

# Multifunctional Magnetic Vibration Simulator for EDS Maglev

Y. Sakamoto, T. Murai, M. Shibuya, T. Asahara, H. Yoshioka & E. Suzuki  
*Central Japan Railway Company, Tokyo, Japan*

**ABSTRACT:** This paper proposes a magnetic vibration simulator with a new excitation coil arrangement. By controlling the current of excitation coils, the proposed simulator can generate alternating magnetic fluxes that simulate harmonic magnetic fluxes generated by not only 60-degree pitch levitation coils but also 120-degree pitch propulsion coils at the same time. Furthermore it can generate steady levitation and propulsion forces. It is useful for advancing the stationary test apparatus for EDS maglev.

## 1 INTRODUCTION

Concerning the development of railway vehicles of wheel-rail systems, stationary test apparatuses for bogies and car bodies have effectively been applied to evaluate their dynamic performance. One of them is the bogie dynamic simulator shown in Figure 1 that has rotating wheels that simulate track rails running backward while the vehicle runs forward. This test apparatus can simulate the dynamic behavior of vehicle running with a stationary vehicle.

As for the development of superconducting electro-dynamic suspension (EDS) maglev, it is difficult to use stationary test apparatuses such as the rotating track, because they would need to be large in scale to simulate ground coils which pass superconducting coils of wide surface area. Therefore an apparatus called a magnetic vibration simulator (Fig. 2) has been used to evaluate AC loss and vibration characteristics of the superconducting coils for EDS maglev (Suzuki 1994). The simulator generates magnetic flux that simulates harmonic magnetic flux while the vehicle runs by using three-phase excitation coils fed by inverters. But it can only generate one wavelength of magnetic flux, so that it can only simulate either the harmonic flux of the levitation system or that of the propulsion system (LSM: linear synchronous motor). Therefore it does not have enough functions as to be a complete stationary test apparatus for EDS maglev driven by LSM.

This paper discusses a method of realizing a stationary test apparatus for EDS maglev driven by LSM by improving a magnetic vibration simulator. One main task is to simulate harmonic magnetic fluxes of the levitation system and propulsion sys-

tem simultaneously. Another task is to generate steady levitation force, guidance force and propulsion force which act on the superconducting coils while the vehicle runs. Furthermore, a method of magnetic levitation on the test apparatus by controlling these steady forces is proposed. A new type of magnetic vibration simulator is proposed, and studied with respect to fundamental performance by numerical computation.

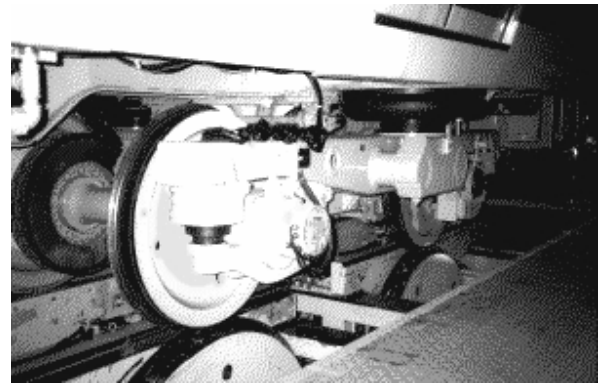


Figure 1: Stationary test apparatus for railway vehicles (Railway Technology Research Institute web site).

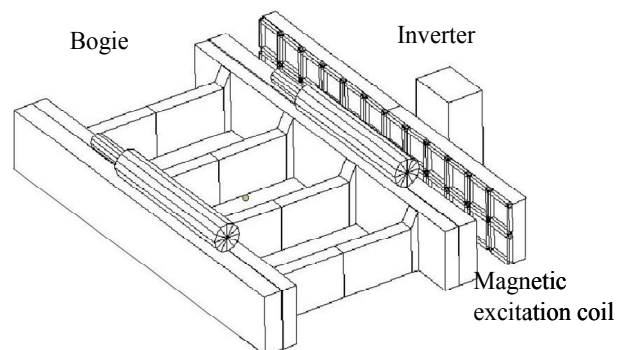


Figure 2: Magnetic vibration simulator for EDS maglev.

## 2 THE EDS-LSM SYSTEM AND THE EXISTING SIMULATORS

### 2.1 EDS-LSM system

Figure 3 shows the composition of superconducting maglev system, which is suspended by EDS and driven by LSM (Miyamoto et al. 2004). The superconducting maglev system is composed of superconducting coils on board and levitation coils for EDS and propulsion coils for LSM on the ground. The levitation coils are arranged with a 60-degree pitch and the propulsion coils with a 120-degree pitch. Superconducting coils are used for field poles of both EDS and LSM, so that they are applied by both steady levitation and propulsion forces and alternative forces caused by harmonic magnetic fluxes by levitation and propulsion coils.

