# THE CHARACTERISTICS OF THE LEVITATION SYSTEM OF LINIMO (HSST SYSTEM)

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## Abstract

Gap fluctuation value of levitation magnet can be estimated by calculation between guideway irregularity PSD and levitation control transfer function. We performed this calculation based on the data acquired in advance in our Oe test site and confirmed that our new train Linimo will run smoothly without contact to guideway rail on the mainline Tobu-Kyuryo.

## 1 Introduction


**Photo.1 Linimo Train**

Tobu-Kyuryo-Line, which is called Linimo after public naming invitation, will start revenue service next March. It is the first perpetual commercial application of HSST, the maglev transportation system developed by CHSST, which adopts normal-conducting electro-magnetic levitation. Prior to the test run on Tobu-Kyuryo-Line, we accomplished verification test on our Oe test track, Nagoya, with a set of cars manufactured in advance for this purpose. However Oe test track has some restrictions against Linimo operation, this test run gave us various valuable acknowledgements. They were reflected in design improvement of Linimo before its mass production. In this paper we describe our study on spectral analysis of the levitation performance of Linimo, especially with regard to its stiffness against guideway irregularity.

## 2 Stiffness of the levitation

Here we are going to investigate stiffness of the levitation system. Power spectral density (PSD) of levitation gap can be obtained by multiplying PSD of guideway irregularity by levitation transfer function. It will show eventual gap fluctuation value caused by guideway irregularity.

### 2.1 Spectrum of the guideway irregularity

Major guideway irregularities that dominate vertical movement of magnets are random irregularity and bending of the girder. We are going to investigate these items one by one.

### 2.1.1 Random Irregularity

Guideway irregularity is usually expressed with the deviation value measured at the midpoint of certain chord stretched between two points of the rail. In this paper we call this deviation as Versine. It is known that this value follows the Gauss distribution and we define the root mean square of versine as $\sigma$ .

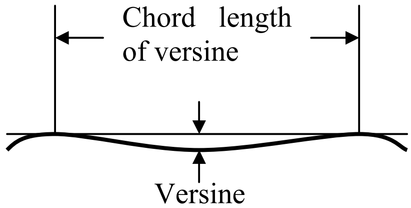


**Fig.1 Expression of guideway irregularity**

According to our predecessors' study (Ref.1) and our experience, as well, PSD of guideway random irregularity can be expressed as below.

$$\Phi_{zr}(\omega) = \frac{Av}{\omega^2} \cdot \frac{(\Phi_1 v)^2}{\omega^2 + (\Phi_1 v)^2}, A = \frac{4C^2}{9\pi l} \qquad \text{Eq.1}$$

$\Phi_{zr}$ : PSD of random irregularity
$A$ : Coefficient of random irregularity
$v$ : Vehicle running velocity
$\omega$ : Angular velocity of disturbance
$C$ : Upper limit of vertical versine during guideway construction and maintenance
$l$ : Length of the chord in measuring above versine
$\Phi_1$ : Cut-off radian per meter of guideway irregularity

The value A was determined by the maintenance practice and data in Oe test track. Maximum velocity of Linimo is designed as 100km/h, but Oe test track does not allow it to run beyond 70km/h. Therefore, in this study, we set $v = 70/3.6(m/s)$ in Eq.1. PSD calculation was performed from $\omega_1 = 0.1 \times 2\pi(rad/s)$ to $\omega_2 = 51.2 \times 2\pi(rad/s)$ with $0.1 \times 2\pi(rad/s)$ division. Thus the subject rail profile is expressed in the function of irregularity frequency as follows.

$$H_r(f) = \sqrt{\Phi_{zr}(2\pi f) \times 0.1 \times 2\pi} \quad \text{Calculation in every 0.1Hz} \qquad \text{Eq.2}$$

$H_r$ : Amplitude of random irregularity

Fig.2 shows samples of random irregularity profiles obtained as a combination of every spectrum. Note that both ends of the levitation rail are regulated to zero level.

