Development of a superconducting magnet for simplified ground coils

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Abstract

In the superconducting Maglev system, it is important to reduce the costs to realize a commercial system. Simplifying the structure of ground coils is effective to reduce the costs, but the harmonic magnetic fields caused by ground coils increase. The on–board superconducting magnets vibrate due to these harmonic fields. Excessive vibration gives rise to large heat loss. We have studied a superconducting magnet for simplified ground coils. In this paper, we report the design of the superconducting magnet, including the results of emplacement tests and several analyses.

1 Introduction

The superconducting Maglev system that is now under development recorded the maximum speed of 581 km/h in December 2003 on the Yamanashi test line. The system was evaluated by the Technological Assessment Committee of Ministry of Transport (now Ministry of Land, Infrastructure and Transport) in March 2000, and three technical problems were point out for commercial operation. We continuously promote and develop our project to solve these problems [1].

In the Maglev system, it is important to reduce the construction and the maintenance costs, since ground coils to propel, levitate and guide are built on a guideway all along the whole line. Therefore, we required simplify the ground coil in order to reduce the costs.
On the other hand, the on-board superconducting magnets (SCMs) are subjected to electromagnetic disturbance by the harmonic magnetic field from the ground coils. Consequently, the SCMs cause electromagnetical and mechanical heat loss. The selection of the ground coils has great influence on the reliability and the durability of SCM and the load capacity of the on-board refrigerator. Since the disturbance that the SCM is subjected to becomes larger than that by the present ground coils, we proposed the performance improvement of the SCM.

Therefore, we reviewed the SCM (hereinafter referred to as " the SCM for simplified ground coils ") that would realize the performance to reduce the cost of ground coils when simplified ground coils were built in the guideway.

In this paper, we report the background and the characteristics of the development of an SCM for simplified ground coils including the results of emplacement tests and several analyses.

2 Structure of present SCM

Figure 1 shows the structure of the present SCM for Yamanashi Maglev. The SCM is composed of two sections, a tank section and a coil section. The tank section consists of a liquid helium tank, a liquid nitrogen tank and a on-board refrigerator. The on-board refrigerator liquefies gas helium and gas nitrogen evaporated in the coil section due to vibration disturbance. The coil section consists of a superconducting coil, inner vessel, radiation shield, outer vessel and several other parts. The liquid helium cools and keeps the superconducting state in the inner vessel of the superconducting coil made of niobium-titanium alloy wire. The radiation shield to prevent the penetration of radiation heat is cooled by the liquid nitrogen. The outer vessel keeps these parts in a vacuum. The SCM is energized by an exciting system at the train depot, and operated in the persistent current mode during running tests.

3 Background of the design of SCM for simplified ground coils

3.1 Simplified ground coil

Figure 2 shows the ground coil of the Maglev system. It is composed of the coils for propulsion, levitation and guidance. Propulsion coils or levitation coils also play the role of guidance coils.

The levitation coils of the Yamanashi test line are arranged at present at 60-degree pitches. The 120-pitch levitation coils can cut the number of coils to a half. The propulsion coils of the Yamanashi test line are arranged to compose a double layer. The simplified propulsion coils are designed as single layer coils. As a future system, we have developed a PLG coil that combines the propulsion coil, levitation coil and guidance coil [2].

In discussing the influence on the SCM of the installation of simplified ground coils, we evaluate the characteristics of the heat loss of the SCM for simplified ground coils by using an electromagnetic vibration test simulator [3]. Consequently, the heat loss in the low frequency range exceeds the capacity within the on-board refrigerator and that at a specific frequency is in excess of approximately three times the capacity of the on-board refrigerator. On the other hand, it was assumed that the heat loss influence of the single layer propulsion coil was comparatively small in the operation of commercial system.

Therefore, we studied the influence on the SCM for 120-degree pitch levitation coils first and on the single layer propulsion coils at the final stage.