Figures 4 a, b show spectra of  $x$ -direction wavelengths of magnetic fluxes generated by levitation and propulsion coils, respectively. The order of space harmonics  $n$  is the integer used in the expression for the wavelength  $2\pi/n$ .

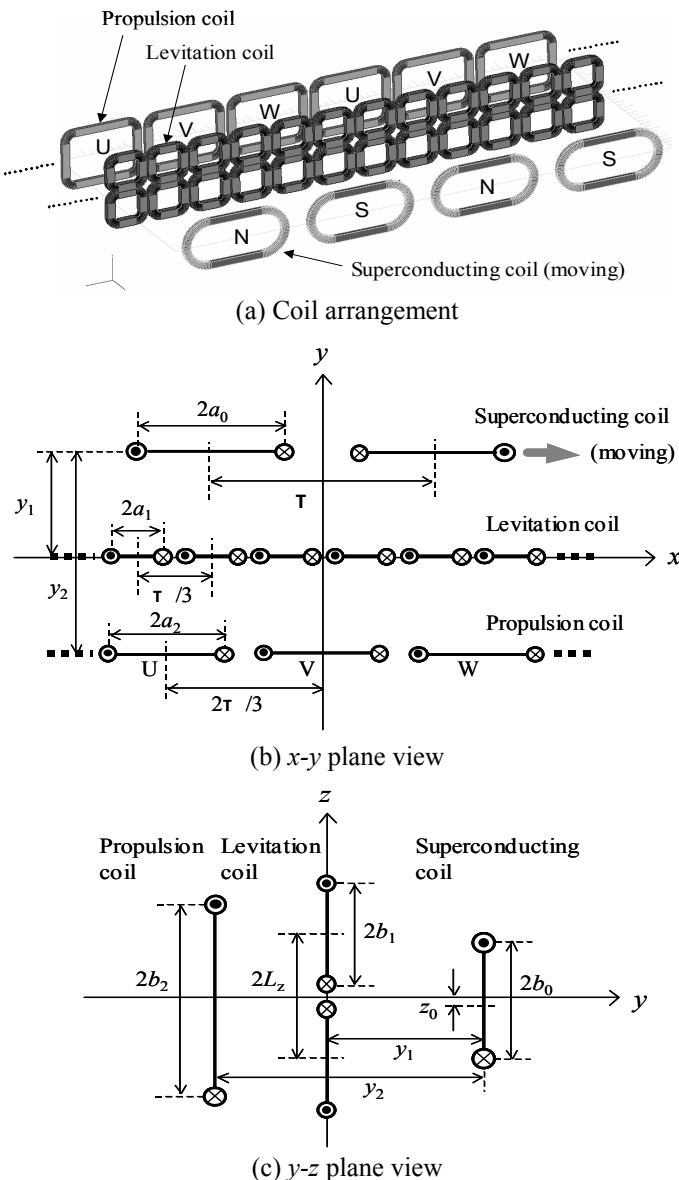
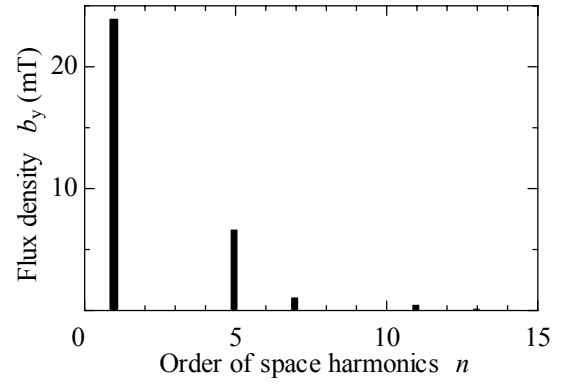
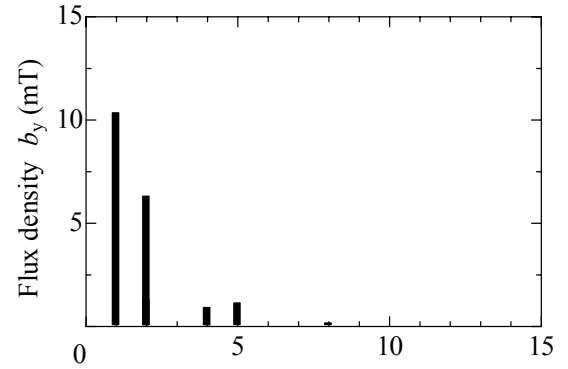


Figure 3: Composition of the combined EDS and LSM system.



(a) 60-degree pitch levitation coils



(b) 120-degree pitch propulsion coils

Figure 4: Spectra of magnetic fluxes generated by EDS and LSM system.

