Characteristics of Magnetic Springs for Guidance of Superconducting Maglev Vehicles

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The lateral and rolling components of the magnetic springs of superconducting Maglev vehicles are strongly coupled, and their characteristics are barometers to decide the take-off velocity of the vehicle. In order to design Maglev vehicles effectively, it is important to understand the principles to be applied to determine the spring specifications with respect to the design parameters: the gap and the magnetomotive force of the superconducting magnet. In this paper, a study using computer simulations on the effect of changing the design parameters is described, referring to the principles of electrodynamic suspension and the vehicle dynamics of Maglev vehicles.

Keywords: superconducting Maglev, gap, magnetomotive force, take-off velocity, curved section

1. Introduction

The superconducting Maglev has been developed as a high speed transport system. The levitation and guidance functions of the superconducting Maglev vehicle are served by electrodynamic suspension (EDS) provided by electromagnetic interaction between superconducting magnets (SCMs) on the vehicle and levitation/guidance coils on the ground. The propulsion function of the Maglev vehicle is served by a linear synchronous motor (LSM) whose primary side comprises the propulsion coils on the ground and whose secondary side comprises the SCMs on the vehicle. Figure 1 shows the composition of the Maglev vehicle.

The fundamental theory on electromagnetic force characteristics for levitation and guidance has already been established in a previous study [1]. A design method for Maglev vehicles has also already been devised in another previous study [2]. This design method however, was invented only to optimize ground coil specifications. Treating other factors as design parameters, for example, gap [3] (electrical gap; lateral distance between the center of the conductor of the superconducting coils and that of the levitation/guidance coils), magnetomotive force of the SCM, and mass supported by each bogie, can give freedom to improve the Maglev system design, compared to the conventional design method. This potential for improvement justifies a more detailed study of the Maglev system design method.

In terms of fundamental research, the effect of changing certain design parameters, such as the gap and magnetomotive force of the SCM, on electromagnetic force characteristics has been studied [3] [4].

The Maglev system design must be considered along with the detailed design of each component in the Maglev system, such as SCMs, ground coils, or vehicle suspensions. An optimized design cannot be achieved by examining electromagnetic force characteristics alone. Various design parameters must be considered, and there is a broad range of assessment factors, that can serve as barometers to assess the quality of the design.

Studies described in previous papers [3][4], or in this paper, do not deal with all of the design parameters and assessment factors mentioned above, rather, they deal with the design parameters or the assessment factors related to electromagnetic force and vehicle dynamics characteristics.

A study using computer simulations of the characteristics of magnetic springs for guidance is described in this paper in relation to the fundamental theory of electromagnetic force and vehicle dynamics.

In the case of electromagnetic force characteristics, a study is made of the effect of changing the gap and the magnetomotive force of the SCM - the design parameters of the Maglev system - on the characteristics of magnetic springs for guidance.

In the case of vehicle dynamics characteristics, a study is made of the effect of magnetic springs for guidance - whose values change when the gap or the magnetomotive force of the SCM changes - on the equilibrium position of the vehicle running in curved sections.

Studying the relationships between the design parameters and these characteristics, should provide insight into the characteristics in relation to fundamental theory. The outcome of this study may help reduce the time and effort required for trial and error in the design of Maglev systems [2] and improve the overall design method.

![Fig. 1 Composition of the superconducting Maglev vehicle]
2. Fundamental theory of magnetic springs for guidance

This section describes the fundamental theory of electromagnetic force and vehicle dynamics characteristics with regard to magnetic springs for guidance.

Figure 2 is a schematic drawing of the superconducting coil and levitation/guidance coil arrangement and definition of the axes [4]. Four superconducting coils are arranged on one side of the bogie, as shown in Fig. 2. The levitation/guidance coils are arranged close to each side of the bogie at a given pitch, as shown in Fig. 2.

