vessel by support structures which consist of eight lateral supports, two vertical supports, and a longitudinal support.

Means to reduce heat load to helium vessel

Heat load caused by vibration in the magnet made in 1990 amounted to several tens of watts in the electromagnetic vibration tests which simulated the 6th harmonic of ground levitation coils. The mechanism of the heat load was that eddy current was induced in the inner helium vessel due to magnetic ripples generated by relative vibration between the aluminium thermal shield and the coil in the high magnetic field of the superconducting coil. In order to reduce the heat load caused by eddy current of the inner vessel, magnet designs were changed as follows.

1. High resistivity of thermal shield. Carbon fibre reinforced plastic (CFRP) was applied to the thermal shielding. Electric resistivity of the carbon fibre is two orders higher than that of pure aluminium. Actually, CFRP itself is electrically insulating, because the plate of CFRP consists of carbon fibre and epoxy. This highly resistive thermal shield prevents the generation of magnetic ripples leading to relative vibration between the thermal shield and the superconducting coil. The thermal shield, however, has the role of removing conductive heat from support structures, so it is necessary for it to be of high thermal conductivity. The equivalent heat conductivity of the CFRP plate is $30 \text{ W m}^{-1} \text{ K}^{-1}$.

2. Increase of outer vessel thickness on the ground coil side. In order to shield the flux ripples generated by ground coils, the thickness of the outer vessel of aluminium was increased from 10 to 15 mm. In the 1990 magnet, the aluminium thermal shield plates shielded the coil from the flux ripples penetrating through the outer vessel.

3. Low resistivity of inner vessel. High purity copper plating was applied on the surface of the inner vessel to reduce the heat load caused by eddy current. A low residual resistance ratio (RRR) of the copper plating is desirable. The RRR applied to the one coil model was 50, and the thickness of the copper plating was 0.5 mm. There was no heat load caused by vibration of the thermal shield, and the heat load caused by eddy current due to the flux ripples penetrating through the outer vessel was reduced using the above design change. Electromagnetic vibration tests, however, showed that the mechanical heat load generated by vibration of the inner vessel became apparent for a higher frequency range where the heat load by eddy current was negligible. Means to reduce the vibration of the inner vessel were added to the above design changes of the one coil model.

4. High rigidity of outer and inner vessel. The number of lateral support structures was increased from four points to eight points, and a reinforcing structure was used for the outer vessel on the vehicle side to increase the rigidity of the outer and inner vessels.

Means applied to the one coil model are summarized in *Table 1*. Two kinds of one coil model were manufactured, the difference in the models being that the improved model has higher rigidity than the first model because of the lightweight honeycomb structure applied to the outer vessel on the vehicle side.

Electromagnetic vibration test for the one coil model[4]

Test method

The one coil model of a superconducting magnet was supported on the vehicle side by support frames (*Figure 2*). Vibration coils facing the one coil model were installed on the opposite side. Vibration coils consisted of two layers and two stages of upper and lower parts. A three-phase current was supplied to the vibration coils to simulate flux ripples of levitation coils. The total current of the superconducting coil was 700 kA, and that of the outer and inner vibration coils was 9.5 and 5.9 kA, respectively. Heat load was measured by helium evaporators and vibration of the vessels was measured by acceleration sensors.

Test results

Figure 3 shows the relation between heat load and vibration frequencies. The heat load increased extremely at some resonance frequencies, and the vibration of the coil increased at the same time. The coil was in torsion vibration mode
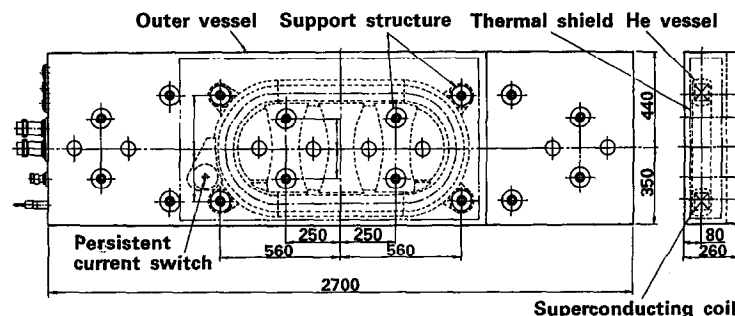

Figure 1 Superconducting magnet model of one coil which corresponds to 1/4 of an actual magnet