These figures show that main space harmonic fluxes are 5th component in 60-degree pitch levitation coils and 2nd component in 120-degree pitch propulsion coils. Since these harmonic fluxes are unsynchronized with the vehicle motion, they are observed as traveling fluxes from vehicle-based coordinates. The frequencies of the 5th space harmonic component of these traveling fluxes correspond to the 6th harmonic component, and those of the 2nd space harmonic component correspond to the 3rd harmonic component. And these traveling fluxes cause excitation forces oscillating at the frequencies of the 6th and 3rd harmonic components, respectively.

### 2.2 Existing simulators

Figure 5 a shows the excitation coil arrangement of the existing magnetic vibration simulator for 5th space harmonic component, and Figure 5 b shows the spectrum of magnetic fluxes generated by this simulator. This simulator has double layer excitation coils arranged with a  $2\pi/15$  pitch, which is the wavelength of the 5th space component  $2\pi/5$  divided by 3, the number of phases. This simulator generates the traveling magnetic flux of wavelength  $2\pi/5$  as shown in Figure 5 b. By feeding excitation currents at the frequency of 6th harmonic, this simulator can simu-

late excitation forces that act on superconducting coils in EDS of 60-degree pitch levitation coils.

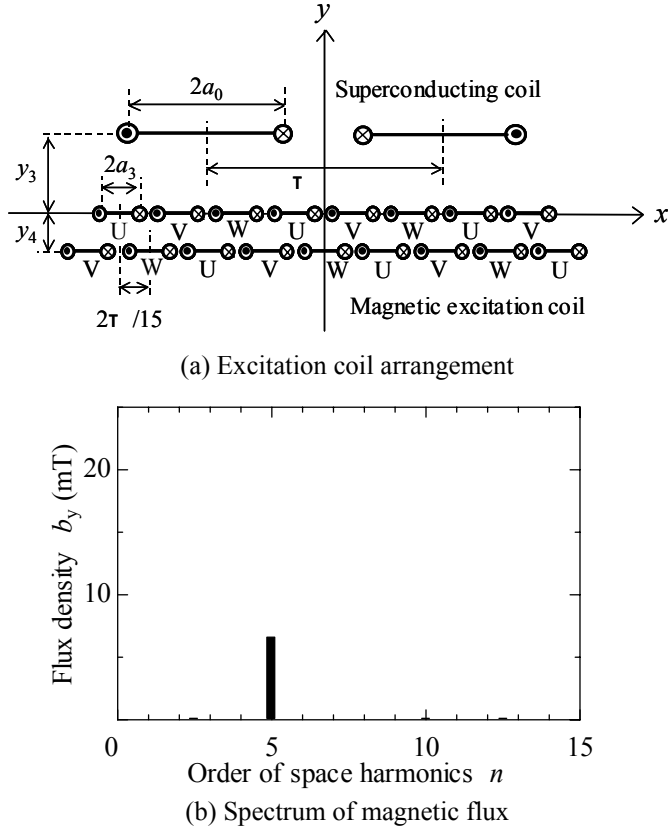


Figure 5: Existing simulator for 60-degree pitch levitation coils.

