Optimized Design of 8-Figure Null-Flux Coils in EDS

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Abstract

This paper describes the design of 8-figure null-flux coils to optimize not only the basic performance for levitation, guidance and propulsion but also the vibration of superconducting magnets. By using both optimization program and modal analysis, we reveal the relationship between the characteristics and the dimensions of 8-figure coils.

1 Introduction

The superconducting Maglev system, which is currently under running tests on the Yamanashi Test Line, had been certified to be ready for application by 1999 and entered new development to confirm the reliability and improve the aerodynamics and the economical efficiency in 2000. In order to reduce the costs, a levitation system with a 120-degree coil pitch and a combined propulsion, levitation and guidance system (PLG system) are now being developed. However, it is important to improve not only the ground coil but also the superconducting magnet (SCM) because these systems will encounter a larger vibration of SCM [1].

On the other hand, our previous papers described the characteristics of asymmetric 8-figure coils and their optimized design with a 60-degree or 120-degree pitch [2][3][4]. However, we discussed only the basic performance for levitation, guidance and propulsion without referring to the vibration of SCM. In addition, we didn’t clarify the relationship between the coil pitches of 8-figure coils and their performance.

The 8-figure coils including the PLG coils have mainly longitudinal and vertical dimensions such as the coil pitch in a single layer and the heights of upper and lower coils. Therefore, this paper discusses an optimized design of these dimensions not only to balance characteristics of levitation, guidance and propulsion but also to decrease the magnetic disturbance to SCM. By implementing a modal analysis, we can also predict the vibration of SCM at different coil pitches and reveal the dimensions of 8-figure coil to decrease vibration.

2 PLG system

Figure 1 shows the coil composition of PLG system, which can suspend and propel Maglev vehicles by the same ground coils. This system is composed of on-board superconducting coils (SCs) and 8-figure coils on the sidewall of guideway whose design is the subject of this study. The 8-figure coils on opposite walls are connected to make a null flux circuit and those along the guideway are connected to make serial circuits. Since it is desirable for the coil pitch to divide 360-degree of electrical angle into integral numbers while considering the connection to the power source, we examine the characteristics of 60-degree pitch (one-sixth), 72-degree pitch (one-fifth), 90-degree pitch (one-fourth) and 120-degree pitch (one-third).

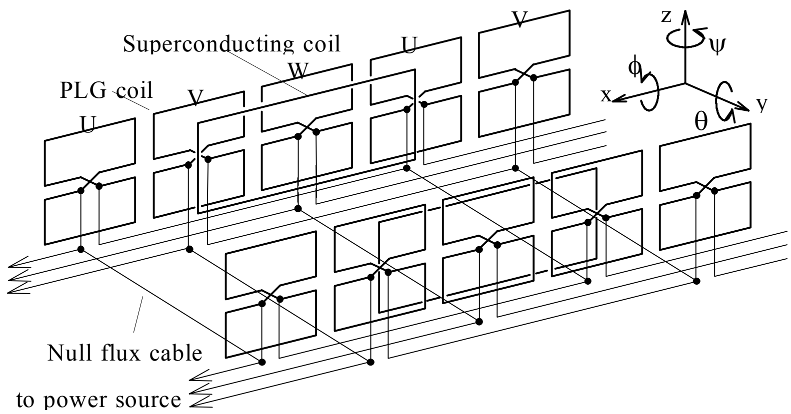

Fig. 1 Coil composition of PLG system

3 Basic performance

3.1 Design by optimization program

It is difficult to examine the basic performance for levitation, guidance and propulsion of entire combination of pitches and heights, so we would design the dimensions to optimize the performance at each coil pitch by an optimization program and compare the performance of these pitches.

Therefore, we utilize the coil design method by the non-linear optimization program in the references [3] and [4]. Though the detail of this method is omitted here, the assumptions are summarized as follows.

(1) The specifications of SC are constant.

(2) The volume per length of 8-figure coil is constant.

(3) The upper and lower coil heights b_{1u} and b_{1b} and the cross section of 8-figure coils are variables, and their length a_1 is the largest in the range not to overlap with neighboring coils.

(4) The air gap between SCs and 8-figure coils is constant.

