Numerical Analysis of the Vehicle Dynamics of the Superconducting Maglev System at the Yamanashi Test Line

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Abstract

Simulations of the vehicle dynamics of the superconducting maglev system currently under tests in Yamanashi, Japan, have been performed. This research focuses on how imperfections in the guideway influence ride characteristics. In order to identify the resonance frequencies of the system, periodic imperfections in the guideway were introduced. First, a simple, one-dimensional model was analyzed and resonance peaks near 1.16 Hz and 4.63 Hz were found. Then, a more accurate, six-dimensional model, where the forces between each coil are calculated, was used to confirm the results, and, at resonance, the ride was judged as poor. However, in reality, because the guideway imperfections are not periodic, a simulation, where the imperfections in the guideway were randomly determined, was performed. When the imperfections are within a certain range, the ride remained good.

1 Introduction

Numerical analysis of the superconducting maglev vehicle in Yamanashi Prefecture, Japan has been performed in depth. In this research, the Mc1, M3, Mc2 car set, as shown in Fig.1, is used. The basics of this system and the tests have been described in [1]-[4].

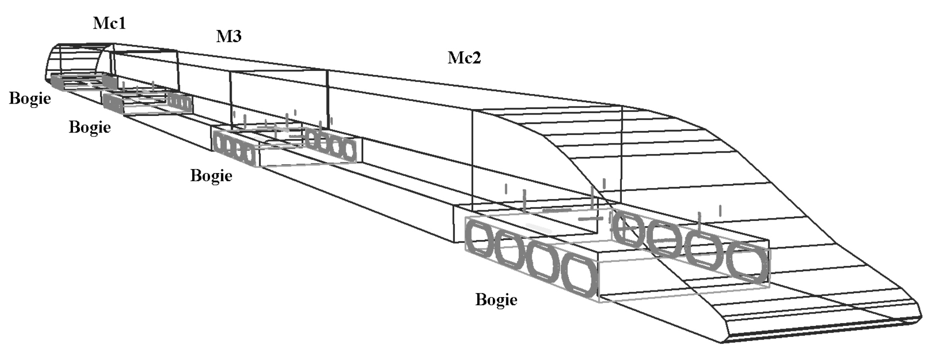

Fig. 1 Wire frame of analysis model for the superconducting maglev vehicle in Japan

Although a significant effort has been made illustrating the electromagnetic phenomena, little numeric analysis of how the electromagnetic force impacts the ride characteristics has been performed. This research will show the influence of the electromagnetic forces by using both a simple, one-dimensional analysis model and a complex, six-dimensional model. For both models, guideway imperfections based on the 12.6 m guideway panels are introduced to disturb the system. First, periodic imperfections are used to induce resonance. Finally, random imperfections are introduced to simulate more realistic conditions.

In this paper, each calculation method will be introduced, followed by the results of simulations using those methods.

2 One-Dimensional Analysis of Vertical Resonance

A simple analysis model where vibration is allowed only in the vertical direction is shown in Fig.2. In this model, electromagnetic levitation forces are modeled by an equivalent linear spring-damper.

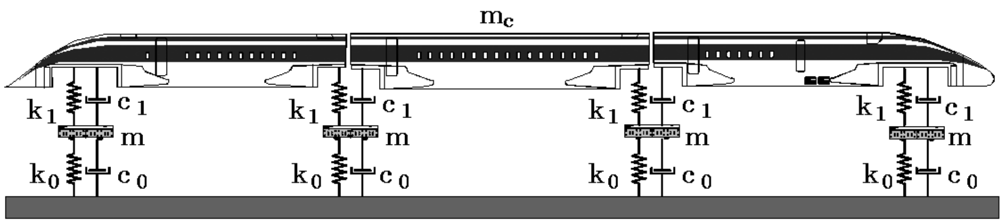

Fig. 2 One-dimensional analysis model

2.1 Model Parameters

In order to simplify the equations of motions, all the cars were modeled as one rigid object with mass, m_c. The bogies were assumed to be of equal mass, m. The suspension was reduced to just the air springs and dampers that are placed in the vertical direction. There are four air springs with a spring constant k_1 and four dampers with a constant c_1 for each bogie. The electromagnetic forces were simplified to be a linear spring-damper with a coefficients k_0 and c_0. The change in the levitation force was assumed to vary sinusoidally with an amplitude, F_0, and a frequency, w. Since the external force is due to guideway imperfections based on the length of a panel, it was assumed that each bogie experiences the same external force but at a slightly different phase. The parameters are shown in Table 1.

