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Dynamic response of a vehicle model with six degrees-of-freedom under seismic motion

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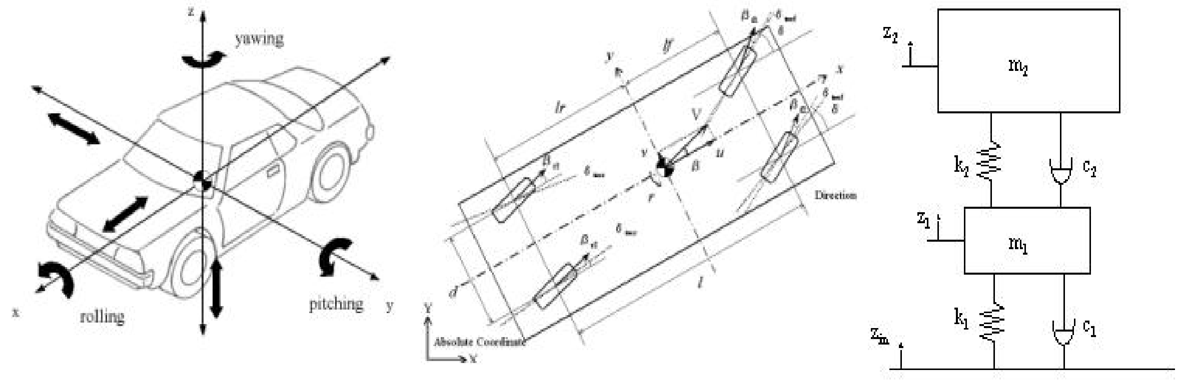
ABSTRACT: In Japan, the seismometer network has been developed along the expressways since the 1995 Kobe earthquake. Using earthquake information from these instruments, the expressways are closed if the peak ground acceleration larger than or equal to 80 cm/s^2 is recorded. However, recent studies on earthquake damage have revealed that expressway structures are not seriously damaged under such level of ground excitation. Hence, we may think of relaxing the regulation of the expressway closure. Before doing this, we need to examine the effects of shaking to automobiles on expressways since the drivers may encounter difficulty in controlling their cars and trucks, and traffic accidents may occur. In this study, a vehicle model with six degrees-of-freedom was made and its responses were obtained under several seismic motions and the effects of seismic motion to the dynamic response of the vehicle model were analyzed.

1 INTRODUCTION

In Japan, after the 1995 Kobe earthquake, higher priority has been given for the countermeasures against earthquakes than before. With good financing, thousands of strong motion seismometers were installed. A number of damage assessment systems were also developed by different organizations (Yamazaki et al. 1998). Under this situation, Japan Highway Public Corporation (JH) has developed the new seismometer network along the expressways. Using earthquake information from these instruments, JH closes the expressways if the peak ground acceleration (PGA) larger than or equal to 80 cm/s^2 is recorded (Maruyama et al. 2000). However recent studies on earthquake damage have revealed that expressway structures are not seriously damaged under such level of ground excitation. Though JH closes the expressways under this ground excitation level, the serious damages that cause the problems in keeping on driving on the expressways are seldom found in the recent years. Hence, we may think of relaxing the regulation of expressway closure.

In this objective, we need to examine the effects of seismic motion to the automobile drivers on expressways since they may encounter difficulties in keeping safety driving and traffic accident may occur. In general, under a large seismic motion, we feel some difficulties to keep remain in doing something that are easily done in the daily life, for instance, operating the computers in nuclear power plants. Shibata et al. (1984) tested the accuracy of typing under the strong motion using a computer set on a two-dimensional shaking table. In nuclear plants, computers manage the system and if a large earthquake occurs, operators have to stop the system immediately. They may feel some difficulties in operating the keyboard of the system under intense shaking.

Yamanouchi & Yamazaki (1999) investigated drivers' response to strong seismic motion using a driving game machine set on a shaking table. However, the driving game machine used in this experiment had lack of reality as it was made for the amusement purpose. Recently, the driving simulators are installed in several organizations that are concerned with vehicle dynamics (Hiramatsu et al. 1994). In 1999, the driving simulator with six servomotor-powered electric actuators was introduced to the Institute of Industrial Science, the University of Tokyo. Using this driving simulator, we can conduct a series of virtual tests to clarify drivers' responses and their feelings



(a) Fundamental motion in 6 DOF (b) Two dimensional coordinate (c) Quarter vehicle model
Figure 1. A vehicle model with six degrees-of-freedom.

while controlling the simulator under seismic motion with good reality. Before doing this, we need to investigate the response of an automobile under seismic motion.

