Riding Comfort Evaluation of Railway Vehicle by a Simulator

Kei YASUMURO*1, Yong HAN *2, Ryosuke GOTO*3, Yuichi NAKAZATO*4, Yasuyuki MIYAJIMA*5 and Haruo SHIMOSAKA*6

*1, 2 Department of Mechanical Engineering, Graduate School of Meiji University
1-1-1 Higashimita, Tama-ku, Kawasaki-shi, Kanagawa-ken, 214-8571, Japan
ce32061@meiji.ac.jp, ce22016@meiji.ac.jp
*3,4 Tokyo Metro, 3-19-6 Higashi Ueno, Taito-ku, Tokyo, Japan
*5 Toshiba, 1-1-1 Shibaura, Minatoku, Tokyo, Japan
*6 Department of Mechanical Engineering, Meiji University
1-1-1 Higashimita, Tama-ku, Kawasaki-shi, Kanagawa-ken, 214-8571, Japan
hshimos@meiji.ac.jp

Abstract

In this paper, railway vehicle comfort can be evaluated in numerically by 7 patterns of test, subjective way and objective way. Subjective way to evaluate the riding comfort is done by pressing a switch when a subject feels bad riding comfort. In contrast, riding comfort can be also evaluated by objective way based on the movement of center of gravity of the subject. As the result, we describe riding comfort by linking vehicle's running acceleration, jerk and the amount of movement of center of gravity.

Keywords: simulator, acceleration, jerk, movement of center of gravity, riding comfort

1 Introduction

Up to now, the riding comfort evaluation has been performed by a test run [1]. But it is difficult to repeat the riding comfort test under same condition with a lot of subjects [2]. One of factors to affect the riding comfort of railway vehicle is vibrational acceleration [3]. In this study, we developed a simulator which can reproduce railway vehicle acceleration. The simulator was devised by combining a universal shaking table with a translation table and an inclination table. Developing the simulator, we can repeatedly conduct riding comfort evaluation test under the same conditions.

2 Simulator

PSD (Power spectral densities) calculated from the acceleration in a direction of movement measured when the railway vehicle decelerates is shown in **Fig. 1**. We can see that frequencies in the region of less than around 0.4Hz are dominant. But it is difficult to reproduce the railway vehicle acceleration by using only the universal shaking table, because the universal shaking table cannot produce sufficient amplitude in the region of lower frequencies. So we developed the translation table and the inclination table. Combining the translation table with the inclination table, the acceleration in the region of lower-frequencies is compensated. The translation table is installed on the universal shaking table. In addition, the inclination table is installed on the translation table. A subject steps on the inclination table. Letting the x direction of the universal shaking table be in accordance with the progressing direction of the railway vehicle, we reproduced the railway vehicle acceleration of a direction X, Y and Z. The simulator which we developed in this study is shown in **Fig. 2**.

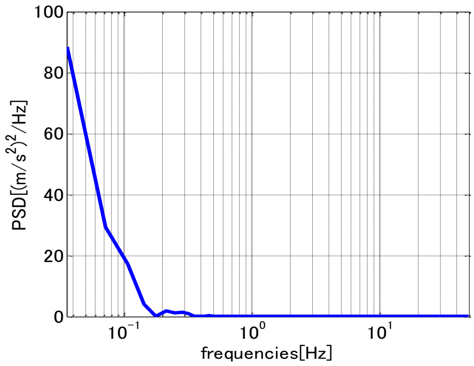


Fig. 1 Acceleration PSD in the progressing direction

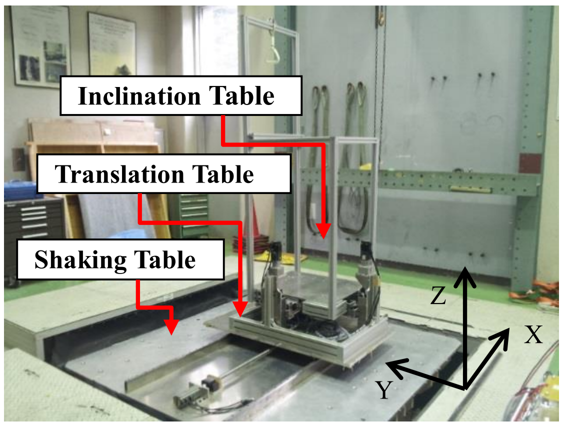


Fig. 2 Simulator

3 Device for measurement of center of gravity

During the riding comfort evaluation test, to know the standing balance of the subject, we developed a device which can measure subject's position of center of gravity. The device for the measurement of center of gravity and its model are shown in **Fig. 3** respectively. Four load meters are set on each around corner.