Table 1 Analysis model parameters

Parameter	Symbol	Value
bogie mass	m	6480 kg
car mass	m_c	50000 kg
equivalent spring constant	k_c	4700000 N/m
equivalent damper constant	c_o	-0.14 Ns/m
air spring constant	k_1	196000 N/m
vertical damper constant	c_1	4900 Ns/m
external force	F_0	8000 N
phase of external force at bogie1	f_1	0 rad
phase of external force at bogie2	f_2	5.39 rad
phase of external force at bogie3	f_3	5.72 rad
phase of external force at bogie4	f_4	5.61 rad

2.2 Equations of Motion

The equations of motion for the bogies are shown in Eq. (2.1), and the equation of motion of the car is shown in Eq. (2.2). The complex vertical position is given by z_i, where i is the bogie number (1-4), and (5) is the car. The first derivative of the position, or speed, is shown by one dot, and the second derivative, the acceleration, is given by two dots.

$$m\ddot{z}_i = -k_0 z_i - c_0 \dot{z}_i + 4k_1(z_5 - z_i) + 4c_1(\dot{z}_5 - \dot{z}_i) + F_0 e^{-i(wt - f_i)} \tag{2.1}$$

$$m_c \ddot{z}_5 = 4k_1(4z_5 - z_1 - z_2 - z_3 - z_4) - 4c_1(\dot{z}_5 - \dot{z}_1 - \dot{z}_2 - \dot{z}_3 - \dot{z}_4) \tag{2.2}$$

Assuming that the complex motion of the bogies and the car is at the same frequency of the external force, the following solution is given for i from 1 to 5.

$$z_i = A_i e^{-iwt} \tag{2.3}$$

Solving the equations for the complex amplitude yields the following.

$$\begin{pmatrix} a_0 & 0 & 0 & 0 & -4w_0 \\ 0 & a_0 & 0 & 0 & -4w_0 \\ 0 & 0 & a_0 & 0 & -4w_0 \\ 0 & 0 & 0 & a_0 & -4w_0 \\ -4w_0 & -4w_0 & -4w_0 & -4w_0 & b_0 \end{pmatrix} \begin{pmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \end{pmatrix} = \begin{pmatrix} F_0 e^{if_1} \\ F_0 e^{if_2} \\ F_0 e^{if_3} \\ F_0 e^{if_4} \\ 0 \end{pmatrix} \tag{2.4}$$

where

$$w_0 = k_0 + ic_0 w \tag{2.5}$$

$$w_1 = k_1 + ic_1 w \tag{2.6}$$

$$a_0 = -mw^2 + w_0 + 4w_1 \tag{2.7}$$

$$b_0 = -m_c w^2 + 16w_1 \tag{2.8}$$

2.3 Solutions

Solving for the real amplitude of the acceleration of the car yields two significant peaks, one near 1.16 Hz and one around 4.63 Hz. The vertical acceleration of the car is shown in Fig. 3.

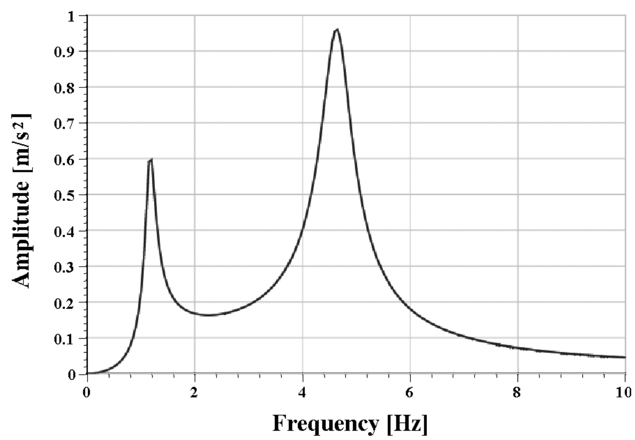

Fig. 3 Vertical acceleration of car for one-dimensional analysis model

2.4 Discussion

A one-dimensional analysis of the vertical resonance frequency yielded two peaks, one at 1.16 Hz and one at 4.63 Hz. Neither peak corresponds to the continual run speed of the vehicle of about 140 m/s, however, both are passed through during acceleration. The lower peak could be caused by a periodic disturbance in a set of eight guideway panels (roughly 100m) at a speed of roughly 116 m/s. The higher peak could correspond to recurring imperfections of period corresponding to two guideway panels (25.2m) at near 116 m/s.