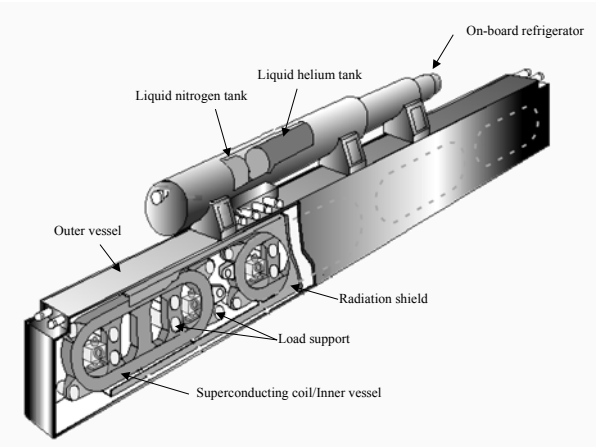


Fig. 1 Outline of the superconducting magnet

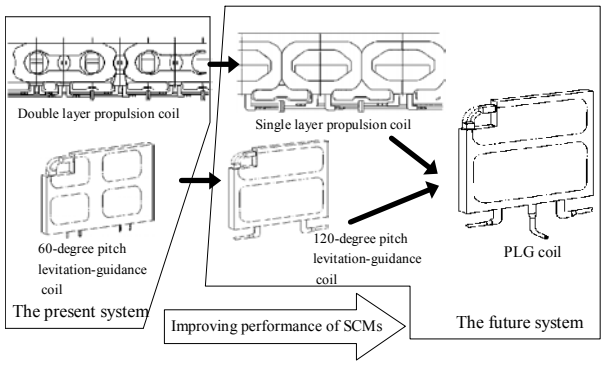


Fig. 2 Structures of ground coils

3.2 Influence on SCM and subjects

To design an SCM for simplified ground coils, we need to problem several improvements against the vibration disturbance that becomes larger than that for the present SCM under some conditions. The performance required for the SCM is as follows.

① Weight shall be less than the required level.
② Vibration shall be less than the design standard when vehicles are running.
③ Heat loss caused by the vibration due to the harmonic magnetic field shall fall within the capacity of the on-board refrigerator.

Because the vibration becomes more intensive, we studied to reduce the vibration specifically.

We explain the exciting vibration power from the levitation coil. Figure 3 (a) shows the 60-degree pitch levitation coil of the Yamanashi Maglev test line. Figure 3 (b) shows the 120-degree pitch levitation coil. The structure of the 120-degree pitch coil can reduce construction costs, but increases the harmonic magnetic fields caused by ground coils. Therefore, we studied the influence of the 120-degree pitch on the SCM. Table 1 compares the 60- and 120-degree pitches. Figure 4 shows the excitation force of superconducting coils at these two coil pitches. The frequency of the harmonic magnetic fields of 120-degree pitch is 154 Hz at 500 km/h. The frequency equals half that of the 60-degree pitch. The lateral excitation force ratio, 60-degree pitch to 120-degree pitch, is 0.2 kN : 5.6 kN. Similarly, the yawing moment ratio, 60-degree pitch to 120-degree pitch, is 0.6 kNm : 1.2 kNm. Because the wavelength of the excitation force in the propulsion direction is long and the excitation force for the SC coil becomes opposite in phase to the next superconducting coil, the SCM bends to a large extent. After all, the SCM vibrates at a low order mode which the SCM to cause the elastic deformation.