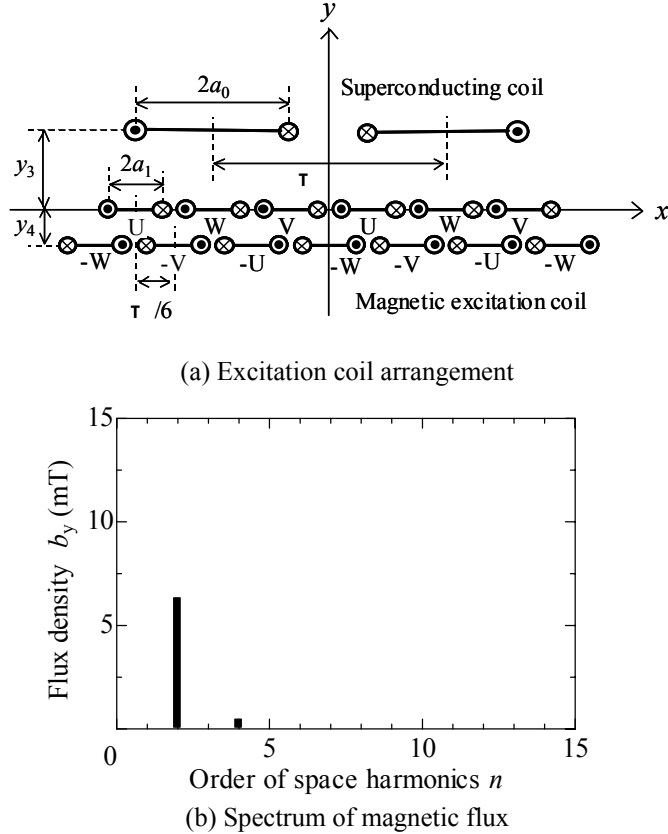


Figure 6: Existing simulator for 120-degree pitch propulsion coils

Figure 6 a, b show the excitation coil arrangement for 2nd space harmonic component and the spectrum of magnetic fluxes, respectively. This simulator has double layer excitation coils arranged in a  $\pi/6$  pitch, which is the wavelength of the 2nd space component  $\tau$  divided by 6, the number of phases. This simulator generates the traveling magnetic flux of wavelength  $\tau$  as shown in Figure 6 b. By feeding excitation currents at the frequency of the 3rd harmonic, this simulator can simulate excitation forces in LSM with 120-degree pitch propulsion coils.

These simulators can simulate only one wavelength of magnetic flux, so that it is impossible to simulate plural harmonic magnetic fluxes simultaneously.

### 3 THE PROPOSED SIMULATOR

#### 3.1 Magnetic vibration simulation

One way to generate plural harmonic magnetic fluxes simultaneously is to install additional excitation coils behind the existing coils. However, the coils would require large excitation currents because of the large gap between the additional excitation coils and the superconducting coils. And a multi-layer structure is inapt for setting excitation coils on the guideway sidewall. Therefore, a new simulator is proposed which can generate harmonic fluxes that simulate both levitation and propulsion coils.

##### 3.1.1 Simulation for 60-degree pitch levitation coils

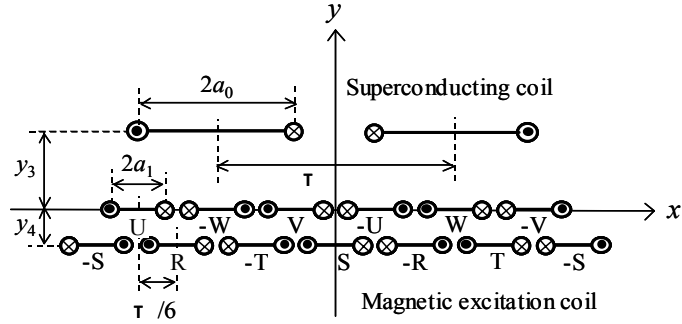
Figure 7 a, b show the excitation coil arrangement of the proposed simulator which is set up for 60-degree pitch levitation coils, Figure 7 c the excitation current vector diagram, and Figure 7 d the spectrum of magnetic flux generated by the proposed simulator. This simulator can generate the traveling magnetic flux of wavelength  $2\tau/5$ , shown in Figure 7 d, by the following principles,

[1] In the EDS system shown in Figure 3, 6-phase currents are induced in levitation coils while the vehicle runs.

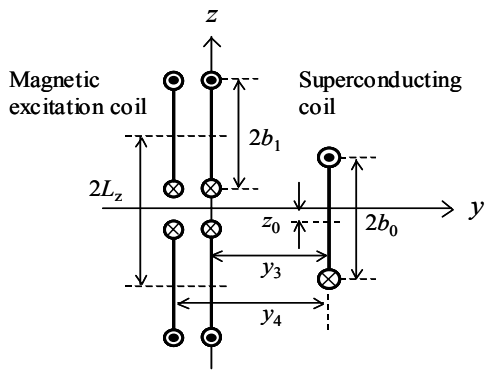
[2] By feeding currents of the six phases U, -W, V, -U, W, -V to the front layer coils that have the same dimensions as that of the levitation coils, the simulator can generate the same magnetic fluxes as that of the EDS system. In this case, the fundamental flux is also observed as a traveling wave in a stationary coordinate system, but this fundamental flux is not needed for the simulation system.

[3] Adding currents of the six phases R, -T, S, -R, T, -S to the back layer coils can cancel the fundamental flux. By shifting the back layer coils forward

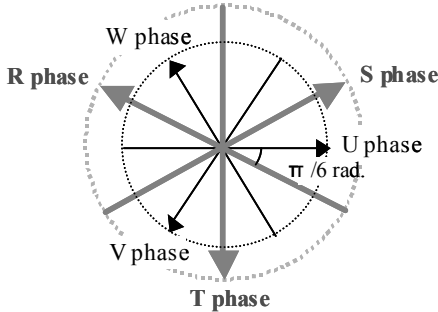
by a  $\pi/6$  pitch from the position of the front layer (Fig. 7 a) and shifting the phases of excitation currents forward by  $5\pi/6$  radian (Fig. 7 c), the fundamental component is canceled. On the other hand, the 5th space harmonic component can be amplified by superimposing fluxes generated by coils of the front and back layers.