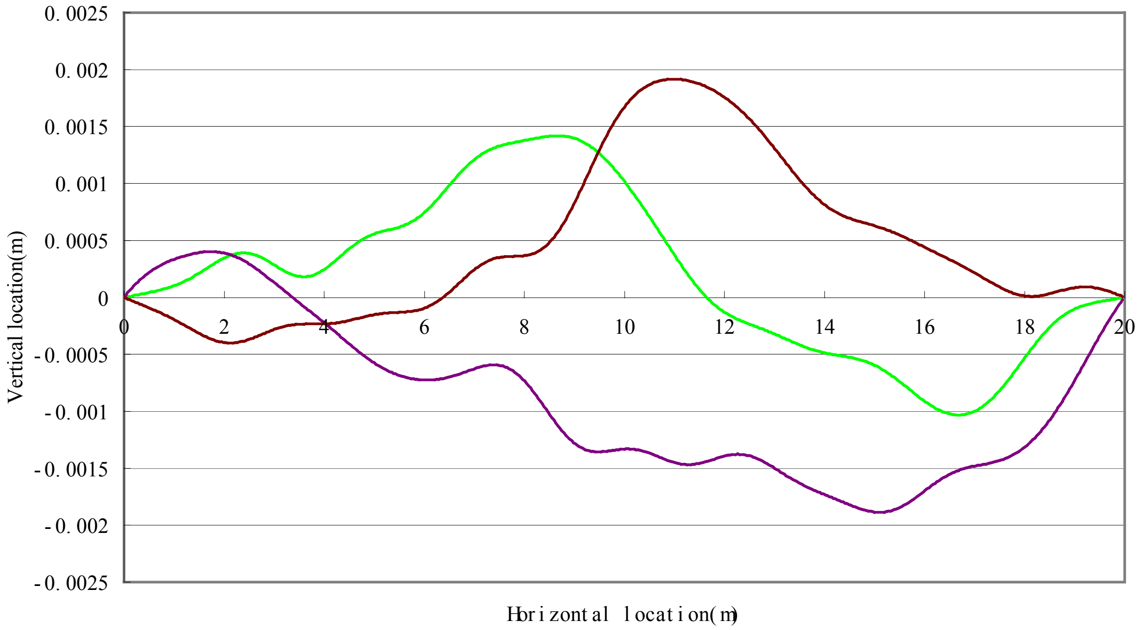


**Fig.2 Examples of random irregularity profiles**

### 2.1.2 Bending of the guideway

Most of the girders in Oe test track have span length of 20m. Assuming that the bending rate of girder is 1/2000, we calculate deviation of bending from horizontal level in every 1/512 length to which the train moves in 10(s) at 70/3.6(m/s). This bending profile can be transformed into spectra through FFT method. Fig.3 shows example of bending profile of the guideway girder.