The definition of the axes is as follows: Direction of travel (longitudinal direction) is defined as the \( x \) axis, the vertical axis is defined as the \( z \) axis, and the lateral axis is defined as the \( y \) axis, as shown in Fig. 2. Rotational directions along \( x, y, z \) axes are defined as rolling \( \phi \), pitching \( \theta \), and yawing \( \psi \), respectively, as shown in Fig. 2 [1][5].

In side-wall type EDS, levitation and guidance functions are combined in the levitation/guidance coils, as described above. In the study of electromagnetic force characteristics for levitation of the vehicle running in a straight section, only the levitation function characteristics were considered, whilst it was not necessary to consider electromagnetic force characteristics for guidance, because the lateral center of the bogie is located at the lateral center of the guideway when the vehicle is running in a straight section. With respect to studying electromagnetic force characteristics for guidance, not only the guidance but also the levitation characteristics must be considered because the vertical center of the bogie is located in the position where the levitation force by EDS and the gravitational force by the mass of the vehicle are balanced [1].

A Maglev vehicle can run in a stable state when running at high speed because sufficient levitation and guidance forces are generated at high speed. However, at low speed, inductive currents flowing in the levitation/guidance coils decrease, and the electromagnetic force for levitation and guidance is insufficient. Therefore, at low speed, the vehicle runs with the support of landing wheels and guidance wheels.

In the case of small vehicle displacements, the electromagnetic force acting on the bogie is regarded as proportional to the displacement of the bogie, then the electromagnetic force acting between the superconducting coils and the levitation/guidance coils is substituted by an interacting force generated by the springs. When the electromagnetic force acting on the bogie is divided by the displacement of the bogie, and multiplied by \((-1)\), a constant called "spring constant of magnetic spring" [1][5] is derived.

In the case of the side-wall type EDS, magnetic springs for the lateral and rolling direction are strongly coupled [5]. For example, when the vehicle moves in the lateral direction, not only is a restoring force in the lateral direction generated, there is also a moment of the rolling direction produced. The coupling effect is strong when the vehicle is running at low speed. The minimum speed for levitated running is called the "take-off velocity." When the velocity of the vehicle is lower than the take-off velocity, the vehicle runs on supporting wheels. The take-off velocity is assessed by the equivalent lateral and equivalent rolling spring constants of the magnetic springs [2][6], due to the effect of the coupling of the magnetic springs for the lateral and rolling direction. In the previous study [2] on the design method for Maglev systems, the required conditions of the levitated run are that the equivalent lateral spring constant should be equal to or larger than 1 MN/m and the equivalent rolling spring constant should be equal to or larger than 3 MN·m/rad. When these spring constants are designed to be larger than in the conventional vehicle design, the take-off velocity is lower, reducing the need for maintenance on supporting wheels which is an advantage.

The definition [5] of the equivalent lateral and equivalent rolling spring constants of the magnetic springs is described below.

When the bogie is displaced or undergoes angular displacement in the \( j \) direction, and does not move in the other directions, and the electromagnetic force acts on the bogie in \( j \) direction, then the spring constant of the magnetic spring is defined as \( k_\phi \). The following equation is the formula with respect to the lateral and rolling directions.

\[
\begin{bmatrix}
F_y \\
N_\phi
\end{bmatrix} = \begin{bmatrix}
-1/k_{yy} & 1/k_{y\phi} \\
1/k_{\phi y} & -1/k_{\phi\phi}
\end{bmatrix} \begin{bmatrix}
y \\
\phi
\end{bmatrix}
\]  

where \( y \) and \( \phi \) are the lateral displacement and the rolling angular displacement respectively; \( F_y \) and \( N_\phi \), the lateral force and the rolling moment acting on the center of gravity of the bogie respectively; and \( k_{yy} \) and \( k_{\phi\phi} \), the coupling spring constants of the magnetic spring having the same values [5].

When the rolling moment is set to zero and only the lateral force is acting on the center of gravity of the bogie, the equivalent lateral spring constant \( k_{eqy} \) is defined by the relationship between the lateral displacement and the lateral force [5]. When the lateral force is set to zero and only the rolling moment acts on the center of gravity of the bogie, the equivalent rolling spring constant \( k_{eq\phi} \) is defined by the relationship between the rolling angular displacement and the rolling moment [5].