However, this analysis roughly calculated the electromagnetic forces and only allowed for one dimensional movement with a total of four degrees of freedom. Complex pitching movements, as well as various phase differences of the cars, can be anticipated with guideway conditions such as these for a three car set. The next section contains a description of an analysis that can more accurately simulate these ride situations.

3 Six-Dimensional Analysis of Vertical Resonance

In order to verify the results obtained with a simple, one-dimensional analysis, a complex model was developed in SIMPACK, a commercial dynamic software package, where parameters from the actual train set currently under running tests in Yamanashi Prefecture, (Mc1, M3, Mc2), are used, and the forces and torques between the superconducting coils in the bogie of the vehicle and the guideway coils are calculated. First, the analysis model will be introduced and followed by an explanation of the calculation method. Then results of several simulations will be shown.

3.1 Analysis Model

As mentioned before, the six-dimensional analysis model, where horizontal, lateral, vertical, rolling (about horizontal axis), pitching (about lateral axis) and yawing (about vertical axis) motion are allowed, is based on the Mc1-M3-Mc2 car set in Yamanashi Prefecture. In this model all bodies are assumed to be rigid bodies and are connected by a suspension system very similar to what is currently being used at the test track. The suspension includes air springs, vertical dampers, horizontal dampers, and anchor and connecting bars. A rough image of the suspension is shown in Fig. 4.

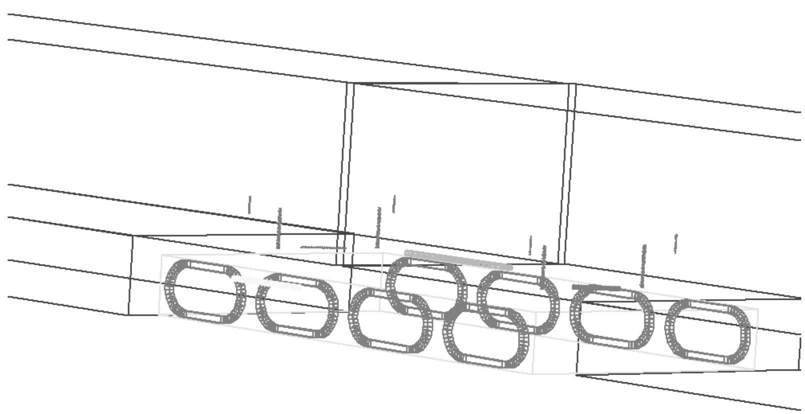

Fig. 4 Image of the suspension

This system, where most of the parts are connected by a complex set of revolute joints, has forty degrees of freedom. Although this system has integrated many of the more complex parts of the suspension, it does not consider the elastic deformations of bodies, which can significantly affect the ride characteristics.

Also, in all simulations, wind resistance was calculated in a very simplistic manner where the force was proportional to the square of the speed. The main reason for the inclusion of the wind resistance was to be able to take into account any oscillations due to the linear synchronous motor.

3.2 Calculation Method

The equations of motion are managed by SIMPACK. However, the electromagnetic forces are calculated by a subroutine that takes into consideration every combination within a specific range of superconducting coils and guideway coils. An image of the superconducting coils on the bogie, the figure-eight levitation coils and the two-layered armature coils for the linear synchronous motor is shown in Fig. 5.

The force or torque, F_a, between two coils is calculated by the following equation.

$$F_a = -i_{SC} i_G \frac{\partial M}{\partial a} \tag{3.1}$$

where a is one of the six-dimensional directions, i_{sc} is the current in a superconducting coil, i_g is the current in a guideway coil, and $\delta M/\delta a$ is the spatial derivative of the mutual inductance. The current in a superconducting coil is determined by the fact that the total flux linking the coil is constant. The current in a levitation coil is calculated by solving the equivalent circuit. Finally, the current in a propulsion coil is determined by the position, speed and acceleration of the front bogie.

The calculation of the spatial derivative of the mutual inductance, $\delta M/\delta a$, consumes the most time and influences the accuracy of the results significantly. In this research, calculation time was significantly reduced by the adoption of the data interpolation method, where mutual inductance values are interpolated from a data set based on the six-dimensional relative position of two coils. Although the thickness of the coils and the resulting eddy currents were not considered, the racetrack shape of the coils were modeled as realistically as possible when the data set was created in order to increase the accuracy. For a more concise explanation of the calculation, see [5] and [6].