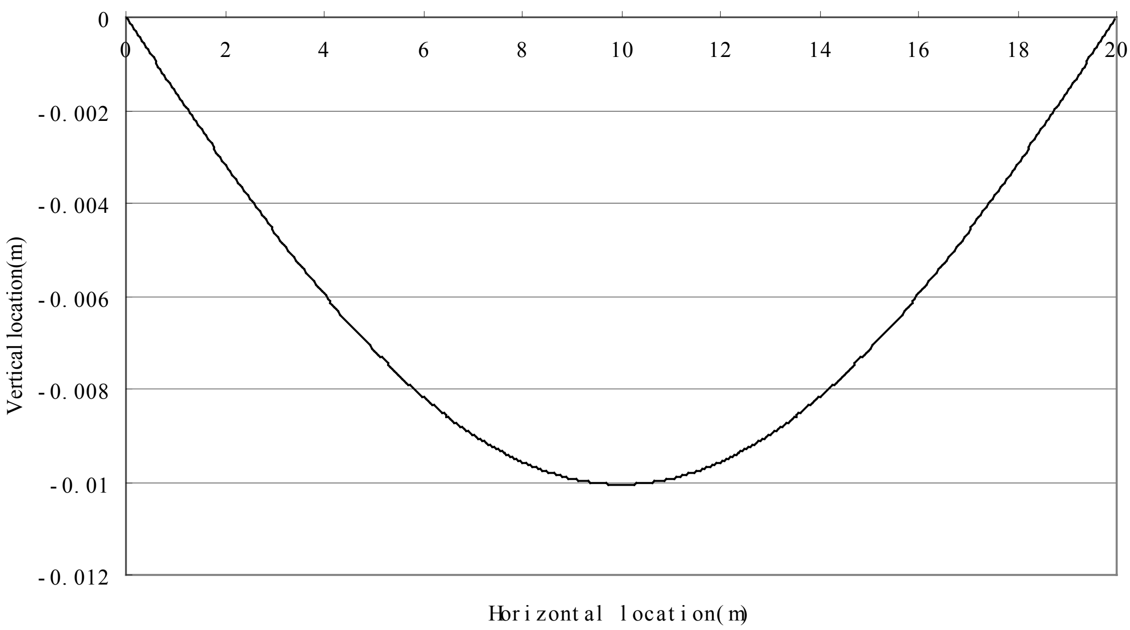


**Fig.3 Example of bending of guideway girder**

#### 2.1.3 Spectrum of the guideway irregularity

$$H_t(f) = H_r(f) + H_d(f) \qquad \text{every 0.1Hz} \qquad \text{Eq.3}$$

$H_t$ : Amplitude of summed guideway irregularity

$H_d$ : Amplitude of bending of the guideway girder

Amplitude of the guideway irregularity can be obtained by adding Eq.1 and Eq.2. Fig.4 shows examples of the summed guideway irregularity profiles.

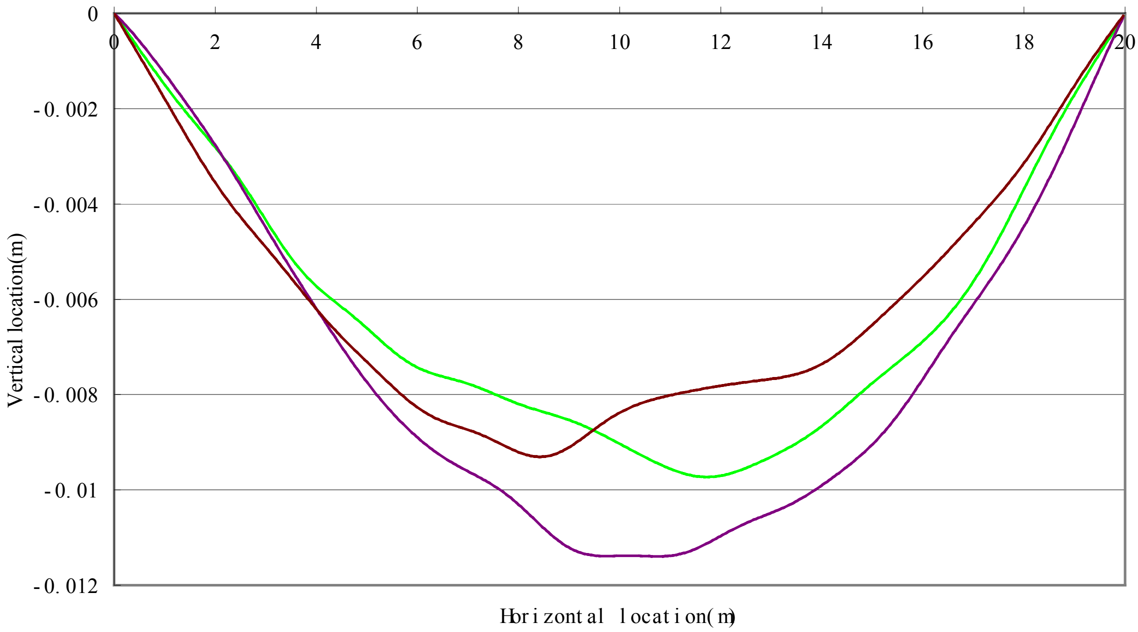


**Fig.4 Examples of guideway profile**

## 2.2 Transfer function

Fig.5 is the block diagram of levitation control of the Linimo. Meanings of constants are shown below.