Table 1 Means to reduce the heat load to the He vessel

Objective	Means	Result of one coil model
High resistivity of thermal shield	High conductive CFRP	Electrical conductivity = insulated Thermal conductivity = 30 W m^{-1} K^{-1}
Low resistivity of inner vessel	High purity copper plating	RRR = 53, thickness = 0.5 mm, emissivity less than 0.1
High rigidity of outer and inner vessel	Increase of coil support Lightweight honeycomb structure (outer vessel)	Eight point support for lateral direction, equivalent weight thickness 15 mm, equivalent rigidity thickness 50 mm
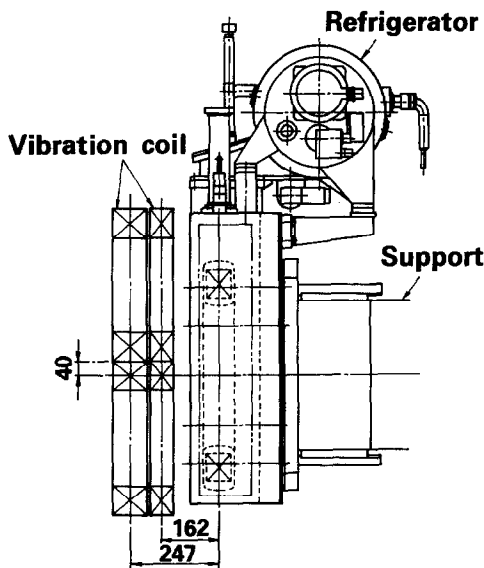
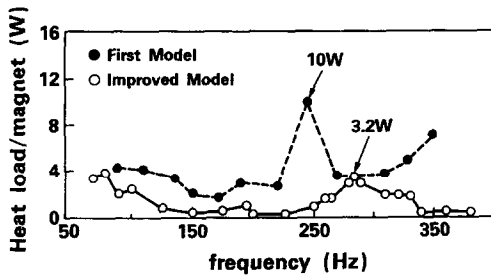**Figure 2** Setup for electromagnetic vibration test

Figure 3 Heat load to He vessel caused by electromagnetic vibration

at the frequencies of the maximum heat load for each model. The maximum heat load of the improved model is restricted to less than 4 W per magnet because of the high rigidity of the outer vessel. Means to reduce the heat load turned out to be effective.

Relation between heat load and vibration[5]

Major causes for heat load are considered to be dependent on vibration frequency ranges.

Low frequency range (60–100 Hz). Heat load in the low frequency range depends on the support rigidity of the coil model, as shown in *Figure 4*. Little difference was found between the charged and uncharged conditions of the superconducting coil. Heat load in the uncharged condition was due to eddy current loss within the inner vessel caused by penetration of magnetic ripples through the outer vessel. The heat load increment of the charged condition over the
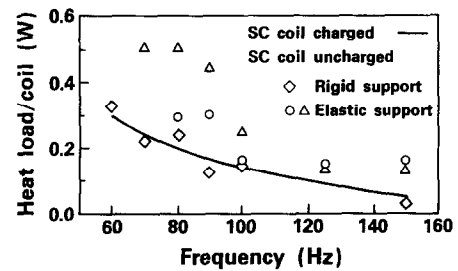

Figure 4 Heat load for one coil in range of low frequencies

uncharged condition was mainly caused by vibration of the coil model. In the case of a rigid support, no increment caused by the vibration was measured. This means that the main cause for heat load is a.c. loss in the low frequencies.

Middle frequency range (100–350 Hz). Heat load in the middle frequency range increases with increasing inner vessel vibration at resonance frequencies. *Figure 5* shows the relation between the heat load and the maximum deformation velocity of the inner vessel, where the vibration velocity is divided into rigid and deformation components. The maximum deformation velocity is defined as half of the maximum relative deformation between adjoining vibration measurement points on the inner vessel. The heat load is fully proportional to the maximum deformation velocity, as shown in *Figure 5*. Friction heat between the superconducting coil and its metal fittings is expressed as follows:

Friction heat = friction force
× slip velocity (deformation velocity)

This expression agrees with the test result that heat loss is proportional to deformation velocity of the coil. There is a threshold of heat load generation for the maximum deformation velocity. This also agrees with the fact that slippage starts from some amount of coil deformation.
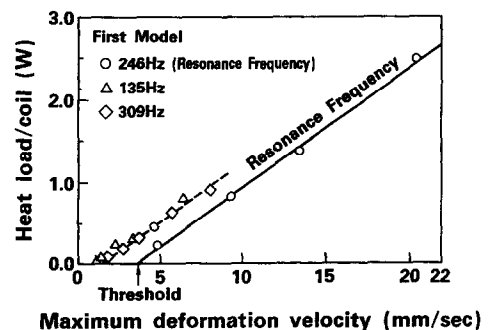