The following equation is obtained for \( k_{eqy} \) and \( k_{eq\phi} \).

\[
\begin{cases}
k_{eqy} = \begin{bmatrix}
k_{yy} & k_{y\phi} \\
k_{\phi y} & k_{\phi\phi}
\end{bmatrix}^{-1} \begin{bmatrix}k_{yy} & k_{y\phi} \end{bmatrix} \\
k_{eq\phi} = \begin{bmatrix}
k_{yy} & k_{y\phi} \\
k_{\phi y} & k_{\phi\phi}
\end{bmatrix}^{-1} \begin{bmatrix}k_{yy} & k_{y\phi} \end{bmatrix}
\end{cases}
\]

3. Calculation results: Magnetic springs for guidance

3.1 Balanced displacement

As a preliminary study for the magnetic springs for guidance, the calculation results of balanced displacement are described in this section.
Mass supported by the bogie is set to 20,000 kg [3], and running velocity is set to 500 km/h. Figure 3 shows the calculation results of the balanced displacement. The gap is set to 185 mm, 175 mm, and 160 mm [3][4]. The magnetomotive force of the SCM is set to 580 kA – 700 kA. Figure 3 indicates that the balanced displacement becomes smaller by increasing the magnetomotive force of the SCM or reducing the gap. Smaller balanced displacements relate to improvement of the electromagnetic force characteristics for levitation [3].

### 3.2 Lateral, rolling, and coupling spring constants

This section describes the calculation results for the magnetic springs for guidance during balanced displacement. The parameters for calculation were the same as those in Section 3.1. Figure 4 shows the calculation results for the lateral spring constant $k_{yy}$, the rolling spring constant $k_{yy}$, and the coupling spring constant $k_{yy}$. The following discussions on $k_{yy}$, $k_{yy}$ can be made based on the indication by Fig. 4.

(a) The lateral spring constant $k_{yy}$ and rolling spring constant $k_{yy}$ rise with the increase in magnetomotive force of the SCM.

(b) The rolling spring constant $k_{yy}$ increases by reducing the gap.

(c) The lateral spring constant $k_{yy}$ increases by reducing the gap when the magnetomotive force of the SCM is large. However, $k_{yy}$ decreases by reducing the gap when the magnetomotive force of the SCM is small.

The discussions (a) and (b) described above indicate that the characteristics of electromagnetic force for guidance improves by reducing the gap or increasing the magnetomotive force of the SCM; this trend is the same as that for the levitation. On the other hand, the discussion (c) described above indicates that the electromagnetic force characteristics for guidance worsen under certain conditions by reducing the gap; this trend is the opposite of that for the levitation.

#### 3.3 Discussion on reasons why the lateral spring constant becomes smaller by reducing the gap

As described in discussion (c) in Section 3.2, there is the fact that “the lateral spring constant $k_{yy}$ becomes smaller by reducing the gap under certain conditions.” The discussion on this fact is described in this section.

Figure 5 shows the calculation results of the relationship between the vertical displacement of the bogie and the spring constants $k_{yy}$, $k_{yy}$. Figure 5 indicates that $k_{yy}$ becomes larger and $k_{yy}$ becomes smaller as the vertical displacement decreases.

Principle of the effect of the gap reduction on the lateral spring constant $k_{yy}$ is explained as follows. When reducing the gap, the superconducting coils on the bogie move closer to the levitation/guidance coils in the lateral direction, which is expressed as the factor “change in lateral direction” in Fig. 6. On the other hand, as described in Section 3.1, the balanced displacement becomes smaller by the improvement of electromagnetic force characteristics for the levitation, and vertical position of the superconducting coils moves upward, which is expressed by the factor “change in vertical direction” in Fig. 6. Summarizing the discussions described above, the gap reduction has two factors: change in the lateral direction and change in the vertical direction.