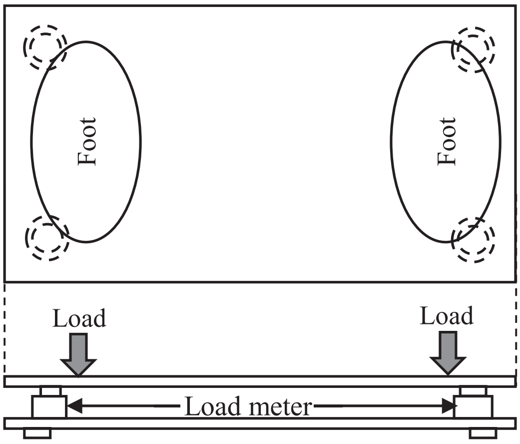


Fig. 3 Model of device for the measurement of center of gravity

4 Button for evaluating riding comfort

We prepared a button which a subject pushes when he/she feels bad. By using this button, the riding comfort is evaluated intuitively.

5 Acceleration data

Acceleration data measured through four test runs are used in this study. We took out seven uncomfortable acceleration behaviors from these acceleration data for around 40 seconds. Those data we took are used as original acceleration data. Measurement condition of test runs is shown in **Table 1**. In addition, one of those uncomfortable acceleration behaviors (Data No.1) is shown **Fig. 4** as an example. Operation condition of Data No.1 is braking to pass the curve.

Table 1 Measurement condition

Date	January 28, 2012
Line	Tokyo Metro
Situation	Trial run in the daytime

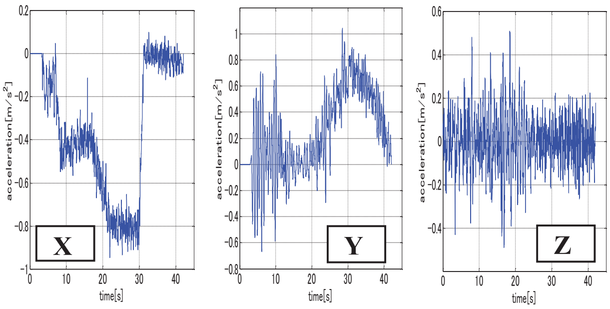


Fig. 4 Railway vehicle acceleration (X, Y, Z)

6 Separation of acceleration

The floor acceleration of the railway vehicle must be properly divided into the universal shaking table, the translation table and the inclination table. Acceleration input to the universal shaking table, the translation table, and the inclination table can be obtained through the program for separation. Flowchart of separation of acceleration in X, Y and Z direction is shown in **Figs. 5, 6**, and **7**.