(5) The levitation force is gained to suspend the vehicle.

(6) Both the equivalent guidance stiffness and the equivalent rolling stiffness, which reflect the coupling stiffness between guidance and rolling [2], are gained to keep levitation stable.

(7) The propulsion force is gained to propel the vehicle against the running resistance with magnetic drag.

Furthermore, the following objective functions are formulated to optimize the performance of the pitch.

(1) At optimizing levitation, the drag ratio should be maximized at the cruising velocity.

(2) At optimizing guidance, the equivalent guidance stiffness should be maximized at the take-off velocity.

(3) At optimizing propulsion, the apparent power for propulsion force without magnetic drag should be minimized at the cruising velocity.

(4) At optimizing levitation and propulsion, the apparent power for propulsion force with magnetic drag should be minimized at the cruising velocity.

3.2 Characteristics of numerical example

Table 1 shows the specifications of the system and coils for numerical calculation. In order to clarify the difference of performance between asymmetric and symmetric 8-figure coils, the 8-figure coil with different heights (asymmetric coil) and that with the same heights (symmetric coil) between upper and lower coils in Fig. 2 are studied.

Figure 3 shows the maximized drag ratio and the heights of upper and lower coils of each coil pitch at optimizing levitation. Figure 4 shows the maximized equivalent guidance stiffness and the heights at optimizing guidance. Figure 5 shows the minimized apparent power and the heights at optimizing propulsion. Figure 6 shows the minimized apparent power and the heights optimized both for levitation and propulsion. The symmetric coil with a 60-degree pitch has no dimensions to satisfy the specifications in Table 1, because their equivalent rolling stiffness is not sufficient for the required value. The apparent powers in Fig. 6 are larger than those in Fig. 5 not due to the difference of optimized performance but due to the existence of magnetic drag.

The drag ratios increase as the coil pitch becomes larger, and the 120-degree pitch has the largest value. Therefore, it is thought that the 120-degree pitch is the most effective for levitation. On the other hand, the equivalent guidance stiffness of 90-degree pitch is the largest, so that the 90-degree pitch is the most effective for guidance. Since the apparent power of 90-degree pitch is the lowest with and without magnetic drag, the 90-degree pitch is the most effective not only for propulsion but also for the combination of propulsion and levitation. Regardless of the coil pitch, the asymmetric coils have larger heights of lower coils than those of upper coils, and more excellent performance for levitation, guidance and propulsion than the symmetric coils.

Table 1 Specifications of system and coil

Operation parameter	
Cruising velocity	500 km/h
Take-off velocity	100 km/h
Levitation force	230 kN/car
Equivalent guidance stiffness	1 MN/m/car
Equivalent rolling stiffness	3 MNm/rad/car
Superconducting magnet	
Pole pitch	1.35 m
Dimensions	1.07 x 0.5 m
Magnetmotive force	700 kA
8-figure coil	
Volume	0.015m^3/m