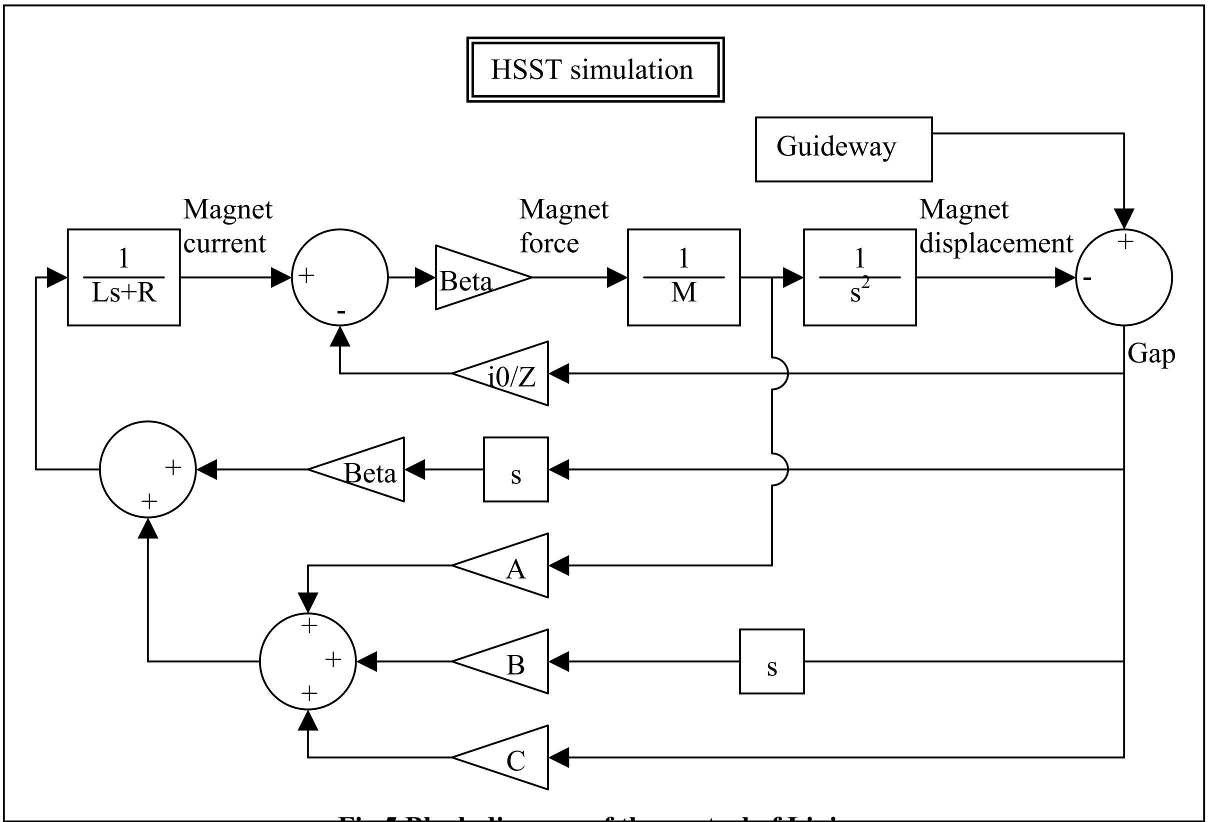


**Fig.5 Block diagram of the control of Linimo**

| | |
|---|---|
| R | : Electric resistance of magnet coil |
| L | : Total Inductance of coil |
| Z | : Target air gap of magnet |
| i0 | : Typical current of magnet coil |
| Beta | : Magnet gain |
| M | : Mass of bogie |
| C | : Proportional feedback gain of gap |
| B | : Differential feedback gain of gap |
| A | : Acceleration feedback gain |

As for calculation of the transfer function, the input port was set at the guideway and the output port was set at the gap itself.