The factor of the change in the lateral direction has an effect of the increase of magnetic flux linkage and is related to the increase of $k_{yy}$.

The factor of the change in the vertical direction has an effect of the change of the vertical position of the superconducting coil in the upward direction, and is related to the decrease of the magnetic flux linkage between the superconducting coil and the lower half of the levitation/guidance coil. Therefore, this factor is related to the decrease of the current which flows in the lower half of the levitation/guidance coil. In addition, the most dominant components [4] for the electromagnetic force for the guidance, the lower lateral straight components of superconducting coil and the lower lateral straight components of the lower half of
Whether the lateral spring constant \( k_{yy} \) becomes larger or smaller by reducing the gap depends on which is larger, the effect of the factor of the change in the vertical direction or the effect of the factor of the change in the vertical direction. When the magnetomotive force of the SCM is small, the effect of the factor of the change in the vertical direction is larger, and as described in the discussion (c) in Section 3.2, \( k_{yy} \) becomes smaller by reducing the gap.

3.4 Equivalent lateral and equivalent rolling spring constants

In this section, the calculation results of the equivalent lateral spring constant \( k_{eqy} \) and the equivalent rolling spring constant \( k_{eq}\), which are the values to assess the take-off velocity, are described.

4. Calculation results: Equilibrium position of the vehicle running in the curved section

Assessment factors for the vehicle dynamics also have wide variety. Calculation results of the equilibrium position of the vehicle running in the curved section, which is one of the assessment factors, are described in this section. Not only in the case of the wheel-supported adhesion railway vehicles, but also in the case of the Maglev vehicles, the centrifugal force acts on the vehicle toward the outer side of the curve. The sidewall of the guideway of the outer side of the curve is placed higher than that of the inner side to cancel the effect of the centrifugal force.

Figure 8 shows the concept of the Maglev vehicle running in the curved section. In the case of the Maglev vehicle, the closest point of the vehicle running in curved section, the distance between the edge of the bogie and the surface of the guideway, must be designed so as to be sufficiently large [6]. The definition of the axis is as shown in Fig. 8. The direction parallel to the bottom of the guideway is defined as \( y \) axis, and the direction perpendicular to the bottom of the guideway is defined as \( z \) axis.

In the calculation described in this paper, the curve radius is set to 8,000 m, and the cant angle is set to 10 degrees [6]. Under this condition, the balancing speed, at which the component of lateral direction of the centrifugal force and that of the gravitational force are balanced, is 420 km/h [6]. When the running velocity of the vehicle is lower...
than the balancing speed, the vehicle is displaced steadily on the inner side of the curve, and when the running velocity of the vehicle is higher than the balancing speed, the vehicle is displaced steadily on the outer side of the curve.

In the calculation described in this paper, as a preliminary study, the magnetic springs for guidance for the vehicle running in the straight section as shown in Fig. 4 are used as the substitutions of the magnetic springs for guidance for the vehicle running in the curved section. The equilibrium position of the vehicle is calculated by solving the motion equations [7] of the lateral and rolling directions of the Maglev vehicle with the gravitational forces and the centrifugal forces [8] acting on the center of gravity of the bogie and that of the car body as external forces. Mass supported by the bogie, 20,000 kg, is divided into the two components, the mass of the bogie, 6,000 kg, and the mass of the car body, 14,000 kg [7]. Running velocity is set to 500 km/h and the other parameters needed for the calculation are set to the same values as those used in the previous study [7].

Figure 9 shows the relationship between the magnetomotive force of the SCM and the values for the equilibrium position of the vehicle running in the curved section. Figure 9 (a) (b) show the lateral displacement and the rolling angular displacement of the center of gravity of the bogie, respectively. Figure 9 (c) shows the lateral displacement of the edge [9] of the bogie.