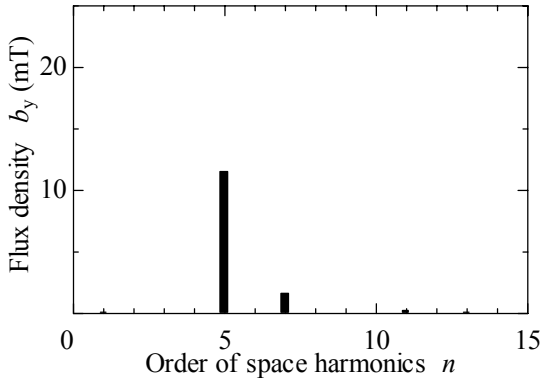
(a) Excitation coil arrangement (x-y plane view)



(b) Excitation coil arrangement (y-z plane view)



(c) Excitation current vector diagram



(d) Spectrum of magnetic flux

Although this simulator requires extra inverters for the back layer and simultaneous control of the currents in the front and back layers, it can also generate harmonic flux in the propulsion coils, as described in detail in Section 3.1.2.

The mechanisms of canceling the fundamental component and amplifying the 5th space harmonic component by superimposing fluxes generated by coils of the front and back layers are as follows.

Except for the zero-phase component, the magnetic flux  $b_1(x, t)$  generated by 6-phase armature coils can generally be expressed as follows.

$$b_1(x, t) = \sum_{l=1}^{\infty} \{ B_{3l-2} \sin(\omega t - \lambda_{3l-2}x + \alpha_{3l-2}) + B_{3l-1} \sin(\omega t + \lambda_{3l-1}x + \alpha_{3l-1}) \} \quad (1)$$

$$\lambda_n = n\pi/\tau \quad (2)$$

where  $3l-2$  and  $3l-1$  ( $l=1, 2, 3, \dots$ ) indicate the order of space harmonics  $n$ ,  $B_{3l-2}$  and  $B_{3l-1}$  the amplitude spectra of the space harmonics,  $\omega$  the angular velocity,  $\alpha_{3l-2}$  and  $\alpha_{3l-1}$  the phase angles which depend on the definition of the coordinate system. In Equation 1, the first term expresses the positive phase sequence components of traveling fluxes, and the second term the negative phase sequence. Assuming that Equation 1 denotes magnetic fluxes generated by surface layer coils, magnetic fluxes generated by back layer coils  $b_2(x, t)$  can be expressed as in Equation 3 by transformation of  $t \rightarrow t + 5\pi\omega/6$  and  $x \rightarrow x - \tau/6$  in Equation 1.

$$b_2(x, t) = \sum_{l=1}^{\infty} \left[ B_{3l-2} \sin \left\{ \omega t - \lambda_{3l-2}x + \alpha_{3l-2} + \frac{(l+1)\pi}{2} \right\} + B_{3l-1} \sin \left\{ \omega t + \lambda_{3l-1}x + \alpha_{3l-1} - \frac{(l-2)\pi}{2} \right\} \right] \quad (3)$$

After adding Equations 1 and 3, the synthesized magnetic flux  $b(x, t)$  is given as follows.

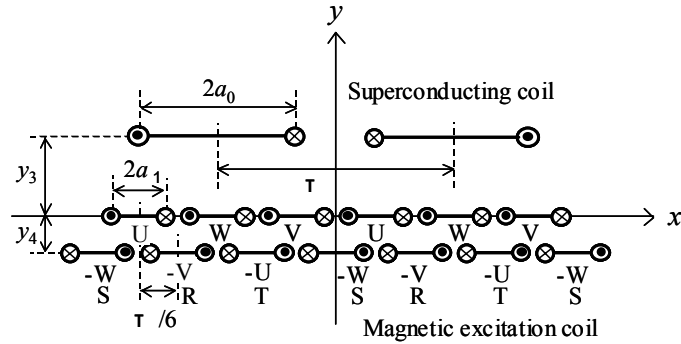
$$b(x, t) = \sum_{l=1}^{\infty} \left\{ \sqrt{2} B_{12l-10} \sin \left( \omega t + \lambda_{12l-10}x + \alpha_{12l-10} - \frac{\pi}{4} \right) + \sqrt{2} B_{12l-8} \sin \left( \omega t - \lambda_{12l-8}x + \alpha_{12l-8} - \frac{\pi}{4} \right) + 2 B_{12l-7} \sin \left( \omega t + \lambda_{12l-7}x + \alpha_{12l-7} \right) + 2 B_{12l-5} \sin \left( \omega t + \lambda_{12l-5}x + \alpha_{12l-5} \right) + \sqrt{2} B_{12l-4} \sin \left( \omega t + \lambda_{12l-4}x + \alpha_{12l-4} + \frac{\pi}{4} \right) + \sqrt{2} B_{12l-2} \sin \left( \omega t - \lambda_{12l-2}x + \alpha_{12l-2} + \frac{\pi}{4} \right) \right\} \quad (4)$$

