# Characteristics of SC Coil Configuration for EDS Maglev to Reduce Leakage Flux with Strengthened Magnetomotive Force

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**Abstract**

An improved configuration of SC coils for EDS maglev, which has small-size coils on its end can reduce the environmental magnetic field, so that it can strengthen the magnetomotive force of SC coils. This paper describes their characteristics of levitation, guidance and propulsion performance at strengthening the magnetomotive force.

## 1. Introduction

Vehicles of superconducting maglev system are suspended and driven by superconducting (SC) coils, which have a strong magnetic field, and their passenger cabins must be shielded from the leakage flux of the SC coils. Therefore, the passenger cabins keep away from the SC coils by concentrating them on articulated trucks, and magnetic shielding by industrial-pure steels and electromagnetic steels are also installed on the cabins. As a result, the maximum magnetic flux is less than the target value, though the weight of magnetic shielding is not small. For this reason, we examined a method to design magnetic shielding by an optimization program [1], and proposed an improved configuration of SC coils to reduce their leakage flux [2].

The improved configuration of SC coils has end coils whose smaller length reduces the main leakage flux from the end coils. Our previous papers examined the reduction of magnetic shielding weight and the characteristics of levitation and propulsion in this system with constant magnetomotive force of SC coils [3].

On the other hands, due to the reduction of leakage flux, the improved configuration can reinforce their magnetomotive force. This does not reduce the weight of magnetic shielding, but provides better performance for levitation and propulsion. In order to commercialize the maglev system, the reduction of running energy and take-off velocity are strongly expected [4].

Therefore, this paper studies the characteristics of magnetic field, levitation, guidance and propulsion in the improved configuration of SC coils at strengthening the magnetomotive force. By using a numerical example, realistic specifications and their performance are clarified.

## 2. Configuration and Principle

Figure 1 shows the conventional configuration whose SC coils have a constant length. The magnetic fields by inner coils are canceled by the magnetic fields generated by the opposite poles placed in their vicinity. However, the end coils do not have neighboring opposite poles at any side. Therefore, they strengthen the leakage flux on the side without a neighboring coil. Thus, the magnetic fluxes spread at the end of articulated truck mounting the SC coils, and increase the weight of magnetic shielding on the cabin, the magnetic field of crossing cars and that outside the guideway.

In order to reduce this leakage flux, the improved configuration has end coils whose length is smaller than that of conventional configuration as shown in Fig. 2. Consequently, the improved configuration can reduce the far field on the cabins, crossing cars and outside the guideway while keeping the closed field on the ground coil constant.

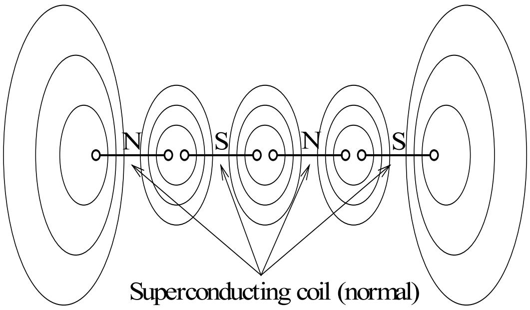


**Fig. 1 Conventional configuration of SC coils**

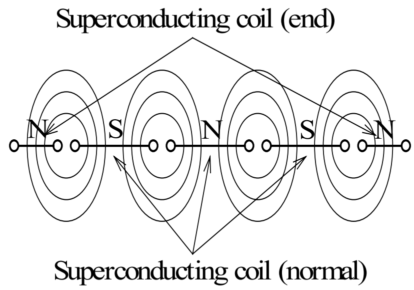


**Fig. 2 Improved configuration of SC coils to reduce leakage flux**

## 3. Analysis model

In analyzing the performance of magnetic field, levitation, propulsion and guidance, we assume the following model and method.

(1) SC Coils

Figure 3 shows an analytical model of SC coil configuration. The model has four poles, whose end coil length is reduced with x when the inner coil pitch is τ and the gap between neighboring coils is constant. In this case, the improved configuration can easily apply to a part of the original train-set because its phase of magnetic flux agrees with the original one. However, it is necessary to strengthen the magnetomotive force of SC coils when the whole length of SC coil configuration decreases.