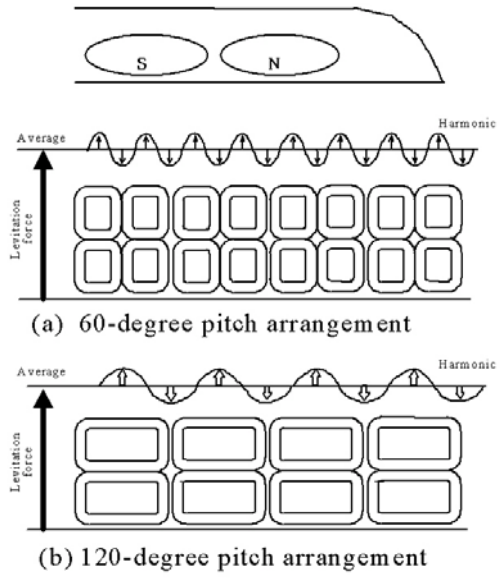


Fig. 3 Structures of 60-degree pitch coils and the 120-degree pitch coils

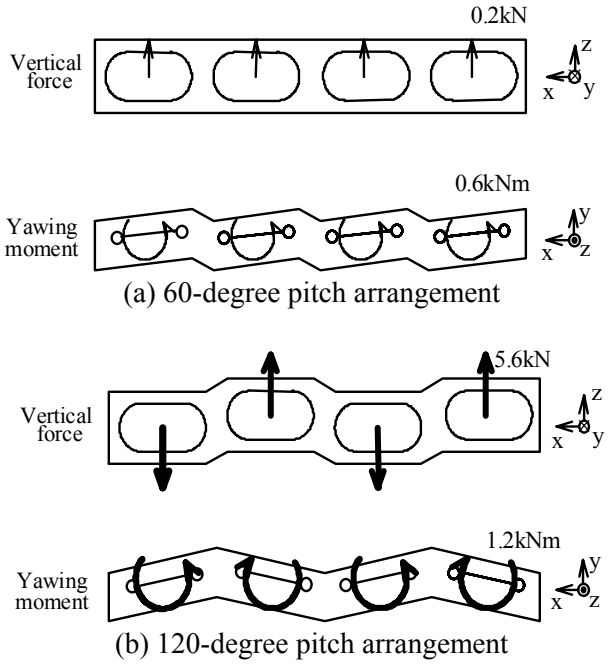


Fig.4 Excitation force of SCs vs. coil pitch

Because the frequency of the harmonic magnetic field becomes a half, it is easy in low-speed running for the harmonic magnetic field to penetrate from the outer vessel at the ground coil side more into the inner vessel than into the present ground coil. An eddy current loss is generated in the radiation shield and the inner vessel.

Table 1 Comparison between the 60-degree pitch and the 120-degree pitch

	60-degree pitch	120-degree pitch
Main harmonic field order	Sixth	Third
Frequency of excitation force	60～308Hz	30～154Hz
Amplitude of excitation force	Small	Large
Phase of excitation force between neighboring SC coils	Same	Opposite

4 Several improvements and effects

We describe several improvements for the problem of the SCM for simplified ground coils. We suggest a new method to evaluate the vibration in the electromagnetic vibration test and running. This method gives three improvements on the side of SCM and one improvement by the side of the ground coil. The two other improvements for more optimization are being described. As for the solution, we verified an experiment and an analysis and evaluated the coil performance as a whole SCM.

4.1 Evaluation of vibration in electromagnetic vibration test and running

The electromagnetic vibration test which is done to evaluate the SCM is to evaluate vibration force in running as much as possible, but it is difficult in the test to realize the vibration force in running under all positing conditions. Therefore, we defined the vibration force that is equal to the yawing moment. The yawing moment has a significant effect on the SCM. However, in the 120-degree pitch coil vibration test, it is cleared that the heat loss of the SCM is closely related to that in the vertical bending vibration. This issue inspires that a new standard becomes necessary. Therefore, we suggest a new evaluating method assuming the SCM as a beam. The generalized force for the vertical bending mode standard function is suggested [4]. We compared the new evaluating method with the harmony response analysis that used a finite element method.

4.1.1 Generalized force

As for each eigenvalue, the vibration mode standard function $W_i(x)$ is sought like the type (1) as the function at an optional point x under the assumption that SCM is a uniform beam of the end of the free with length 1 and seeking the eigenvalue of the vertical vibration.

$$W_i(x) = \cos k_i x + \cosh k_i x - \alpha_i(\sinh k_i x + \sin k_i x) \qquad (1)$$

where

$$k_i = \lambda_i / l \qquad (2)$$

$$\alpha_i = \frac{\cos \lambda_i - \cosh \lambda_i}{\sin \lambda_i - \sinh \lambda_i} \qquad (3)$$

λ is the eigenvalue of the vibration mode and the eigenvalue about the vertical first and second bend modes is λ_1=4.73 and λ_2=7.853, respectively.

The generalized force $V_{z,i}(t)$ can be expressed by the equation (4) which integrates this standard function and the product of the vibration force $F_z(x,t)$ of the vertical direction over the full length.

$$V_{z,i}(t) = \int_{x=0}^{l} W_i(x) \cdot F_z(x,t) dx \qquad (4)$$

We seek the generalized force of the electromagnetic vibration test and running about the first and second vertical vibration modes by using the equation (4). The vibration force $F_z(x,t)$ introduces an

electromagnetic field analysis, but omitted the explanation these of [4]. The amplitude of vibration ratio in the case of the electromagnetic vibration test and running is shown in Table 2.