Equation 4 shows that the harmonics component of  $n = 12l-1$  and  $n = 12l-11$  (including  $n = 1$ ) are

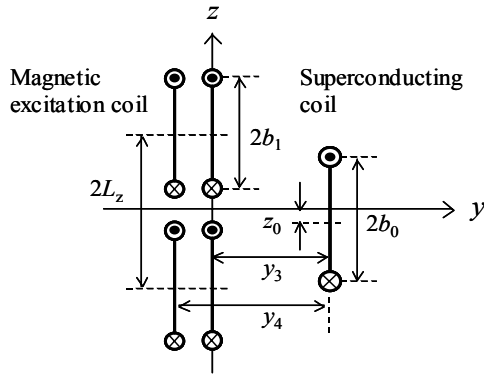
canceled and that the harmonics component of  $n = 12l-5$  and  $n = 12l-7$  (including  $n = 5$ ) are amplified because the fluxes of the front and back layers are in phase. Thus the proposed simulator can cancel the fundamental flux component and generate the 5th space harmonic component.

### 3.1.2 Simulation for 120-degree pitch propulsion coils

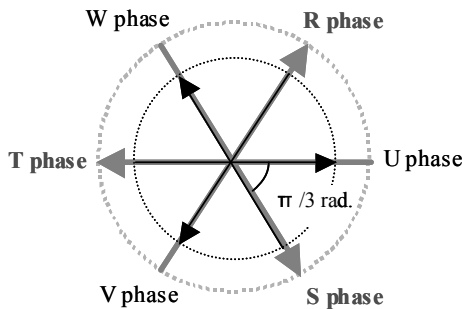
Figures 8 a, b show the excitation coil arrangement of the proposed simulator which is set up for 120-degree pitch propulsion coils, Figure 8 c the excitation current vector diagram, and Figure 8 d the spectrum of magnetic flux generated by the proposed simulator. This arrangement is similar to that of the existing simulator shown in Figure 6a, and can generate a traveling magnetic flux of wavelength  $\tau$  as shown in Figure 8 d. As for the arrangement in the  $y$ - $z$  plane (Fig. 8 b), in-phase currents are fed to both



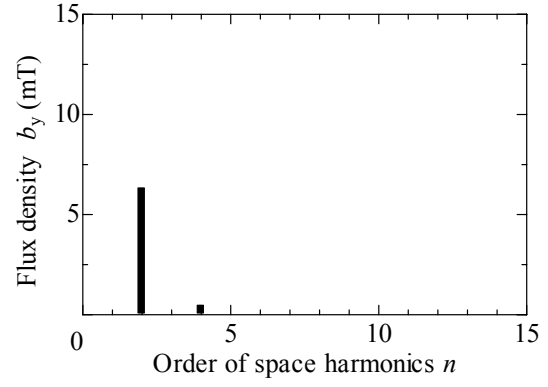
(a) Excitation coil arrangement (x-y plane view)



(b) Excitation coil arrangement (y-z plane view)



(c) Excitation current vector diagram



(d) Spectrum of magnetic flux

Figure 8: Proposed simulator set up for 120-degree pitch propulsion coils.

the upper and lower excitation coils where the inverse currents are fed for the simulation of levitation coils. Thus the proposed simulator can be used for the simulation of 120-degree pitch propulsion coils by switching the direction of an excitation current.

### 3.2 Steady force simulation

Figure 9 shows the configuration for steady force simulation using the proposed simulator (Murai et al. 2003). The basic composition is the same as that of Figures 7 a and 8 a, but the excitation coils at the longitudinal positions corresponding to the ends of the superconducting coils (coils 1, 4, 9, and 12 in Fig. 9) have a smaller width. Furthermore, the inverters are divided into plural units. This configuration enables the simulator to generate steady levitation, guidance, and propulsion forces by using DC currents. When the simulator generates levitation and guidance forces, the coils 1, 2, 3, 7, 8, and 9 are fed DC currents in one direction and the coils 4, 5, 6, 10, 11, and 12 are fed DC currents in the opposite direction. In the case of levitation force, currents of opposite directions are fed into the upper and lower coils. And in the case of guidance force, currents of the same direction are fed into the upper and lower coils. On the other hand, when the simulator generates propulsion force, the coils 1, 6, 7, and 12 are fed DC currents in one direction and the coils 3, 4, 9, and 10 are fed DC currents in the opposite direction. And currents of the same direction are fed into the upper and lower coils.