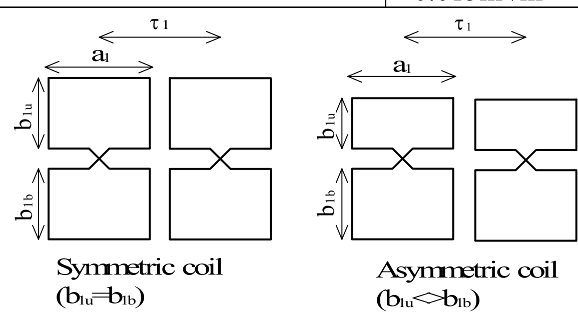

Fig. 2 Dimensions of 8-figure coil

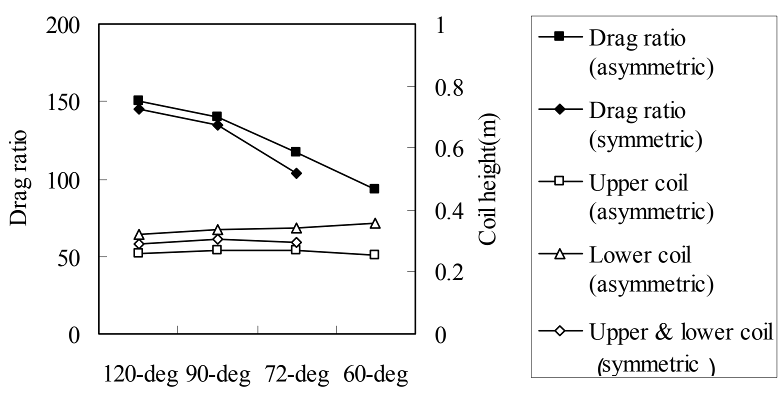

Fig. 3 Maximized drag ratio

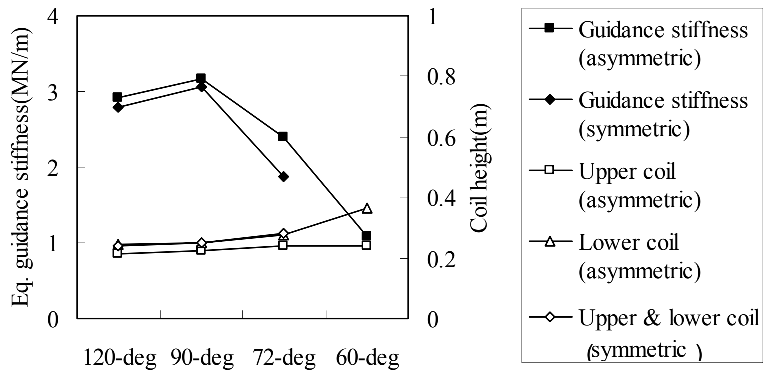

Fig. 4 Maximized equivalent guidance stiffness

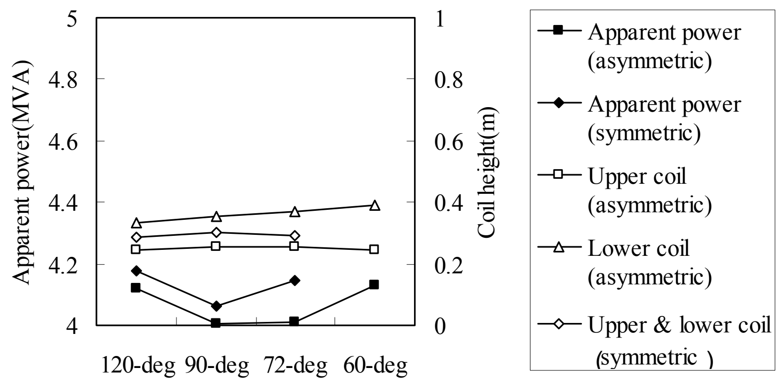

Fig. 5 Minimized apparent power without magnetic drag

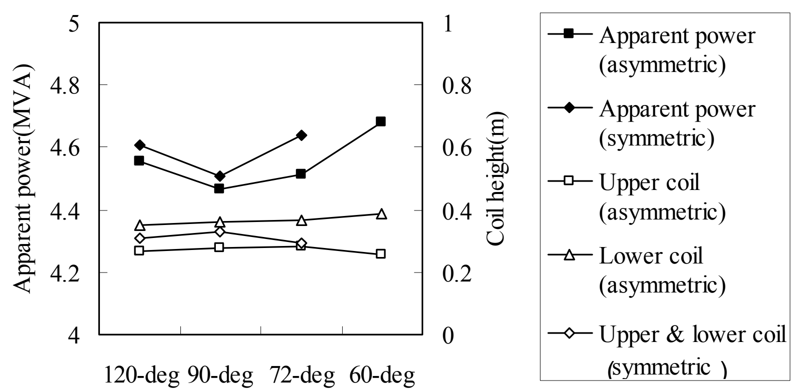

Fig. 6 Minimized apparent power with magnetic drag

4 Vibration of superconducting coil

4.1 Feature of magnetic force

By applying the Fourier series analysis as in the reference [2], the magnetic forces of k-th SC $\boldsymbol{F}_{ik}$ (i=x, y, z) at the position of x=kτ are expressed as follows: (The coordinate system has the x-axis in the longitudinal direction, y-axis in the lateral direction and z-axis in the vertical direction.)