Figure 5 Heat load for one coil *versus* maximum deformation velocity of the He vessel
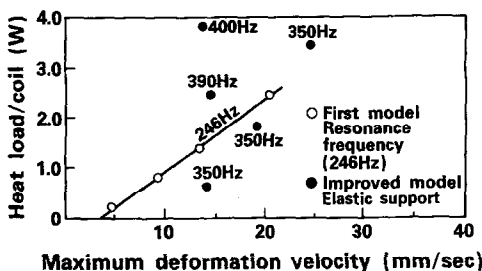
Figure 6 Heat load for one coil *versus* maximum deformation velocity of the He vessel in the range of high frequencies

High frequency range (more than 350 Hz). The frequency of vibration corresponding to a vehicle speed of 550 km h^{-1} is 340 Hz. A high frequency range of more than 350 Hz is actually of no use. In the case of an elastic support for the coil model, a larger heat load was measured than was estimated from the maximum deformation velocity, as shown in *Figure 6*. The vibration of the outer vessel increases at certain frequencies. For the high frequency range, additional heat load due to the outer vessel vibration is added to the mechanical friction loss in the inner vessel.

Electromagnetic vibration test analysis[6]

Electromagnetic analysis and vibration analysis were carried out to investigate the vibration characteristics of the magnet model, and the results were compared with the test results.

Electromagnetic analysis

Electromagnetic analysis of the induced current flow within the outer vessel caused by flux ripples of the vibration coil and of electromagnetic forces acting on the induced current in the magnetic field of the superconducting coil was performed. An analytical model is given in *Figure 7*, showing a thin shell model of the outer vessel.

Figure 8 shows the results of eddy current density and electromagnetic force distribution. Three eddies per superconducting coil corresponding to the vibration coils appear in the upper and lower side, and the eddies move longitudinally within the plate of the outer vessel. Electromagnetic forces become large at the points on the outer vessel corresponding to the corners of the superconducting coil, giving the outer vessel torsional moment. The maximum electromagnetic force was 20 kPa.
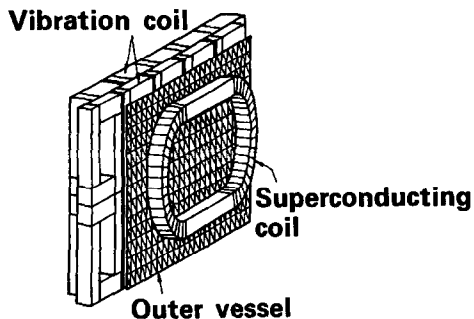

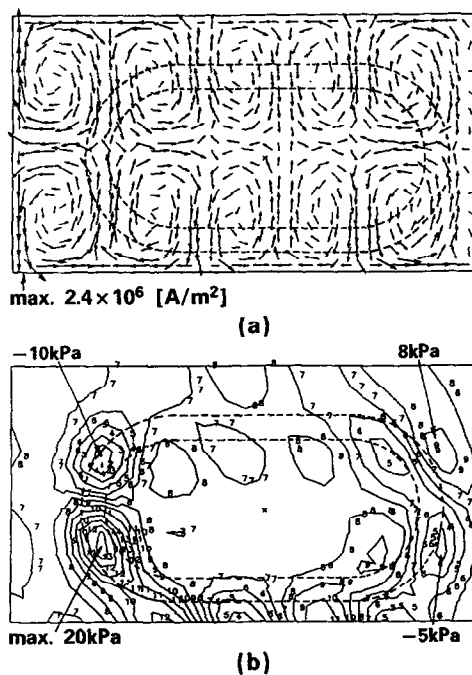**Figure 7** Electromagnetic analysis model

Figure 8 Results of electromagnetic analysis: (a) eddy current density distribution of the outer vessel; (b) electromagnetic force of the outer vessel

Vibration analysis[7]

Modal analysis was firstly carried out for the one coil model in order to measure the natural vibration frequencies and vibration modes. The results of the modal analysis were compared with those of finite element analysis (FEM) to check the suitability of the FEM model. An analytical model is shown in *Figure 9*, showing a thin shell model of the outer vessel, and a beam model of the coil, with elastic spring of the supports. *Figure 10* shows the comparison of the transfer function sums. The difference between FEM analysis and modal analysis was less than 10% at natural vibration frequencies.