(2) Ground Coils

Figure 4 shows an analytical model of ground coils. The model applies a combined propulsion, levitation and propulsion coil with 120 degrees of coil pitch whose specifications are constant. Table 1 shows specifications of numerical example.

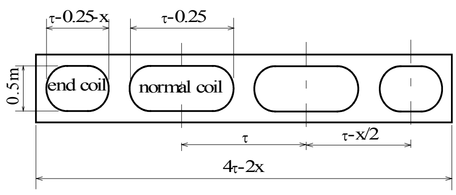


**Fig. 3 Configuration of SC coils with small-size SC coils on these ends (4-poles)**

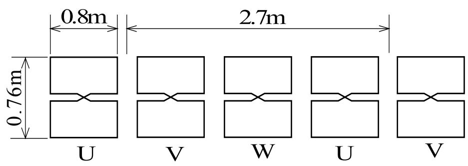


**Fig. 4 Configuration of ground coils**

Table 1 Specifications of numerical example

| | |
|---|---|
| [Superconducting coil] | |
| Coil pitch | τ m |
| Shape | Race track type |
| Magnetomotive force | 700-1000kA |
| [Ground coil] | |
| Coil pitch | 0.9 m |
| Lateral displacement | 0.185 m |
| Propulsion current | 1000 A |
| [System] | |
| Levitation force | 230 kN/truck |
| Propulsion force | 30 kN/truck |

(3) Magnetic Shielding

Figure 5 shows an analytical model of magnetic shielding. Magnetic shielding plates are installed around the articulated truck mounting SC coils to reduce the magnetic field of cabins. The two cabins are connected by a corridor, which has a smaller width and higher bottom than those of cabins to avoid a strong magnetic field. The areas of slanting lines indicate the magnetic shielding plates, which are installed at the top, bottom, side and end of cabins and corridor.

We evaluate the weight of magnetic shielding plates, which are designed by the optimized design method for magnetic shielding referred in [1].

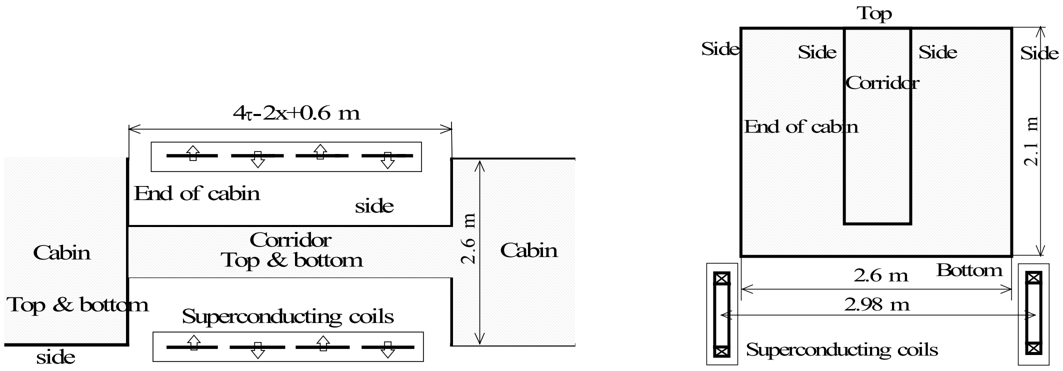


**Fig. 5 Configuration of magnetic shielding system**

# 4. Performance results

## 4.1 Magnetic field of crossing cars

To represent the environmental magnetic field, we examine the magnetic field at a crossing car with a smaller end coil and different coil pitch τ of 1.35 to 1.55 m. The maximum whole length of SC coil configuration is restricted to 5.4 m and the minimum length of straight part on the end coil to 0 m.

Figure 6 shows the maximum magnetic flux density at 1 kA of magnetomotive force of SC coils at a 3 m point from SC coils in the lateral direction. The reduced size of 0.5 m has the lowest flux density, which is 27-45 % of that of original configuration at any coil pitch. Therefore, their flux density increases only to 39-64 % in this case even if the magnetomotive force increases to 1,000 kA, or 1.4 times of that of the original one.