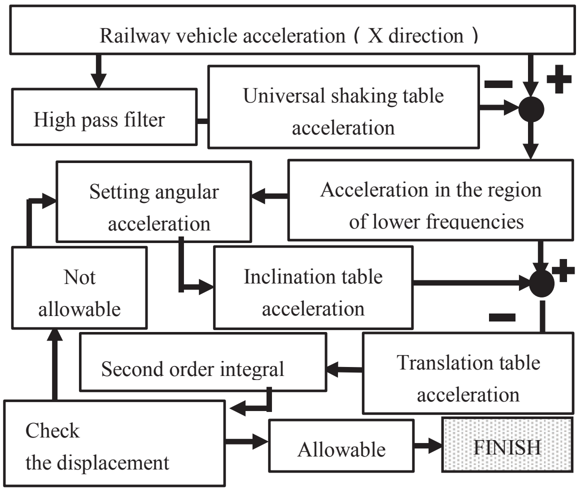


Fig. 5 Flow chart of program（X direction）

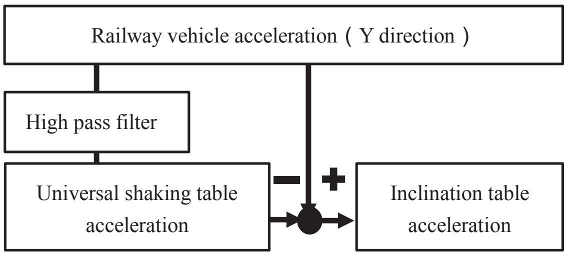


Fig. 6 Flow chart of program（Y direction）

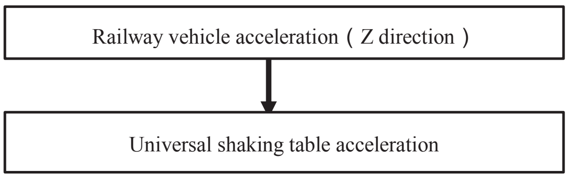
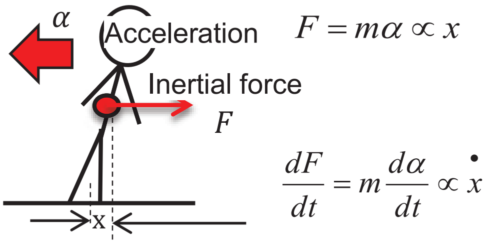


Fig.7 Flow chart of program（Z direction）

7 Human's vibrational property analysis

Inertial force makes passengers swing when a vehicle accelerates (**Fig. 8**). In other words, acceleration affects his/her balance. So we can know human's vibrational property by comparing with railway vehicle acceleration's vibrational property. Therefore, we derived the PSD of railway vehicle acceleration and displacement of passenger's center of gravity which we measured in a test run. The PSD of railway vehicle acceleration and displacement of passenger's center of gravity are shown in **Figs. 9** and **10**. Moreover, we compared between PSD of jerk and PSD of moving velocity of passenger's center of gravity too. PSD of jerk and PSD of moving velocity of passenger's center of gravity are shown in **Figs. 11** and **12**.



$$\frac{dF}{dt} = m\frac{d\alpha}{dt} \propto \dot{x} \quad (2)$$

Fig. 8 Acceleration and Inertial force

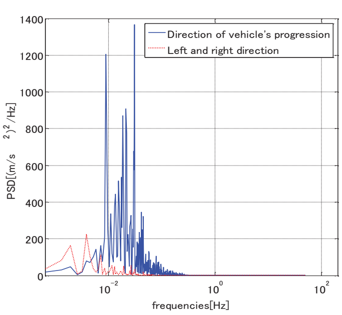


Fig. 9 Acceleration PSD

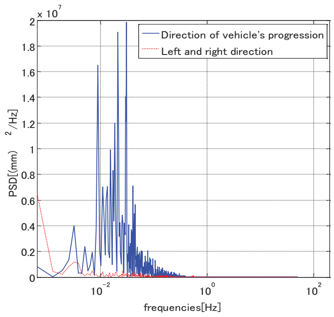


Fig. 10 Displacement PSD

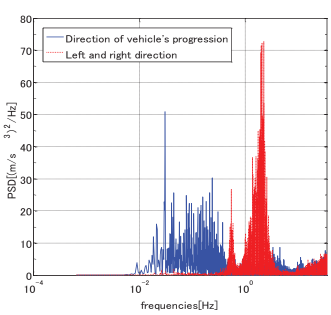


Fig. 11 Jerk PSD

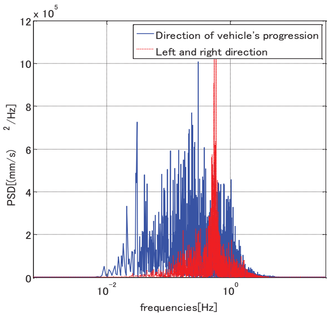


Fig. 12 Moving Velocity

From **Figs. 9** and **10**, PSD of the displacement of subject's center of gravity and PSD of acceleration are dominant infrequencies less than 1.0Hz. From **Figs. 11** and **12**, we think it can be said vibrational jerk more than 1Hz has little or no effect on riding comfort because their value are so small. So we use only vibrational jerk data less than 1.0Hz when we analyze riding comfort.