## 2.3 PSD of the air gap

According to ref. 1 PSD of gap can be calculated as below.

$$\Phi_x(\omega) = |T(j\omega)|^2 \Phi_z(\omega) \qquad \text{Eq.4}$$

$\Phi_x$ : PSD of magnet air gap

$T$ : Transfer function from guideway to gap

$\Phi_z$ : PSD of guideway irregularity

$$\Phi_z(2\pi f) = \frac{H_t(f)^2}{0.1\times 2\pi} \quad \text{for each 0.1Hz division} \quad \text{Eq.5}$$

$$\Phi_x(2\pi f) = \left|T(2\pi fj)\right|^2 \Phi_z(2\pi f) \quad \text{Eq.6}$$

$$H_x(f) = \sqrt{\Phi_x(2\pi f)\times 0.1\times 2\pi} \quad \text{every 0.1Hz} \quad \text{Eq.7}$$

Hx: Gap amplitude (spectrum function of frequency)

PSD of guideway irregularity is obtained by a square of amplitude divided by the incremental division of $0.1\times 2\pi(rad/s)$. And we calculate PSD of gap by multiplying it by a square of absolute value of transfer function. Finally we calculate amplitude of gap by multiplying PSD of gap by the interval $0.1\times 2\pi(rad/s)$ and by finding a square root of it. Fig.6 is the calculated spectra of gap.

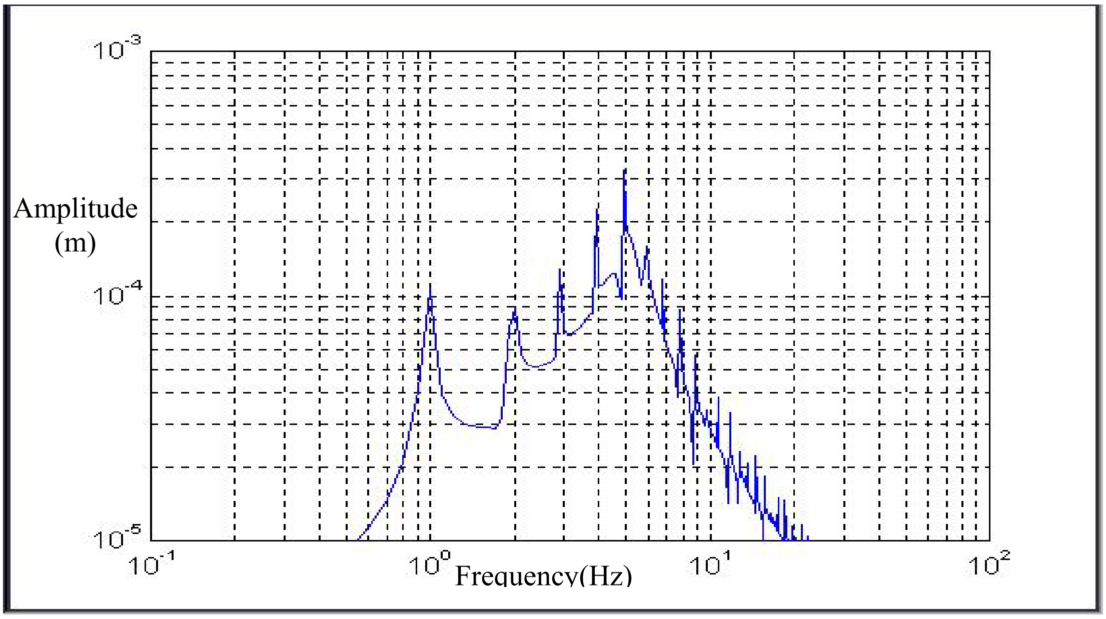


**Fig.6 Calculated spectrum of gap**

Fig.7 shows, for comparison purpose, measured spectra of gap of Linimo in Oe test track. running at 70km/h.