$$F_{ik} = \sum_{m=-\infty}^{\infty} \sum_{\gamma=-\infty}^{\infty} (-1)^{(m'+1)k} I_L(m) P_{0i}(m') \exp(j2l\gamma\omega t) \tag{1}$$

$$m' = m + 2l\gamma \qquad l = \tau / \tau_1$$

where τ and τ_1 are pitches of SCs and 8-figure coils, respectively; I_L(m) is the coil current, and P_{oi}(m) is the function determined by the dimensions and positions of SCs and 8-figures coils. In addition, 2lν indicates the time harmonic order and m' indicates the space harmonic order. Since the low harmonics generally have large magnitudes, special attention should be paid to the magnetic forces at m=1, ν=-1 and m=1, ν=-1. Though only the expression of magnetic forces is indicated here, the magnetic moments are derived in the similar expression.

This expression indicates that the excitation forces neighboring SCs have a negative phase at 2l = odd and a common phase at 2l = even, and these frequencies are proportional to 2l as in Table 2. Furthermore, the vibration of SCs depends on the vibration mode of SCM since the 4 SCs are fixed to the cryostat that composes an SCM. Figure 7 shows the relationship between the lateral excitation forces to SCs and the vibration modes of SCM. According to this Figure, the lateral forces and the yawing moments to SCs by the odd harmonics will generate a second bending mode and a third bending mode of SCM, respectively, which will occur at the low frequencies. In contrast, the lateral forces and the yawing moments to SCs by even harmonics will generate a rigid-body mode and a high order mode of SCM with the wavelength of pole pitch at the high frequency, respectively.

Consequently, in order to reduce the vibration of SCs, the resonance frequency of vibration mode of SCM should not agree with that of excitation force. For example, the 90-degree pitch that has even harmonics generates the excitation force a low frequency but the vibration mode a high frequency. Furthermore, even in the coil pitches that generate odd time harmonics, the vibration of SCs can be reduced since the low frequency mode has a simple relationship between the vibration modes of SCM and the excitation forces to SCs. For instance, the asymmetric 8-figure coil can reduce the lateral force and yaw moment to SCs as compared with the symmetric 8-figure coil.

Table 2 Feature of excitation force of SCs

Coil pitch	Harmonics 2l	Excitation freq. 100-500 km/h	Excitation phase
60-degree	6th	62-309 Hz	Common
72-degree	5th	51-257 Hz	Negative
90-degree	4th	41-206 Hz	Common
120-degree	3rd	31-154 Hz	Negative

(a) Lateral force by odd harmonics (c) Lateral force by even harmonics

(b) Yawing moment by odd harmonics (d) Yawing moment by even harmonics

Fig. 7 Relationship between SCs force and vibration mode

4.2 Vibration analysis of SCM

We will perform the modal analysis to examine the vibration of SCM. The modal analysis not only reveals the characteristics of vibration but also obtains all of frequency transfer functions (FRFs) by a part of measured ones. Therefore, the vibration of SCM in running can be predicted by the procedure shown in Fig. 8.

1. Measuring a column of FRFs by a single reference
2. Identifying the modal model by measurements
3. Synthesizing the entire FRFs by the modal model
4. Calculating vibration in running by multiplying the FRFs by running excitation forces

Fig. 8 Calculation by modal analysis

4.3 Characteristics of numerical example

4.3.1 Vibration mode of SCM [5]

Figure 9 shows typical modes of vibration by applying the modal analysis to the SCM. The modes in this Figure indicate the outer vessel of SCM (back) and the C1 coil of the first SC and the C3 coil of the third SC from the left (front). The C1 coil misses the data on the lower right side at measuring.

In the region of frequency under 200 Hz, the outer vessel generates simple modes such as the second bending mode and the third bending mode and the SCs generate the rigid-body modes such as translation and rotation. For example, the vibration mode at 147 Hz, which generates the largest vibration by the 120-degree pitch, is the third bending mode of W-figure. In contrast, in the region of frequency over 200 Hz, the complex high-order modes occur in the outer vessel and the elastic-body modes such as bending and twisting occur in the SCs.

4.3.2 Excitation forces at each coil pitch

Figure 10 shows the lateral excitation forces to SCs (averaged over four coils) when optimizing both levitation and propulsion. We will examine the forces caused by the levitation system, which are larger than those by propulsion.