8 Evaluation method of riding comfort

Riding comfort can be numerically evaluated by a subjective way and an objective way. The subjective way is carried out by pressing a switch button when a subject feels bad. The objective way is carried out by measuring a movement of the center of gravity of a subject. In the objective way running acceleration of a railway vehicle, jerk and the movement of center of gravity of the subject are referred.

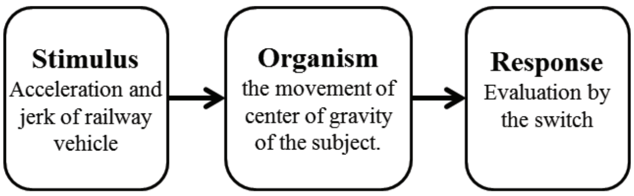


Fig. 13 Stimulus-Response model

8.1 The subjective evaluation method by pressing switch button

A subject presses the switch button when he/she feels bad. Time to press the switch button after feeling bad may be different among subjects.

8.2 The objective evaluation method

Among factors that affect riding comfort, there is the movement of center of gravity of the subject. When the center of gravity of the subject greatly moves, he/she feels bad. A load meter has devised to measure the movement of center of gravity of a subject. A subject stands at right angle to the direction of vehicle's progression.

8.3 Test results

A subject stands at right angle to the direction of vehicle's progression. **Table 2** shows parameter of subjects. The acceleration shown in **Fig. 4** experiments were carried out. We calculated jerk from acceleration through low-pass filter at 1.0Hz. **Figures 14** and **15** show the acceleration less than 1.0Hz and the jerk less than 1.0Hz.

Table 2 Parameter of the subjects

	Height[cm]	Weight[kg]	Age
Subject1	183.5	74.0	25
Subject2	183.0	76.5	22
Subject3	176.0	68.3	23
Subject4	174.5	56.6	23
Subject5	183.0	82.0	23
Subject6	173.5	62.3	23

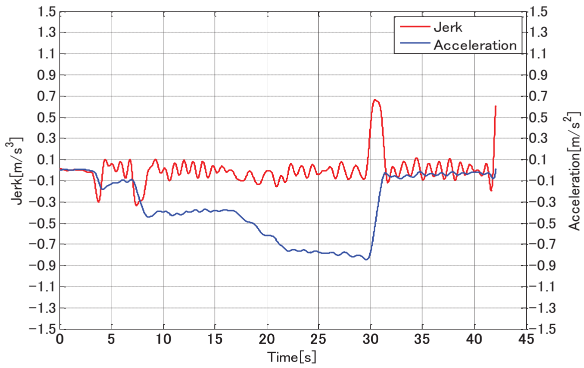


Fig. 14 Acceleration and Jerk (X Direction)

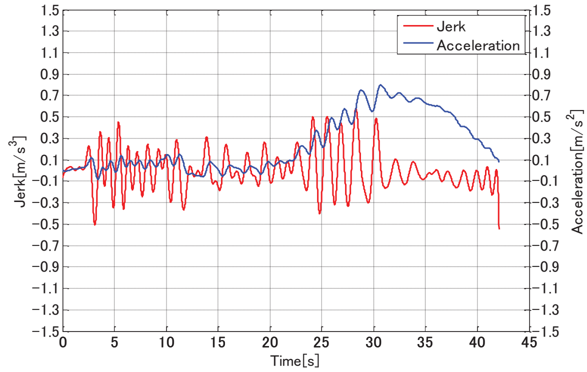


Fig. 15 Acceleration and Jerk (Y Direction)

The displacement and velocity of center of gravity of the subject is shown in **Figs. 16**, **17**, **18** and **19**. In addition, **Table 3** shows evaluation value which we used in this test. **Figure 20** shows when and how long the subjects pressed the switch button.