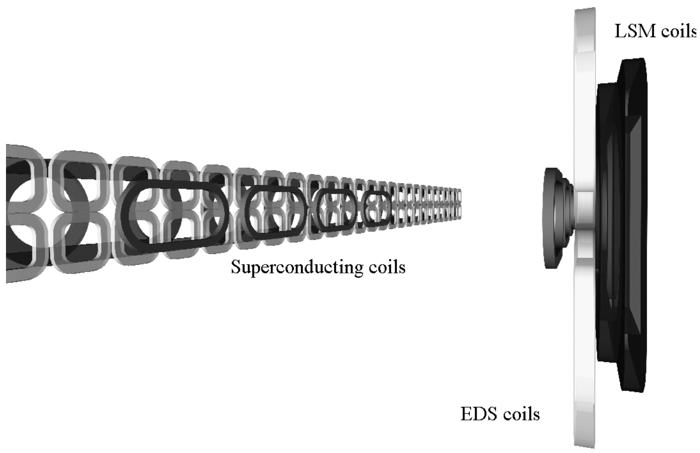

Fig. 5 Image of the coil system

3.3 Simulation Results

In order to verify the resonance peaks obtained in Section 2, guideway irregularities as shown in Fig. 6 and Fig. 7 were introduced.

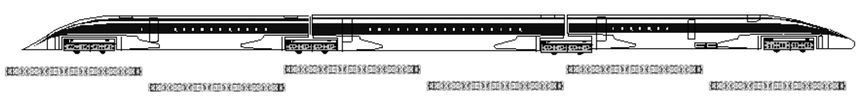

Fig. 6 Irregularities in the panel placement that occur every other panel

Fig. 7 Irregularities in the panel placement that occur every eight panels

3.3.1 Irregularities: Every Other Panel

The vertical displacement of every other panel as shown in Fig. 6 was set to 5 mm higher than normal. Otherwise, the panels were perfectly placed.

A vehicle going near 116 m/s over two panels of a total of 25.2 m in length should approach the 4.63 Hz resonance peak. A wide range of speeds were tested over this guideway to verify the existence of the peak. Fig. 8 shows the vertical acceleration of the middle car, M3, at its center of mass. As can be seen by this graph, there exists a peak near 114m/s. However, as shown in Fig. 9, when the peak vertical accelerations of each car are compared to the one-dimensional analysis, there is a slight difference of the peak's location. Also, the phases of at the maximum values of the vertical accelerations as well as the pitch angle are quite different for each car, suggesting quite complex movements. However, the peak value of the acceleration suggests a very poor ride.

A direct comparison to the one-dimensional model can be misleading. The amplitude of the external force in one-dimensional model is several times smaller than the average variation in the total force acting on a bogie when all the forces between the surrounding coils are calculated. Also, this analysis assumes that the car bodies are rigid. However, in the future, it is important to consider the first modal elastic movement of each car. It may be especially interesting to observe a phase situation where the combined three car set approaches its third modal vibration, where, for example, while the middle of the end cars bend downward, the middle of the middle car flexes upward.