The lateral force is the largest at the 120-degree pitch, and becomes smaller at 72-degree, 90-degree and 60-degree pitches in this order. The rolling moment is the largest at the 120-degree pitch, and becomes smaller at 72-degree, 60-degree and 90-degree pitches in this order. The yawing moment is the largest at the 120-degree pitch, and becomes smaller at 90-degree, 60-degree and 72-degree pitches in this order. The 120-degree pitch has the largest excitation force in any component.

4.3.3 Vibration response by each coil pitch

Figs. 11-14 show examples of vibration response of SCs calculated by multiplying the FRFs and the forces of each coil pitch in Fig. 10. These accelerations are the normalized maximum values of C1 and C3 coils.

The vibration of SCs is the largest at the 120-degree pitch, and becomes smaller at 72-degree, 90-degree and 60-degree pitches in this order. It is thought that the coil pitches with odd harmonics whose excitation force neighbored with each other are in the negative phase, generate larger vibrations. The 120-degree pitch generates the largest vibration of the third bending mode of SCM at frequency of 147 Hz. On the other hand, a small heat load occurs in the rigid-body modes of SCs and a large one occurs in the elastic modes. Therefore, both the 72-degree pitch and the 60-degree pitch might generate a large heat load though they generate small vibrations of SCs.

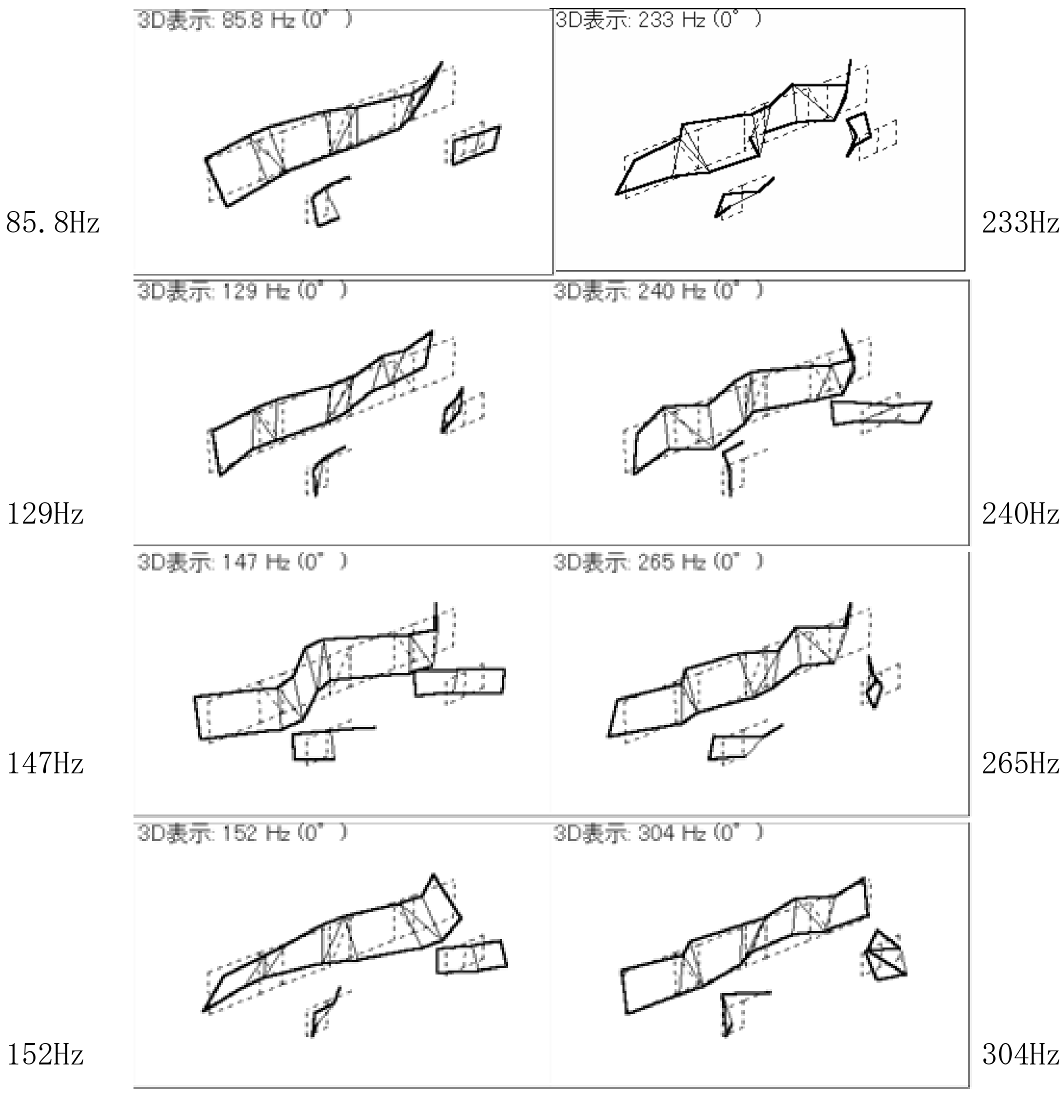

Fig. 9 Typical vibration modes of SCM

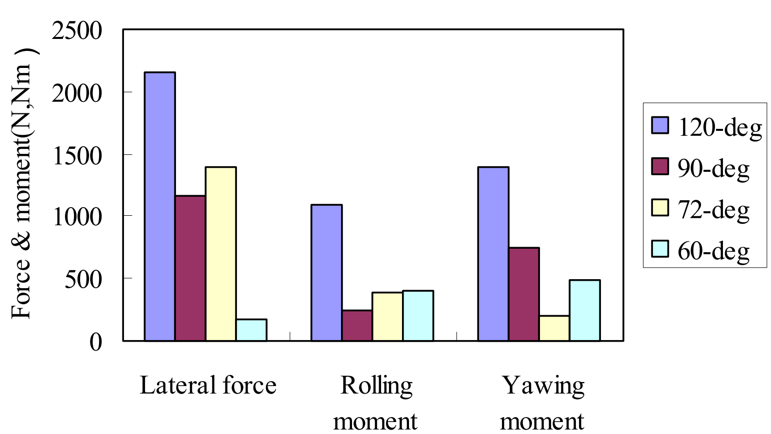

Fig. 10 Excitation forces to SCs vs. coil pitch

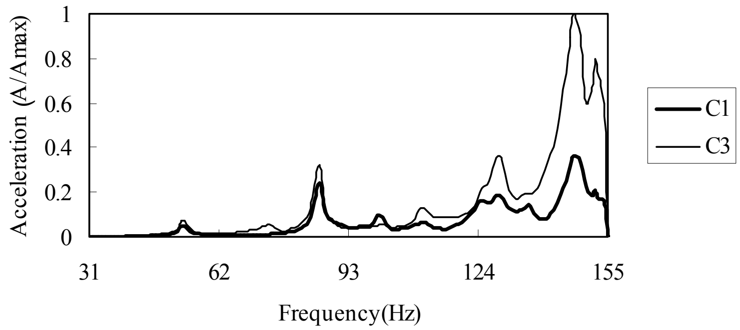

Fig. 11 Vibration response of SCs by 120-degree pitch

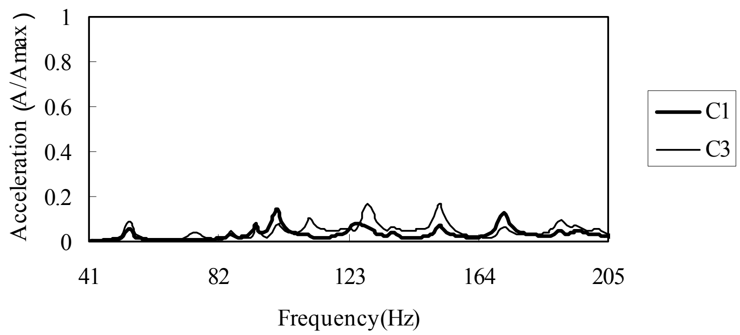

Fig. 12 Vibration response of SCs by 90-degree pitch

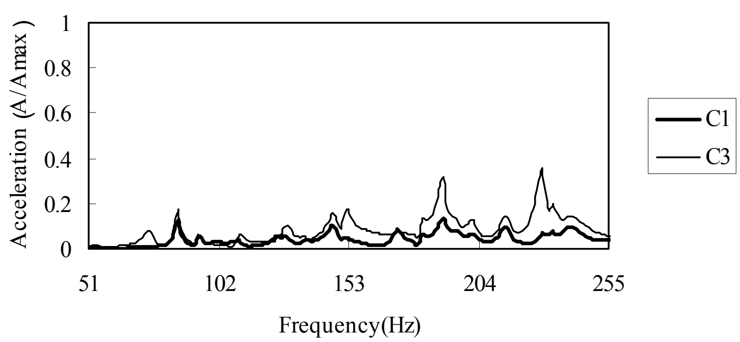

Fig. 13 Vibration response of SCs by 72-degree pitch

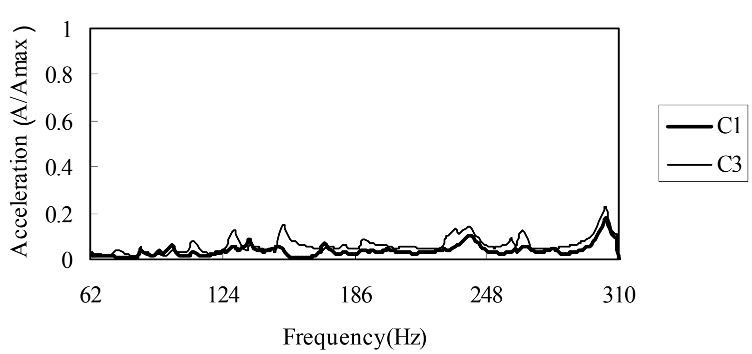

Fig. 14 Vibration response of SCs by 60-degree pitch

4.3.4 Dimensions to reduce magnetic fluctuation

The 120-degree pitch generates large vibration as mentioned above. However, the vibration has simple mode of W-figure as in Fig. 9. Therefore, this vibration will be decreased by reducing the yaw moment of excitation force.

On the other hand, the lateral force and yaw moment of SC are generated by the difference between the opposite forces by the upper and lower coils. Furthermore, in the symmetric 8-figure coil, the lower coil generates a larger force than the upper coil since the SC deviates downward from the center of 8-figure coil whose upper coil is away from SC and lower coil is close to SC with levitation. Therefore, the asymmetric 8-figure coil whose upper coil has a smaller height than the lower coil can reduce the lateral force and yaw moment of SC because the upper coil puts close to SC similarly to the lower coils with levitation.

Consequently, the constraints that the yaw moment of excitation force reduces to 60 % of that of original system should be added in the optimization design. Figs. 16 and 17 show improved dimensions and lateral excitation forces, respectively, when optimizing both levitation and guidance under the above-mentioned condition. The improved coil has a larger height of lower coil and a smaller height of upper coil and a wider cross section in comparison with the original coil. In addition, the yawing moment decreases to 60 % of that of the original one and the lateral force decreases to 80 %.

Figure 18 shows examples of vibration response of SCs calculated by the forces in Fig. 17. In the improved coil, the vibration of the third bending mode at 147 Hz decreases to 60 % of that of the original coil similarly to the yaw moment of excitation force. However, the apparent power of improved coil increases to 105 % of that of original coil, so that it is necessary to balance the magnetic disturbance to SCs and the basic performance for levitation, guidance and propulsion.