Table 3 Evaluation value

0	Less than 20% of the subjects feel bad
1	More than 20% of the subjects feel bad
2	More than 50% of the subjects feel bad
3	More than 80% of the subjects feel bad

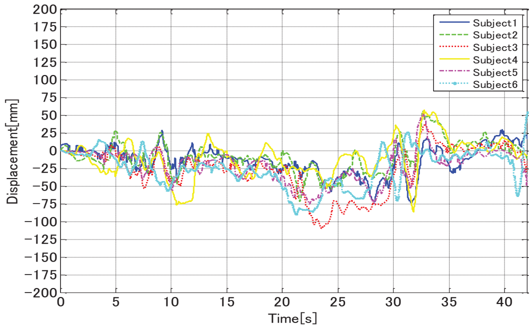


Fig. 16 Displacement(X Direction)

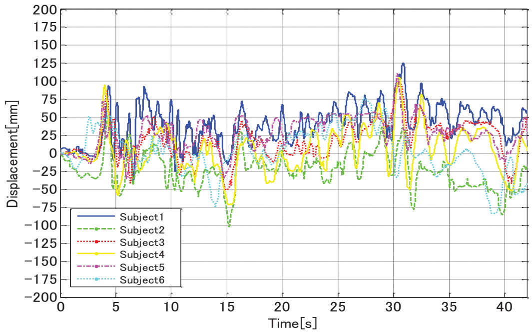


Fig. 17 Displacement(Y Direction)

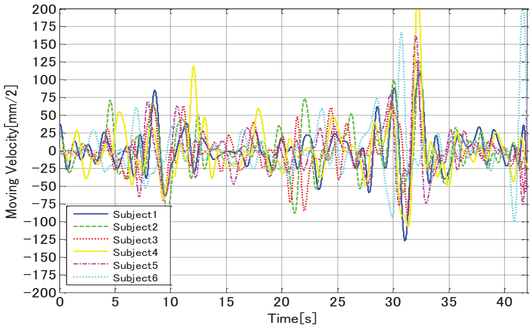


Fig. 18 Moving Velocity(X Direction)

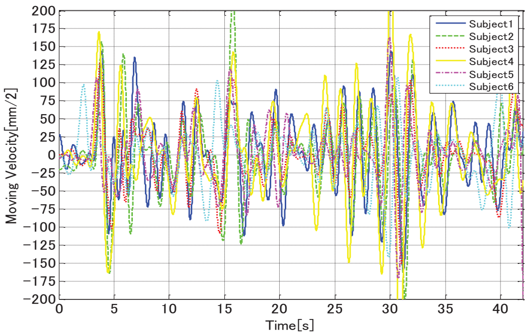


Fig. 19 Moving Velocity(Y Direction)

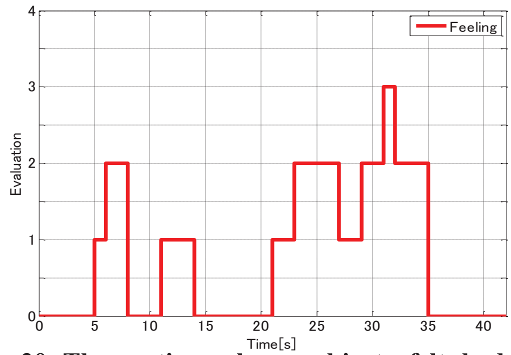


Fig. 20 The section where subjects felt bad ride comfort

The subjects feel bad when the center of gravity greatly moved. From **Figs. 16**, **17**, **18**, and **19**, the displacement and velocity of center of gravity of the subject is almost the same behavior. Then to show relevancy, coefficients of correlation values are calculated by employing eq (3).

$$r = \frac{\sum_{i=1}^{n}(X_i-\bar{X})(Y_i-\bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i-\bar{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i-\bar{Y})^2}} \qquad (3)$$

Coefficients of correlation value in each subject between acceleration of less than 1.0Hz and the displacement of the center of gravity of each subject in the direction of X and Y were calculated, as shown in **Table 3**. Moreover we calculated correlation coefficients between jerk of less than 1.0Hz and the moving velocity of the center of gravity of each subject in the direction of X and Y adjusting the time lag, as shown in **Table 4**.