Figure 11 shows the response of coil vibration, using the electromagnetic forces mentioned in Section 3.1, where the damping coefficient is assumed to be 5%. The simulated results generally agree with the measured results at the resonance frequencies of 286 and 396 Hz for the improved model.
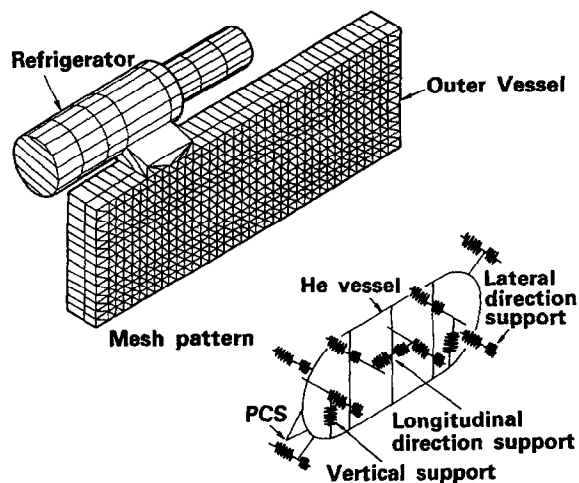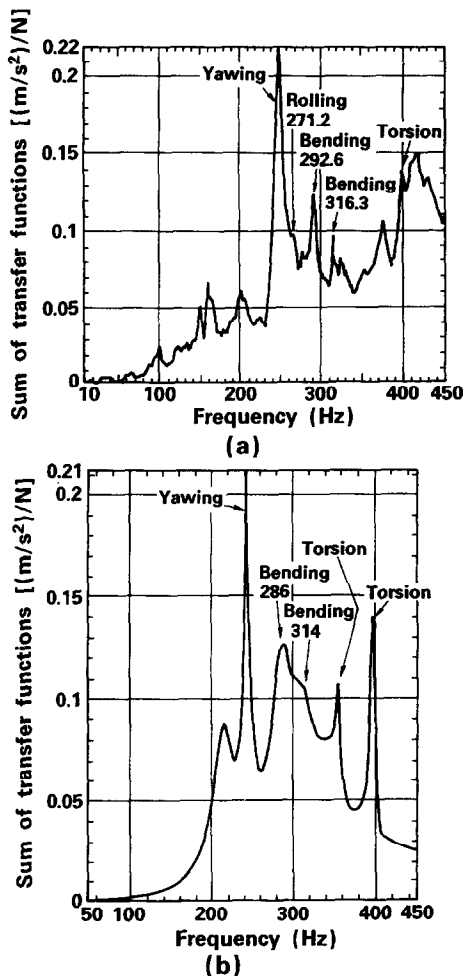

Figure 9 Vibration analysis model

Figure 10 Sum of transfer functions caused by mechanical vibration: (a) measured transfer functions by modal analysis; (b) simulated transfer functions by FEM analysis

Figure 11 Response acceleration caused by electromagnetic vibration: (a) bending mode (286 Hz); (b) torsional mode (397 Hz)

(2) The main cause of heat load for the low frequencies of less than 100 Hz was eddy current loss in the inner vessel due to flux penetration through the magnetic shield of the outer vessel. For frequencies from 100 to 350 Hz, mechanical friction loss due to coil deformation is dominant, and for frequencies of more than 350 Hz, additional loss due to outer vessel vibration adds to the mechanical friction loss in the inner vessel.

(3) The friction loss in the inner vessel has a linear relation with the maximum deformation velocity of the coil. For the maximum deformation velocity, there is a threshold of generating friction loss.

(4) The vibration of the magnet can be estimated by electromagnetic analysis for the outer vessel and vibration analysis for the magnet. Analytical results generally agree with experimental results where a damping constant of 5% is used.

Conclusion

Heat load tests have been performed using electromagnetic flux ripples for a superconducting magnet model of one coil which corresponds to 1/4 of an actual magnet. In order to reduce the heat load due to vibration, some ideas were applied to the inner vessel, outer vacuum vessel, and thermal shield of the magnet model. As a result, effective restriction of the heat load could be achieved. Conclusions are as follows.

(1) Means applied for the magnet model to reduce the heat load were low resistivity of inner vessel, high resistivity of thermal shield, and high rigidity of outer and inner vessel. These means were effective, and the maximum heat load due to vibration was restrained to less than 4 W per magnet.
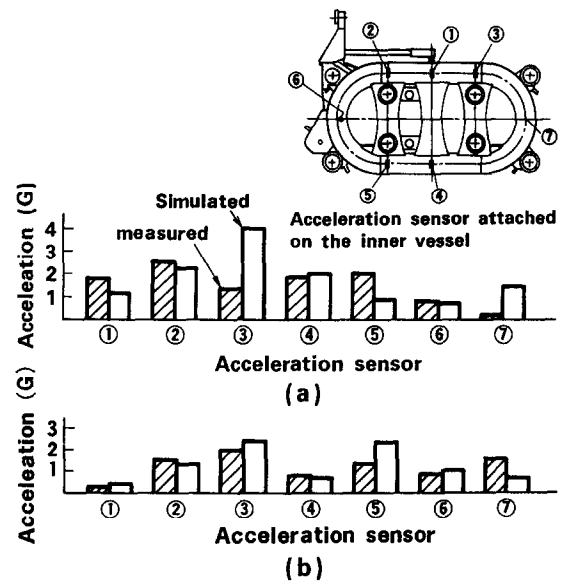
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