Figure 7 shows the magnetic field distribution in the longitudinal direction of the original and improved configurations, and the latter has a small-size coil on its end, whose reduced length x is 0.45 m and the coil pitch τ is 1.5 m. The values of lateral and whole flux density are indicated By and B, respectively. The flux density at the end of the improved configuration is not large in contrast to that of the original one.

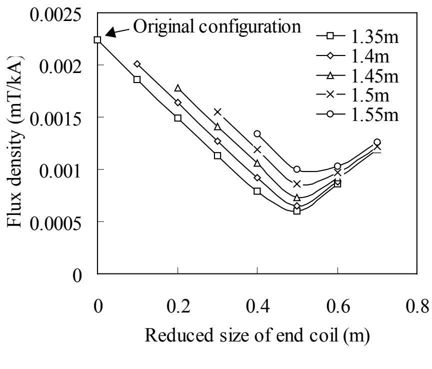


**Fig. 6 Flux density vs. reduced size of end coil**

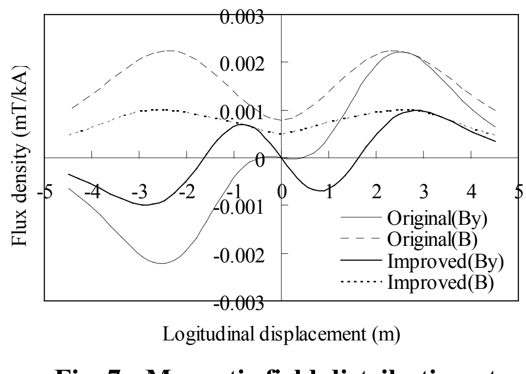


**Fig. 7 Magnetic field distribution at reduced size of end coil**

## 4.2 Magnetic shielding

Figure 8 shows the weight of magnetic shielding of the original and improved configurations. The weight of magnetic shielding of the improved configuration can reduce to 73 %, 84 % and 77 % at the cabin, corridor and in total in comparison with that of the original one, respectively. If the weight of magnetic shielding is proportional to the magnetomotive force of SC coils, the weight of the improved configuration at the magnetomotive force of 1,000 kA is thought to be the same as that of the original one at the magnetomotive force of 700 kA.

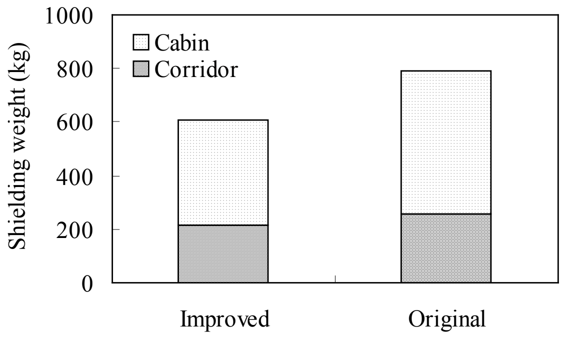


**Fig. 8 Magnetic shielding weight at reduced size of end coil**

## 4.3 Levitation performance

To investigate the levitation performance, we examine the drag ratio when the end coil size is reduced to 0.5 m and the SC coil magnetomotive force of SC coils increases. The drag ratio means the ratio of the levitation force to the drag force for levitation. Figure 9 shows the drag ratio at the cruising speed of 500 km/h at different coil pitches of 1.35 to 1.55 m. The drag ratio increases as the magnetomotive force and coil pitch become larger. However, the increase of drag ratio by the coil pitch also depends on the increase of the whole length of SC coil configuration. The drag ratios of the improved configuration at the magnetomotive force of 1,000 kA when the coil pitch $\tau$ is 1.35 m and 1.55 m increase to 1.4 times and 2 times that of the original one at 700 kA, respectively.