Table 4 Coefficients of correlation value of the displacement of the subject and between jerk and moving velocity

		Subject1	Subject2	Subject3
Acceleration & Displacement	X	0.703	0.647	0.844
	Y	0.559	0.069	0.622
Jerk & Moving Velocity	X	0.449	0.384	0.413
	Y	0.422	0.374	0.379
		Subject4	Subject5	Subject6
Acceleration & Displacement	X	0.322	0.704	0.734
	Y	0.438	0.403	0.068
Jerk & Moving Velocity	X	0.409	0.459	0.329
	Y	0.462	0.108	0.331

The coefficient of correlation value is high between acceleration less than 1.0Hz in X and Y direction and the displacement of the center of gravity in X and Y direction. Moreover we found correlation between the jerk and the moving velocity of the subjects is high. Then the PSDs of displacement of center of gravity of the subjects and running acceleration of the vehicle are respectively shown in **Figs. 22**, **23** and **24**.

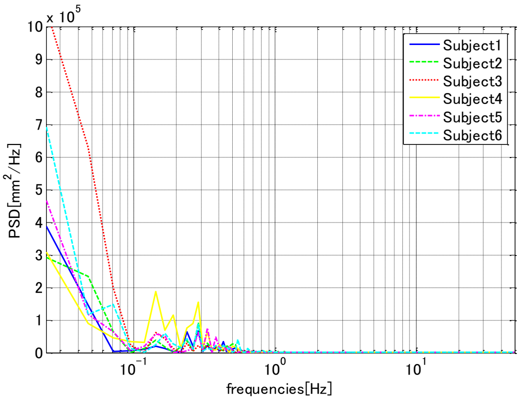


Fig. 22 Displacement of center of gravity PSD (Direction of vehicle's progression)

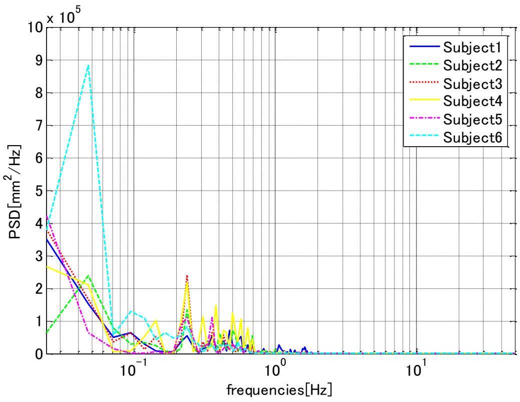


Fig. 23 Displacement of center of gravity PSD (Left and right direction)

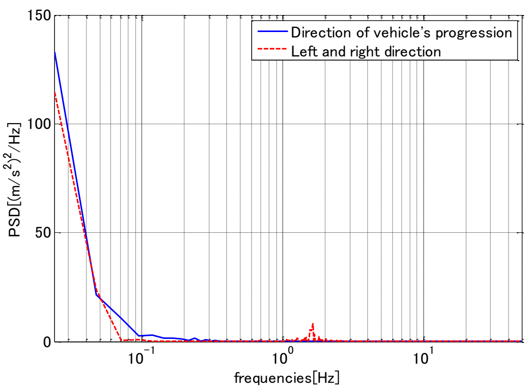


Fig. 24 Acceleration PSD

From **Figs. 22**, **23**, and **24**, PSD of the displacement of center of gravity is dominant in frequencies less than 1.0Hz. For this reason components of frequencies in the region of more than 1.0Hz are small. Taking a look into **Figs. 22**, **23**, and **24**, which denote the direction of the movement of the running vehicle, may seem to be very similar to each other.

8.4 The moving distance of center of gravity

Then relating the distance of center of gravity with frequency of beginning to press switch, we can evaluate ride comfort. **Figure 21** shows results from 6 subjects in 7 tests.

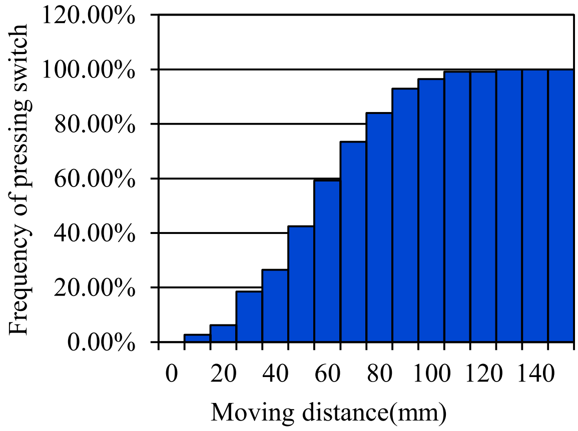


Fig. 21 The moving distance of center of gravity

The Subjects feels bad when the center of gravity moves more than 60mm.