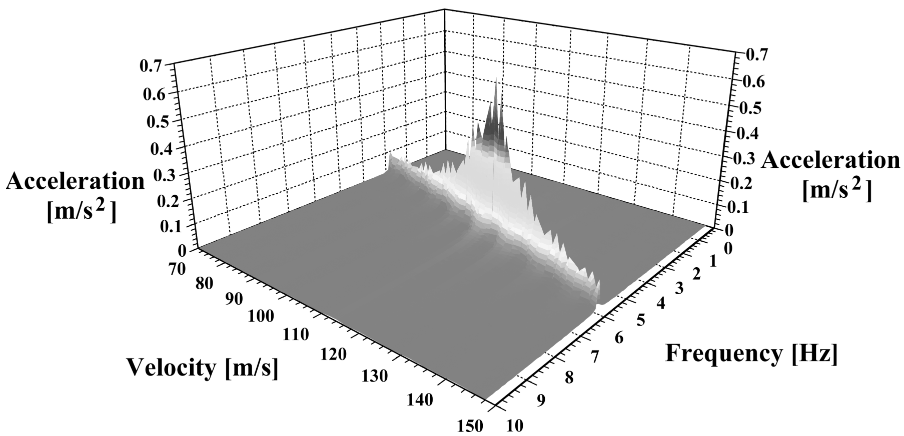

Fig. 8 Vertical acceleration spectrum of the middle cabin

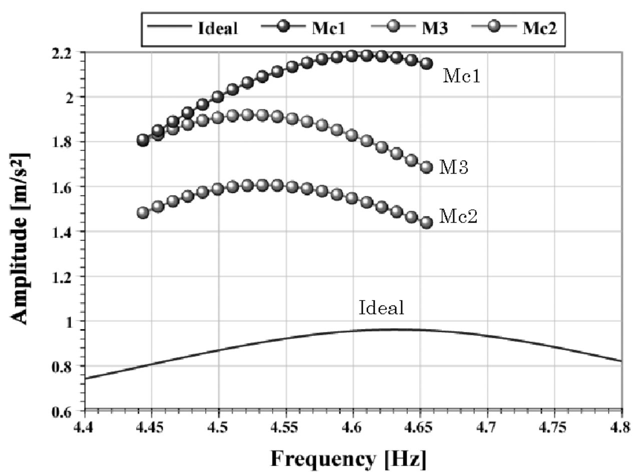

Fig. 9 Vertical acceleration spectrum of the cabins (around 4.63 Hz)

3.3.2 Irregularities: Every Eight Panels

Next, the vertical displacement of every eight panel as shown in Fig. 7 was set to 5 mm higher than normal. The panels were grouped by fours. Otherwise, the panels were perfectly placed.

A vehicle going near 117 m/s over eight panels of a total of 100.8m in length should approach the 1.16 Hz resonance peak. A wide range of speeds were tested over this guideway to verify the existence of the peak. As shown in Fig. 10, when the peak vertical accelerations of each car are compared to the one-dimensional analysis, there is a slight difference of the peak's location and even the existence of what appears to be two peaks. Also, similar to the previous simulations, the phases at the maximum values of the vertical accelerations as well as the pitch angle are quite different for each car, suggesting quite complex movements.

Similar to the previous analysis, a direct comparison to the one-dimensional model can be misleading. In this simulation, the imperfections in the guideway were repeated at a wavelength greater than the length of the entire three car set. This makes pitching in the cars quite significant when analyzing vertical acceleration.

Also, this analysis assumes that the car bodies are rigid. However, as previously stated, in the future, it is important to consider the first modal elastic movement of each car. It may be especially interesting to observe a phase situation where the combined three car set approached it first modal vibration, where, for example, while as the middle of the end cars bend downward, the middle of the middle car reaches even further downward. At frequencies approaching 1 Hz, this could be possible.

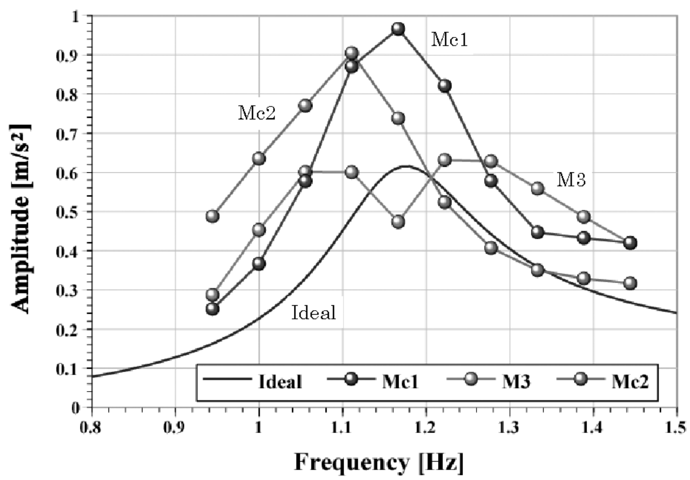

Fig. 10 Vertical acceleration spectrum of the cabins (around 1.16 Hz)

3.3.3 Random Guideway Imperfections

For practical purposes, the placement of the panels at the Yamanashi Test Line are adjusted so that any imperfections do not become periodic and excite the cars in such a way that the movement of the system approaches resonance. Therefore, a more realistic simulation, where the imperfections in the guideway are determined randomly was performed. The guideway was assumed to be straight with no curves, gradients or superelevations. However, for placement of each panel, there was a slight deviation from perfect placement in all six dimensions as shown in Table 2. The vertical displacement of each was taken and analyzed to see how random the imperfections were. The resultant vertical spectrum is shown in Fig. 11.