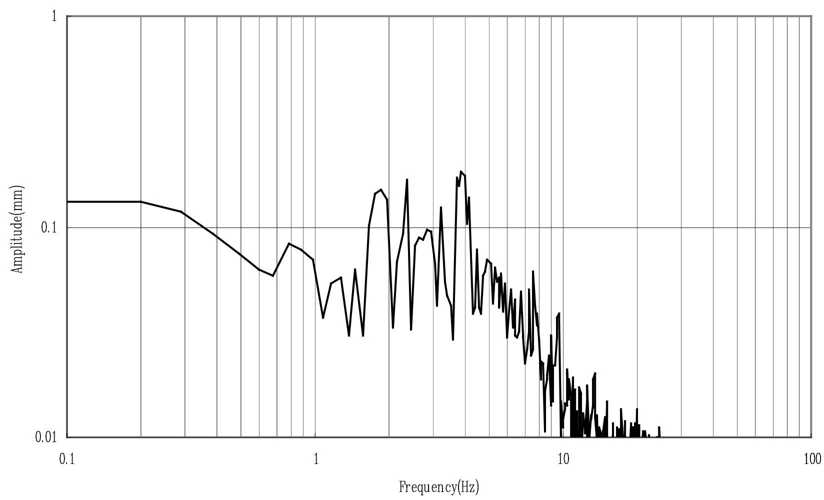


**Fig.7Measured spectrum of gap in Oe test track**

Comparing Fig.6 with Fig.7, we find that the calculation stated above well simulates the characteristics of the levitation control of the Linimo. There are differences in lower frequency range. We could not isolate its cause, but we can say that such lower frequencies do not affect the result of levitation gap.

## 2.4 Root mean square of the gap

According to ref. 1, the root mean square value of magnet air gap can be calculated as below:

$$\sigma = \sqrt{\int_{\omega_1}^{\omega_2} \Phi_x(\omega) d\omega} \qquad \text{Eq.8}$$

$\sigma$ : Root mean square of gap

$\omega_1$ : Lower end of angular velocity bandwidth

$\omega_2$ : Higher end of angular velocity bandwidth

$\Phi_x$ : PSD of gap

where:

$$\Phi_x(2\pi f) = \frac{H_x(f)^2}{0.1 \times 2\pi} \qquad \text{Eq.9}$$

as the result:

$$\sigma = \sqrt{\sum_{k=1}^{512} \Phi_x(k \times 0.1 \times \pi) \cdot (k \times 0.1 \times \pi)} \qquad \text{Eq.10}$$

PSD of gap is obtained by a square of amplitude divided by the incremental division of $0.1 \times 2\pi(rad/s)$. As the result of this calculation, we got $\sigma$ =0.00091(m) by discrete integration from $\omega_1 = 0.1 \times 2\pi(rad/s)$ to $\omega_2 = 51.2 \times 2\pi(rad/s)$ every $0.1 \times 2\pi(rad/s)$. Measured RMS of gap on Oe test track is 0.00081(m). We confirmed good assimilation in this matter.

## 2.5 Assumption on Tobu-Kyuryo-Line

The verification test on Oe test track proved that our calculation well simulates the characteristics of the levitation control of Linimo. Now we are going to estimate the gap fluctuation behavior in Tobu-Kyuryo-Line.