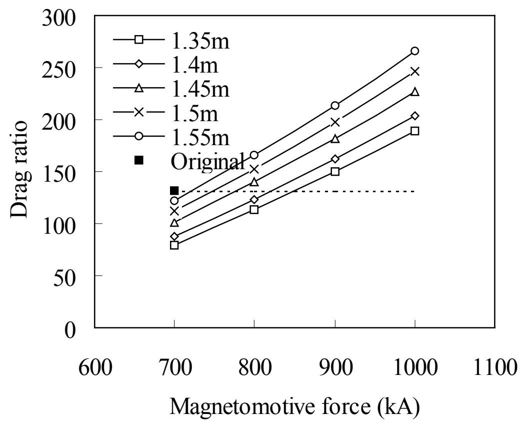


**Fig. 9 Drag ratio at reduced size of end coil**

## 4.4 Guidance performance

Since the side-wall levitation system in the Electro-Dynamic Suspension has a large coupling stiffness between guidance and rolling, it restricts the take-off velocity by the equivalent stiffness $F_{yy}$*

and $M_{\phi\phi}$* as follows.

$$F_{yy}^* = F_{yy}\left(1 - \frac{F_{y\phi}M_{\phi y}}{F_{yy}M_{\phi\phi}}\right) \qquad M_{\phi\phi}^* = M_{\phi\phi}\left(1 - \frac{F_{y\phi}M_{\phi y}}{F_{yy}M_{\phi\phi}}\right)$$

where $F_{yy}$ and $M_{\phi\phi}$ indicate the guidance and rolling stiffness, respectively, and $F_{y\phi}$ and $M_{\phi y}$ the corresponding coupling stiffness thereof. More stable levitation can be obtained as $F_{yy}$* and $M_{\phi\phi}$* become larger. Therefore, this value is one of the criterion for stable levitation [3].

Figure 10 shows the equivalent guidance stiffness at the take-off speed of 100 km/h at different coil pitches of 1.35 to 1.55 m when the end coil size is reduced to 0.5 m and the SC coil magnetomotive force of SC coils increases. The equivalent guidance stiffness also increases as the magnetomotive force and coil pitch become larger. The equivalent guidance stiffness of the improved configuration at the magnetomotive force of 1,000 kA when the coil pitch τ is 1.35 m and 1.55 m increase to 2.4 times and 3.2 times that of the original one at 700 kA, respectively.

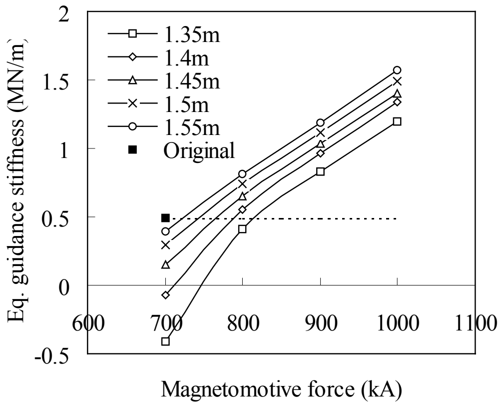


**Fig. 10 Equivalent stiffness at reduced size of end coil**

## 4.5 Propulsion performance

To study the propulsion performance, we examine the efficiency multiplied by the power factor of Linear Synchronous Motor when the end coil size is reduced to 0.5 m and the SC coil magnetomotive force of SC coils increases. Figure 11 shows the efficiency multiplied by the power factor at the cruising speed of 500 km/h when the coil pitches τ is 1.35 to 1.55 m. Although the efficiency multiplied by the power factor also increases as the magnetomotive force and coil pitch become larger, their increasing ratio at the coil pitch over 1.5 m is small. It would be surmised that this property depends on the asynchronized coil pitches between the ground and vehicles when the coil pitch of ground coil is kept constant. The efficiency multiplied by the power factor of the improved configuration at the magnetomotive force of 1,000 kA when the coil pitch τ is 1.35 m and 1.55 m increase to 104 % and 115 % of that of the original one at 700 kA, respectively.

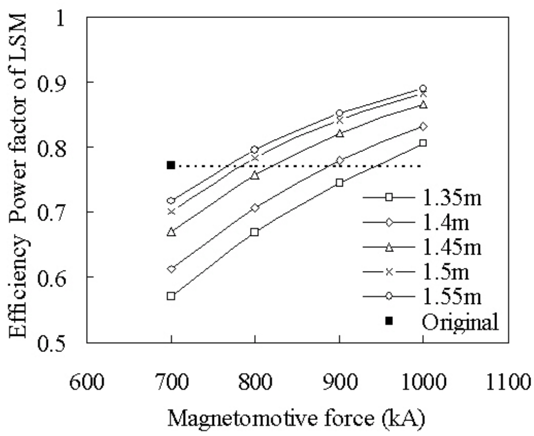


**Fig. 11 Efficiency×power factor at reduced size of end coil**

### 4.6 Proper Specifications

After examining the performance by changing the size and magnetomotive force of SC coils, we found the realistic specifications of the improved configuration as shown in Fig. 12. Furthermore, Fig. 12 shows the equivalent guidance stiffness in the improved and original configurations. In comparison with the original one, the improved configuration features the following.