Table 2 Error ranges of guideway panel placement

Direction	Error
Horizontal	$-5\text{mm} \le x \le 5\text{mm}$
Lateral	$-5\text{mm} \le y \le 5\text{mm}$
Vertical	$-5\text{mm} \le z \le 5\text{mm}$
Rolling	$-4\times10^{-4}\,\text{rad} \le a \le 4\times10^{-4}\,\text{rad}$
Pitching	$-4\times10^{-4}\,\text{rad} \le b \le 4\times10^{-4}\,\text{rad}$
Yawing	$-4\times10^{-4}\,\text{rad} \le g \le 4\times10^{-4}\,\text{rad}$

A simulation was performed where the running speed was constant at 138 m/s. The horizontal, lateral and vertical acceleration spectrums of the middle car, M3, are shown in Figs. 12-14. Ride coefficient 1 is a line that judges ride quality. It is based on a standard determined by JR, where acceleration spectrums below ride coefficient 1 are judged as very good. As can be seen in the results, in all directions ride characteristics can be judged as having a very good ride.

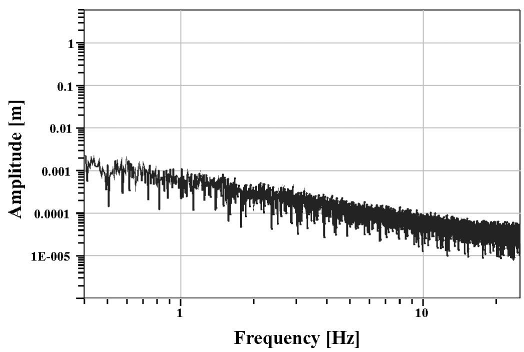

Fig. 11 Irregularities in vertical direction

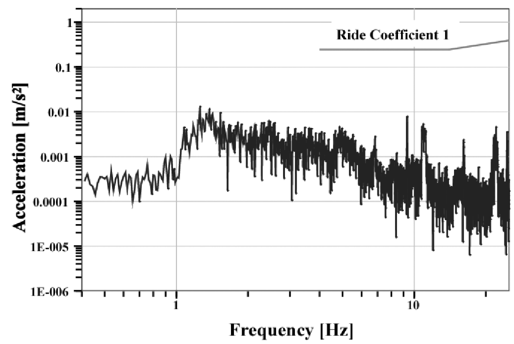

Fig. 12 Horizontal Acceleration Spectrum

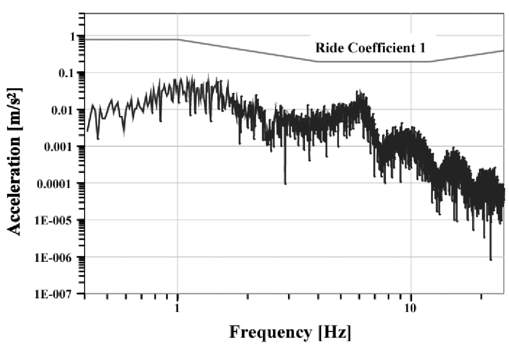

Fig. 13 Lateral Acceleration Spectrum

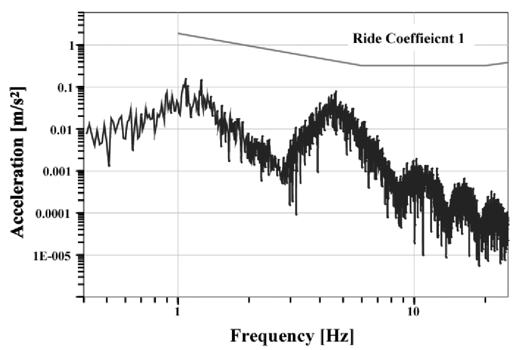

Fig. 14 Vertical Acceleration Spectrum

4 Conclusion

Numerical analysis of the ride characteristics of the Superconducting Maglev vehicle currently under tests in Yamanashi Prefecture, Japan was performed. The vertical resonance frequency was determined in both a one-dimensional and six-dimensional model by assuming periodic imperfections in the guideway. Next, the model was used to perform a more realistic analysis of actual riding conditions where the imperfections in the guideway were determined randomly. In the future, the inclusion of elasticity in the car bodies would greatly increase the accuracy of the analysis.

5 References

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