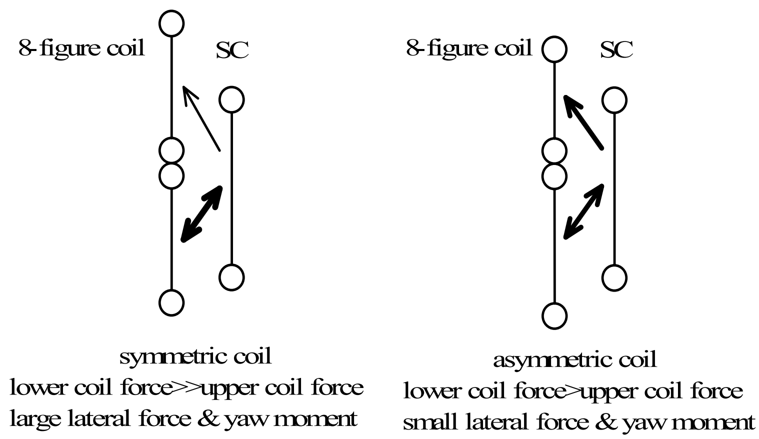

Fig. 15 Excitation force to SC

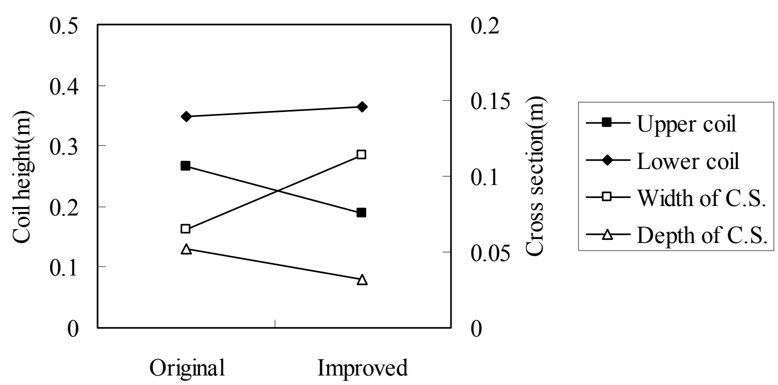

Fig. 16 Dimensions of 8-figure coil to reduce excitation force to SC

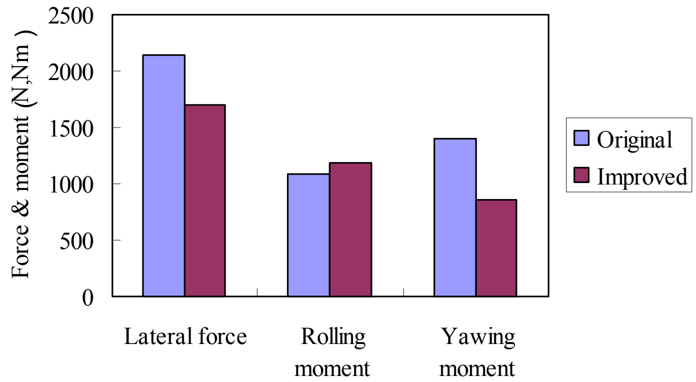

Fig. 17 Excitation forces to SC by improved coil

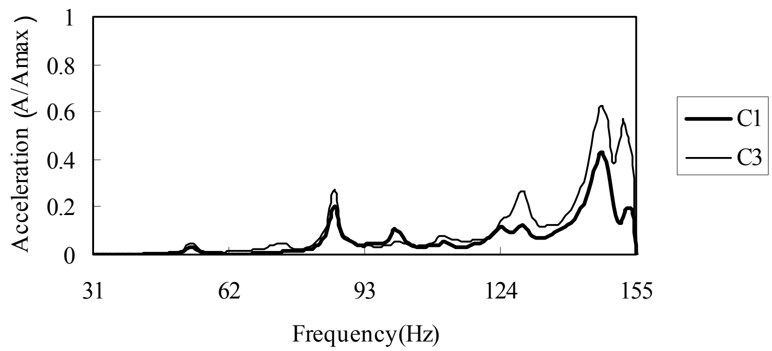

Fig. 18 Vibration response to SCs by improved coil

5 Conclusion

In this study, we examined the optimization of coil dimensions including the coil pitch of the 8-figure PLG coil of EDS Maglev. In addition, by utilizing the modal analysis, the vibration of SCM was investigated. Consequently, we were able to reveal the following features.

1. The 120-degree pitch is most effective for levitation, and the 90-degree pitch is the most effective for guidance, propulsion and also the combination of levitation and guidance when optimizing the basic performance.
2. The asymmetric 8-figure coil with a larger lower coil has better performance.
3. The 90-degree pitch generates smaller vibration of SCM because their excitation forces to SC have a low frequency and common phase.
4. The 120-degree pitch can reduce the excitation force and vibration of SCM owing to the largest and simple vibration mode.

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