### 3.3 EMS control for EDS simulation

Utilizing steady forces generated by DC current, the simulator can levitate the bogie with superconducting coils. In this case, the simulator needs sidewalls with excitation coils on both sides of the bogie. Figure 10 shows the image of the simulator combined with the magnetic excitation function and the magnetic levitation function. In order to levitate the bo-

gie in a stable state, the DC currents should be controlled to maintain a constant bogie position, as in electromagnetic suspension (EMS).

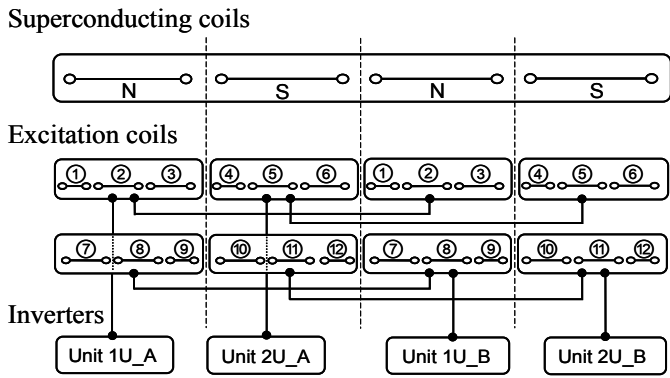


Figure 9: Configuration for generating steady forces.

Figure 11 shows the segmentation of current feeding for stabilizing bogie dynamics of six degrees of freedom. Considering symmetry, it is composed of eight unit inverters. Since the purpose of the magnetic levitation on the simulator is to simulate the actual running conditions, it is necessary to design control systems which provide the same suspension forces and stiffness as those under the running conditions.

### 3.4 Simultaneous simulation of all conditions

Feeding currents with AC and DC components superimposed, the proposed simulator can simulate the EDS-LSM system of an actual vehicle running conditions. In order to feed these superimposed currents, each inverter should be single-phase full-bridge  $\times$  3-phases. Considering both the double layer inverter arrangement and the segmentation for levitation control, the total number of inverters is 16. The phase and polarity of each coil for the simultaneous simulation of all conditions is shown in Table 2. ,

Table 2: Phases and polarities of each coil.

Coil No.	Vibration simulation AC phases		Steady force simulation DC polarities		
	EDS (6th)	LSM (3rd)	Levitation	Guidance	Propulsion
1	0	0	+	-	+
	180	0	-	-	+
2	-60	120	+	-	0
	120	120	-	-	0
3	-120	-120	+	-	-
	60	-120	-	-	-
4	180	0	-	+	-
	0	0	+	+	-
5	120	120	-	+	0
	-60	120	+	+	0
6	60	-120	-	+	+
	-120	-120	+	+	+

7	150	60	+	-	+
	-30	60	-	-	+
8	90	180	+	-	0
	-90	180	-	-	0
9	30	-60	+	-	-
	-150	-60	-	-	-
10	-30	60	-	+	-
	150	60	+	+	-
11	-90	180	-	+	0
	90	180	+	+	0
12	-150	-60	-	+	+
	30	-60	+	+	+

- In each block, top: upper coil, bottom: lower coil.
- units: degrees

Figure 12 shows magnetic fluxes in a condition of superimposing with harmonics by EDS and LSM and steady forces by EDS and LSM simultaneously. Except for the magnetic fluxes of the simulator which are decreased at segments ( $x=-1.35, 0, 1.35$ ) for the superconducting coil pitch, the simulator can accurately simulate the magnetic fluxes of running conditions.

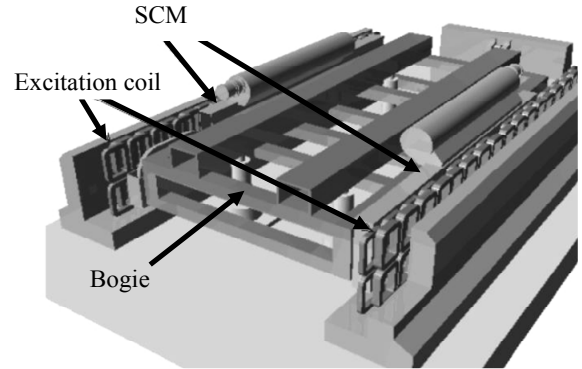


Figure 10: Image of the simulator combined with the magnetic excitation function and the magnetic levitation function.