Figure 9 indicates that the lateral displacement and the rolling angular displacement of the center of gravity of the bogie and the lateral displacement of the edge of the bogie become smaller by reducing the gap or increasing the magnetomotive force of the SCM under all the conditions of the calculation described in this paper. These results indicate that the characteristics of the displacement in the lateral direction of the vehicle running in the curved section are improved by reducing the gap or increasing the magnetomotive force of the SCM.

Basically speaking, whether the lateral displacement of the bogie becomes smaller or larger is mainly assessed by whether the equivalent lateral spring constant $k_{w}$ becomes larger or smaller, because the lateral displacement of the center of gravity of the bogie at the equilibrium position is assessed by the lateral displacement of the center of gravity of the bogie when the external force in the lateral direction is added to the center of gravity of the bogie, if considered with respect to the relationship between the two design parameters, the gap and the magnetomotive force of the SCM, and magnetic springs for the guidance, as described in Section 3.

In calculations described in this paper, as a preliminary study, the magnetic springs for guidance at the equilibrium position of the vehicle running in the straight section is used to calculate the equilibrium position running in the curved section. When the actual characteristics of the Maglev vehicle are considered, the equilibrium position of the vehicle running in curved section has a displacement in the lateral direction from the neutral position. In the actual calculation in the design of the Maglev vehicle, not only the coupling of the motions of the lateral and rolling directions, but also the coupling of them with the motions of the vertical direction must be considered [5] in calculation of the equivalent lateral spring constant. In addition, for example, when the heavy vehicle is running in the curved section at low speed, equilibrium position in the lateral direction has a large displacement from the neutral position. In that case, non-linearity between the lateral displacement of the bogie and the electromagnetic force of the lateral direction must be considered [5].

Discussions described in this paper deal with the simple method with an aim to be associated with the basic principle of the vehicle dynamics, but not with an aim to calculate precisely the actual equilibrium position [6] of the vehicle.

5. Conclusions

There are many design parameters and assessment
factors to be considered in the design of the Maglev system. The authors have been conducting studies on the design with the aim of fundamental examination related to the characteristics of electromagnetic force and vehicle dynamics [3]. In this paper, study on the magnetic springs for guidance in relation to the characteristics of electromagnetic force and vehicle dynamics are described.

As for the study on the characteristics of the electromagnetic force, the effect of the two design parameters, gap and magnetomotive force of the SCM, on the magnetic springs for guidance is studied. Calculation results show that the lateral spring constant becomes smaller by reducing the gap under certain conditions. The results are explained in relation to the fundamental theory of electromagnetic force characteristics. Note that the equivalent lateral and equivalent rolling spring constants increase by reducing the gap or increasing the magnetomotive force of the SCM. This result contributes to reducing the take-off velocity of the Maglev vehicle.

One of the assessment factors of vehicle dynamics characteristics was studied, i.e. the equilibrium position of the Maglev vehicle running in the curved sections, using the values of the spring constant of the magnetic springs for guidance calculated in the study of electromagnetic force characteristics described above. The lateral displacement of the bogie at the equilibrium position decreases by reducing the gap or increasing the magnetomotive force of the SCM, and the characteristics of displacement in the lateral direction of the vehicle running in a curved section are improved. Basically speaking, whether the lateral displacement of the bogie at the equilibrium position becomes smaller or larger is assessed by whether the equivalent lateral spring constant becomes larger or smaller.

In previous studies [2] the equivalent lateral and equivalent rolling spring constants of magnetic springs were used as assessment factors to determine the take-off velocity of the vehicle, and this principle remains the same in the discussions described in this paper. The design method for another assessment factor, the equilibrium position of the vehicle running in curved sections, was already established in previous studies [5][6], and the discussion in this paper does not deny the design method. The results of the study described in this paper do not indicate that the already established design method or results of the design [1][2][5][6] must be changed. This study is performed in order to obtain deeper and more detailed insights, by reconstituting the already established design methods, in relation to the fundamental theories of electromagnetic force and vehicle dynamics characteristics.

More detailed studies will be performed to obtain the knowledge required for a detailed design of Maglev systems.

References


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