(1) The SC coil magnetomotive force of 850 kA, which is 1.2 times that of the original one, is selected in consideration of mechanical designs of SC coils.

(2) Though the magnetomotive force becomes 1.2 times that of original one, the magnetic field on crossing cars can decrease to 56 % and the shielding weight to 93 %.

(3) Due to the strengthened magnetomotive force, the drag ratio can increase to 1.4 times, the equivalent guidance stiffness to two times and the efficiency multiplied by the power factor of LSM to 1.1 times those of original ones, respectively. In particular, the take-off velocity can be decreased to 50 km/h.

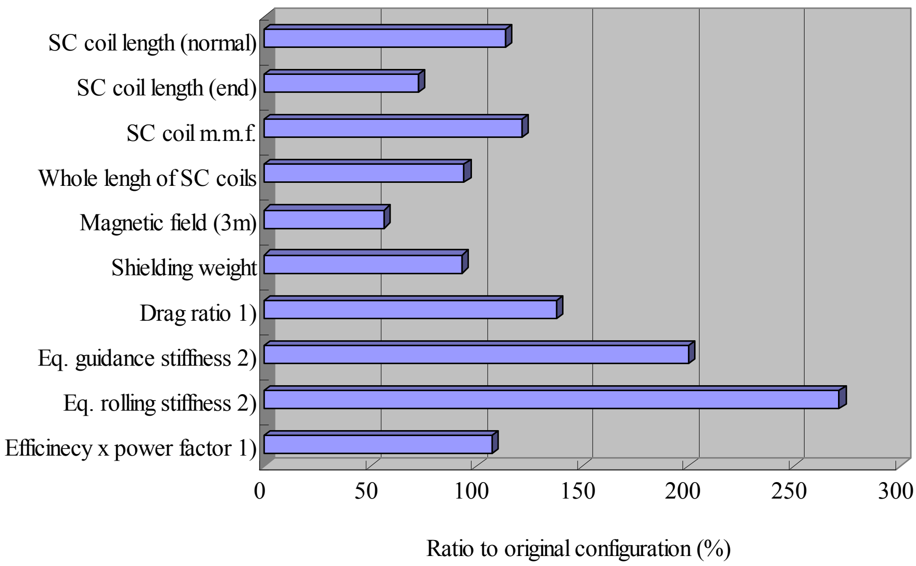


**Fig. 12 Realistic specifications of improved configuration**
**1) At 500km/h 2) At 100km/h**

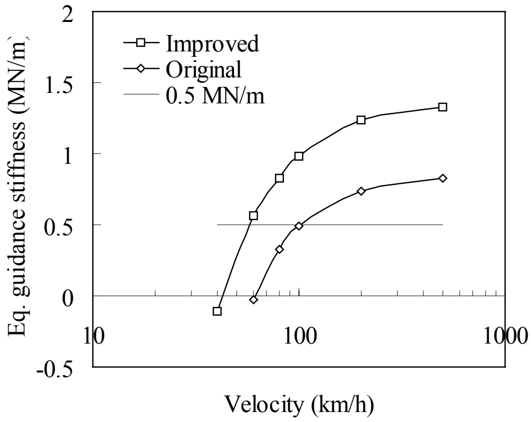

**Fig. 13 Eq. guidance stiffness at reduced size of end coil**

# 5. Conclusion

This paper examined the characteristics of improved SC coil configuration at strengthening its magnetomotive force, which has small-size coils on its end.

First, we explained the principle and the analysis model of improved configuration to reduce their leakage flux. Second, we examined the characteristics of magnetic field, levitation, guidance and propulsion in the improved configuration at strengthening its magnetomotive force. Finally, we proposed the realistic specifications and features of improved configuration.

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