8.5 Boundary value

Figure 25 shows acceleration when percentage of more than 80% and less than 20% of the subjects pressed the switch button. In addition **Figs. 26** and **27** show the acceleration and the jerk of less than 1.0Hz when more than 80% and less than 20% of the subjects pressed the switch button.

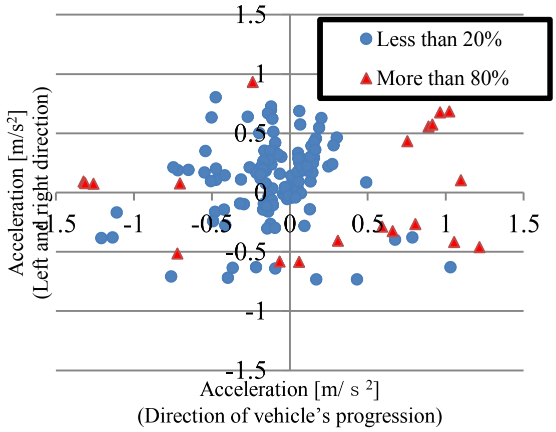


Fig. 25 Acceleration boundary value

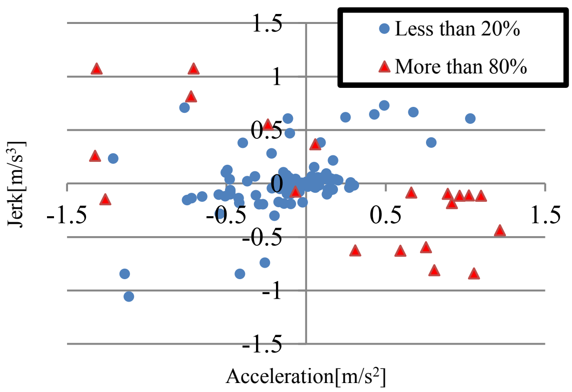


Fig. 26 Acceleration and Jerk Boundary value (Direction of vehicle's progression)

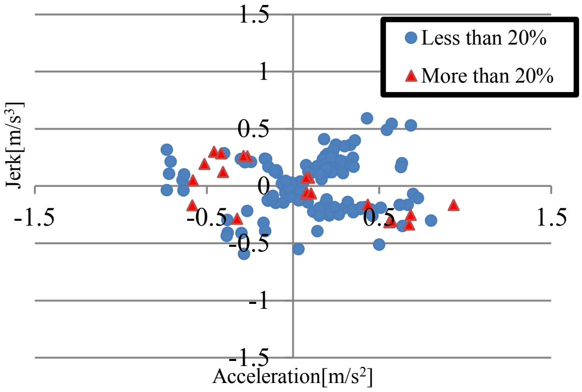


Fig. 27 Acceleration and Jerk Boundary value (Left and right direction)

The acceleration boundary value to cause bad riding comfort are approximately $0.7 m/s^2$ in direction of vehicle's progression and approximately $0.5 m/s^2$ in left and right direction. We think jerk boundary value is more than $0.5 m/s^3$ in direction of vehicle's progression. Furthermore from **Figs. 26** and **27** the jerk which works in the opposite direction to the acceleration tends to make riding comfort worse.

9 Conclusions

In this study, using the simulator that can reproduce the floor acceleration of the railway vehicle and the load meter, we calculated the movement of center of gravity. The obtained conclusions are summarized as follow;

1. We found that the subjects feel bad when the center of gravity greatly moved in standing position.
2. There is a correlation between acceleration of railway vehicle and the displacement of the center of gravity. Moreover there is a correlation between jerk of less than 1.0Hz and moving velocity of the center of gravity of the subject.
3. Acceleration of the vehicle of less than 1.0Hz has an effect on the movement of center of gravity of the subject.

As the result, riding comfort may be determined by acceleration of vehicle, the jerk of less than 1.0Hz and the movement of center of gravity of the subject. We should take account of the parameter of the subjects such as height, weight and so on, and conduct frequent riding comfort evaluation test with a lot of subjects by using the simulator.

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