Table 2 Amplitude ratio at the vertical vibration mode

	electromagnetic vibration test / running test
First mode	3.3
Second mode	0.5

4.1.2 Harmony response analysis

In the previous section, we suggested the generalized force that evaluates the vibration force for SCM. Therefore, by the structure analysis of the SCM, it is verified whether the generalized force was proper as a means to evaluate the input condition of the vibration force in the case of electromagnetic vibration test and running.

Specifically, we modeled the SCM and the bogie as shown in Fig. 5. The z-direction force and the yawing moment to relate with the vertical vibration are input in the outer vessel position of four superconducting coils in the case of electromagnetic vibration test and running, respectively. We analyzed the harmony response.

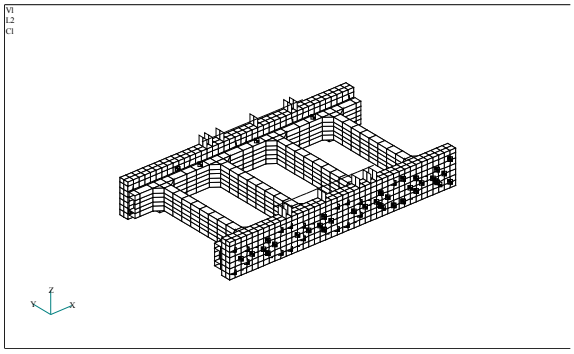
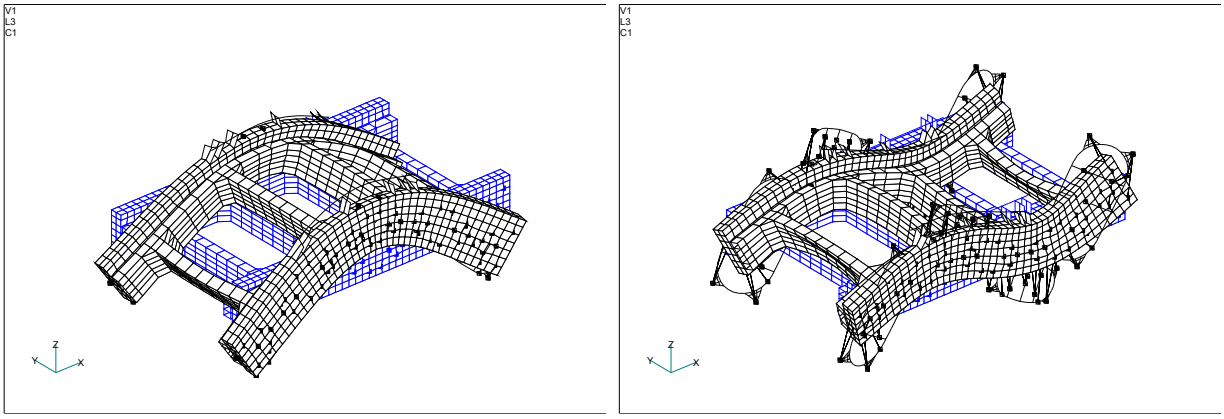


Fig. 5 The SCM model



(a) First mode (b) Second mode

Fig. 6 Vertical vibration modes

We analyzed the eigenvalue first, and cleared the first and second vertical vibration modes as shown in Fig. 6. Figure 6 shows the velocity property of the acceleration at the bottom of the SCM. The vibration response Fig. 6 is normalized for the acceleration at the vertical first vibration mode to compare it with that in Table 2.

4.1.3 Comparison of the analysis and the evaluation of the vibration

We show the ratio of the amplitude in the electromagnetic vibration test to that in running to propose the comparison in Table 2. The analysis for the two cases is in agreement with each other. Therefore, we verified that the evaluation with the generalized force was valid.

When the vibration evaluates from these results, the amplitude of vibration at the first vertical vibration mode in running becomes about 33% (about 10% in the heat loss) in the electromagnetic vibration test. For the result, we decided that the special improvement at the first vertical vibration mode is not necessary. On the other hand, the amplitude of vibration at the second vertical vibration mode in running becomes about twice that in the electromagnetic vibration test. It is clear for the SCM to need some improvements.