Scheduled versine value of guideway in Tobu-Kyuryo-Line is kept same as that in Oe test track. Therefore the coefficient of guideway irregularity in Tobu-Kyuryo-Line is same as that in Oe. Major differences between the operation in Tobu-Kyuryo-Line and that in Oe test track are maximum velocity and the length of girder. Fig.8 shows the comparison between gap spectra on Tobu-Kyuryo-Line and that on Oe test track. The red line is the spectrum of gap amplitude on Tobu-Kyuryo-Line and the black one is that on Oe test track. In the case of Tobu-Kyuryo-Line vehicle velocity is set at 100/3.6(m/s) and the length of girder at 30(m).

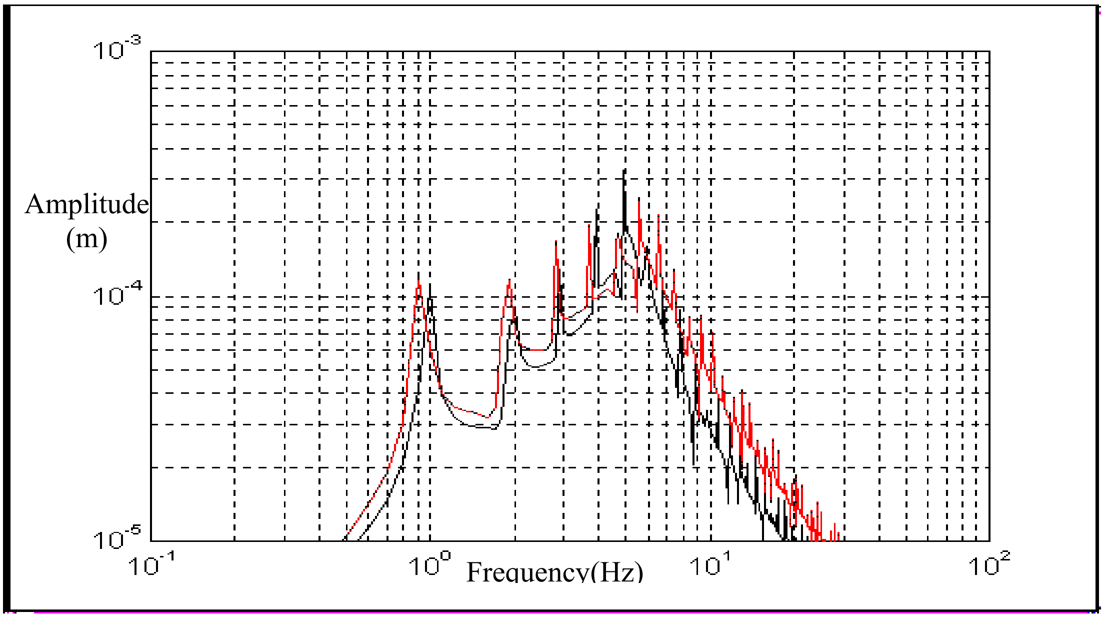


**Fig.8 Comparison of spectrum of gap between Oe and TKL**

As the result, RMS of gap (σ) on Tobu-Kyuryo-Line appeared to be 0.0010(m). Generally speaking, maximum gap is considered to be $3\sigma$, however our experience shows that it can be as far as $4\sigma$. Even with $4\sigma$ estimation criteria, maximum gap falls within allowable limit of 4mm.

## 3 Conclusion

On this paper we made use of a statistical method. The transfer function is based on our experience, PSD function of guideway irregularity is based on the experiences of traditional railways with a modification based on our experience. With these assumptions, we investigated the stiffness of levitation system of Linimo. The result of verification test on Oe test track has shown us that our calculation well simulates the characteristic of the levitation of Linimo. We confirmed that it has little possibility that the magnets will touch the rail.

### References


1. Sakae Yamamura & Shigeru Abe. *Control and Speed-Characteristics of Magnetically Levitated Vehicles of Attracting Magnet Type, The Institute of Electrical Engineers of Japan, 1976*