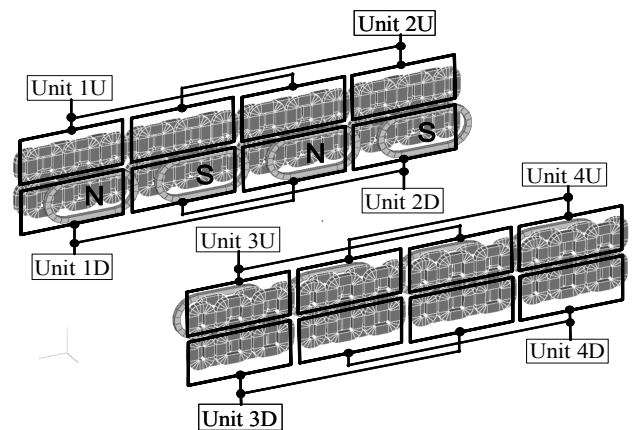
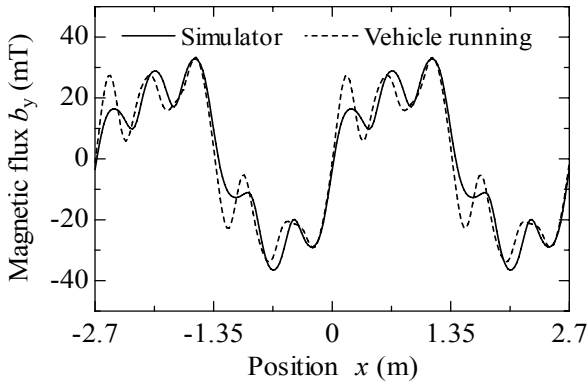
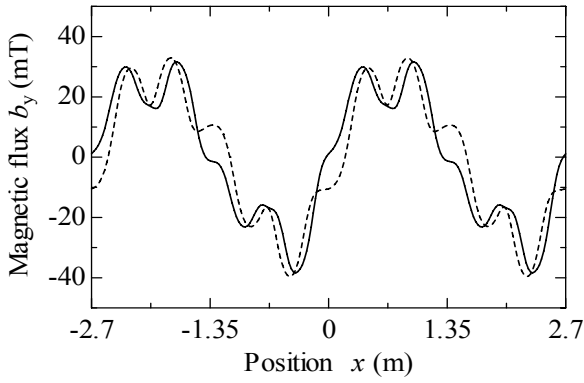


Figure 11: Segmentation of current feeding for magnetic levitation of six degrees of freedom.



(a)  $t = 0$



(b)  $t = 1/4$  cycle

Figure 12 : Comparison of the simulator and the actual running condition with respect to magnetic fluxes.

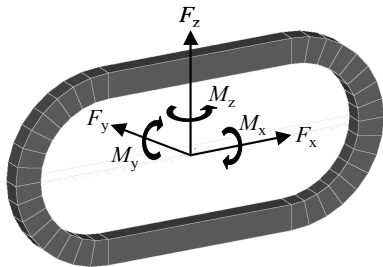


Figure 13: Definition of force directions.

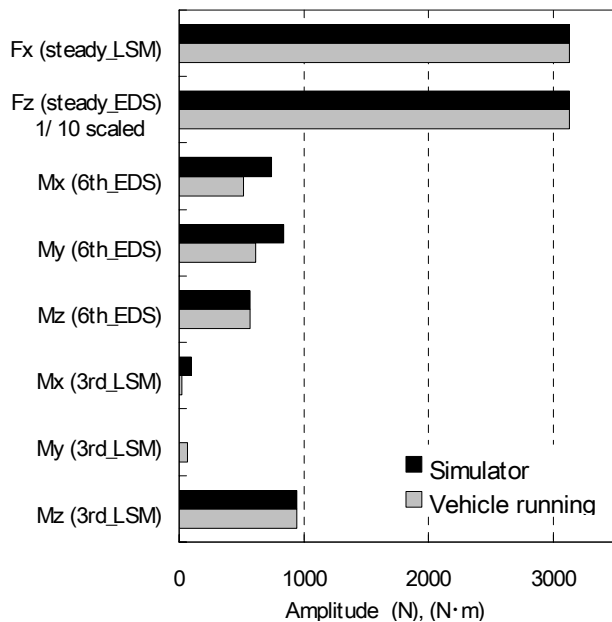


Figure 14: Comparison of the simulator and the actual running condition with respect to forces.

Figure 13 shows a definition of force directions, and Figure 14 shows amplitudes of forces which act on superconducting coils in the condition of Figure 12. With respect to the evaluation of AC losses and vibration characteristics, it has been confirmed experimentally that the moment components are important for equivalent simulation. The simulated forces agree well with those of running.

#### 4 CONCLUSIONS

This paper proposed a new magnetic vibration simulator, which can simulate not only the harmonic magnetic flux in the EDS system but also that of the LSM system. First, the principle of the simulation was described in which harmonic magnetic fluxes of the EDS and LSM systems are generated simultaneously. Second, the configurations to levitate the bogie with the superconducting coils on the simulator were described, and numerical computations revealed that the magnetic fluxes, steady forces and excitation forces agree well with those of actual running vehicles. It was verified that the proposed simulator was useful for developing the stationary test apparatus for EDS maglev driven by LSM.

#### 5 REFERENCES

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