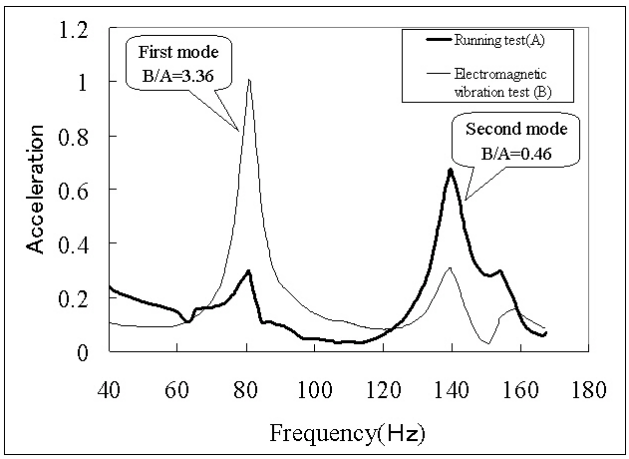


Fig. 7 The vibration response in a running test and an electromagnetic vibration test

4.2 Improvement of vertical support stiffness

By the evaluation of the generalized force, we studied the improvement for the vertical second vibration mode in which the heat loss in running is increases.

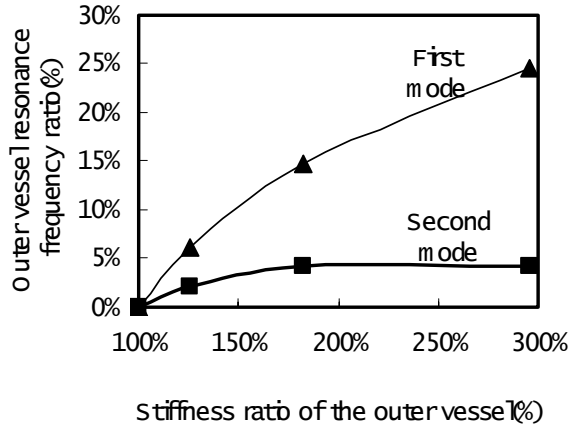


Fig. 8 The resonance frequency varying stiffness of the outer vessel

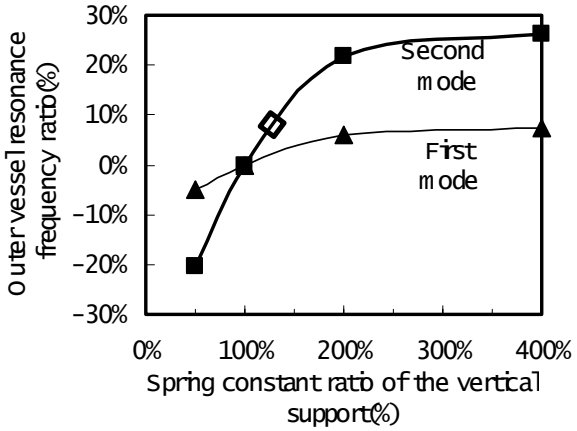


Fig. 9 The resonance frequency varying spring constant of the vertical support between the outer vessel and the inner vessel

By using a structure analysis model shown in Fig. 5, we analyzed the resonance frequency for different values of stiffness of the outer vessel and spring constant of the vertical support between the outer vessel and the inner vessel. We show the result in Figs. 8 and 9, respectively.

When giving the outer vessel stiffness, the frequency of the first vertical vibration mode can be raised, but the frequency of the second vertical vibration mode tends to saturate. On the other hand, Figure 9 shows that it is applied to raise the spring constant of the vertical support between the outer vessel and the inner vessel in order to raise the resonance frequency of the second vertical vibration mode.

As a result, we proved that it was possible to shift the resonance frequency to outside the region of the running velocity for improving the vertical support stiffness. We marked the target in Fig. 9. In this case, we anticipate that the heat loss of the support in the steady state is about 3% up per SCM and there are no problems in increasing the weights.

4.3 Relaxation of the stress in the superconducting coil

The heat loss area for the vibration is divided into the superconducting coil part (the superconducting coil and the inner vessel) and others (piping and tank part). Because the heat loss at the superconducting coil related to the stress occurring in the superconducting coil, the heat loss at the superconducting coil is very small if the superconducting coil doesn't deform [5].

Therefore, we studied that the method of the relaxation of the stress occurring in the support is to add reinforcement in the inner vessel [6-8]. The method is effective for the heat loss caused by the vertical and lateral vibration of the superconducting coil part. We confirmed the effect against the vertical vibration through an experiment. We also anticipate a similar effect for the lateral vibration.

4.4 Increase of outer vessel thickness on the guideway side

This method directly shields the harmonic magnetic field that penetrates from the ground coils into the shield plate and the inner vessel. We expect that it can reduce the alternating current loss in low-speed running to 1/4 [9]. The increase of the thickness also strengthens the outer vessel and becomes a valid method to reduce vibration and heat loss at the resonance frequency.

However, there is disadvantage in the increase of board thickness, such as those related to weight increase.

4.5 Adoption of asymmetrical levitation coil

This method is an improvement on the side of the ground coil. The asymmetrical the 60-degree pitch levitation coil improves the performance of levitation and guidance at high speed and reduces the lateral vibration of SCM. Similarly, we expect that the asymmetrical the 120-degree pitch levitation coil reduce the lateral vibration to about 70% and heat loss to about 50% [10].

4.6 Fundamental analysis of bogie structure to reduce vibration

We think that it is necessary to optimize the design of SCM and bogie structure for vibration reduction. We will study the stiffness improvement for the SCM combined with the bogie and the optimal arrangement of equipment.

4.7 Other improvements

We cannot confirm the durability of the pipes and bellows in the SCM in running tests. Therefore, we will study the design to avoid the resonant frequency and to increase the support and all that, and verify these effects by new endurance tests.

5 Structure of SCM and prospects of heat loss

The structure of SCM that we designed as the basis of the discussion in Chapter 4 is shown in Fig 10. There are three major improvements (Fig.9). The prospect of the heat loss of the SCM for simplified ground coils is shown in Fig.11. The peak of the heat loss for the SCM falls within the capacity of the refrigerator in the speed range up to 500 km/h [11]. We also estimate that the increase of the weight is within 10% of the target weight.

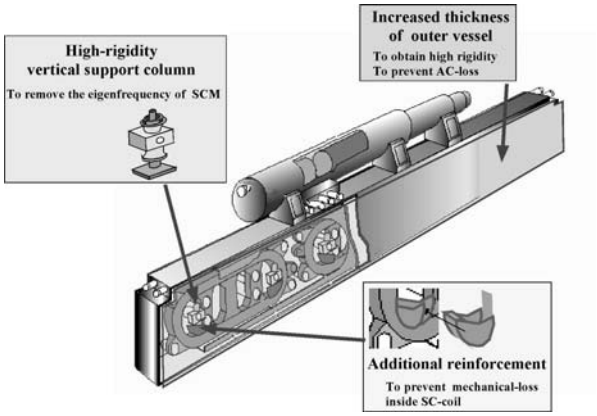


Fig.10 Superconducting magnet for simplified ground coils

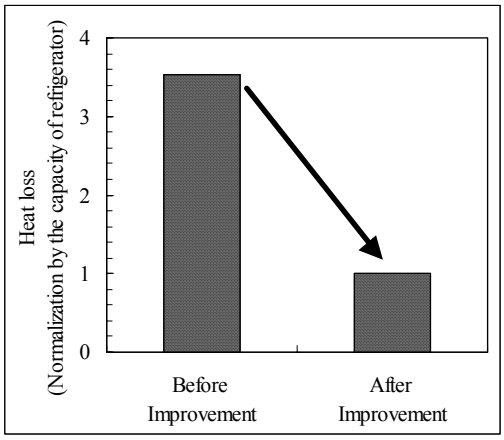


Fig. 11 Prospect of the heat loss at a certain specific frequency of a superconducting magnet for simplified ground coils

6 Conclusion

For the development of the SCM for a simplified ground coil, we suggested a new evaluation method for the vibration in running and obtained the prospect that the serious problem of excessive heat loss at specific velocity is solved by adopting three improvements and an improvement for ground coils.

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