In this study, a vehicle model with six degrees-of-freedom was considered, and its responses under several seismic motions were obtained. Based on the obtained results, the effects of seismic motion to the dynamic response of a vehicle were analyzed.

2 A VEHICLE MODEL WITH SIX DEGREES-OF-FREEDOM

We define three axes set on the center of gravity of a vehicle. The x-axis is the longitudinal direction, the y-axis is the transverse direction, and the z-axis is the vertical direction of the vehicle. Figure 1(a) shows the fundamental motions of a vehicle. The model has three translation motions (longitudinal, transverse, and vertical) and three rotational motions (rolling, pitching, and yawing). Figure 1(b) shows the two-dimensional coordinate for describing these motions on the X-Y plane. In this figure, the X-Y coordinate (the absolute coordinate) is independent of the position of a vehicle. The equations of motion of a vehicle to the longitudinal and transverse direction are described as follows:

$$m(\dot{u} - vr) = \sum F'_{xij} = \sum_i \sum_j \left(F_{xij} \cos\delta_{tij} - F_{yij} \sin\delta_{tij}\right) \tag{1a}$$

$$m(\dot{v} + ur) = \sum F'_{yij} = \sum_i \sum_j \left(F_{xij} \sin\delta_{tij} + F_{yij} \cos\delta_{tij}\right) \tag{1b}$$

where u and v are the velocities in the x and y directions, respectively and r is the angular velocity of yawing. δ is the angle difference between the x-direction and the direction of each tire. F_x and F_y are the longitudinal and transverse forces of each tire, respectively. The index i represents the front or rear wheel and the index j represents the left or right wheel. The yawing motion can be described as follows:

$$I_z \frac{dr}{dt} = (F'_{y11} + F'_{y12}) l_f - (F'_{y21} + F'_{y22}) l_r + (-F'_{x11} + F'_{x12}) \frac{d}{2} + (-F'_{x21} + F'_{x22}) \frac{d}{2} \tag{2}$$

where l_f is the distance between the center of gravity and the front wheel, l_r is the distance to the rear wheel and d is the distance between the right and left wheels. Rolling, yawing, and pitching angles are described by Eq. (3), (4) and (5), respectively.

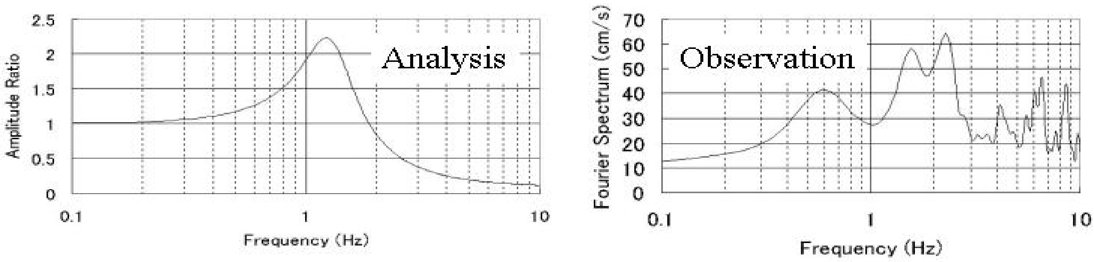


Figure 2. Response characteristics of a vehicle to vertical motion.

$$\phi = \frac{m(\dot{v} + ur)h}{K_\phi - mgh} \tag{3}$$

$$\psi = \int r dt \tag{4}$$

$$\theta = \frac{m(\dot{u} - vr)h}{2K({l_f}^2 + {l_r}^2)} \tag{5}$$

where K_ϕ is the rolling stiffness and K is the suspension stiffness.

From Equation (1) to (5), the motions of a vehicle are described in the x-y coordinate system set on the center of gravity of a vehicle. The velocities in the absolute coordinate can be defined as

$$\dot{X} = u \cos\psi - v \sin\psi \tag{6a}$$

$$\dot{Y} = u \sin\psi + v \cos\psi \tag{6b}$$

So far, we have described the five kinds of motions out of six. The last one is the vertical motion. In order to describe vertical motion, a quarter vehicle model (Fig. 1(c)) is employed (Ellis 1969). The upper mass represents the body of a vehicle and the lower mass represents a tire. The upper spring is the suspension of a vehicle and the lower spring represents the stiffness of the tire. According to this model, the equation of motion to the vertical direction is described as

$$m_1(\ddot{\zeta}_1 + \ddot{z}_{in}) + c_1\dot{\zeta}_1 + c_2(\dot{\zeta}_1 - \dot{\zeta}_2) + k_1\zeta_1 + k_2(\zeta_1 - \zeta_2) = 0 \tag{7a}$$

$$m_2(\ddot{\zeta}_2 + \ddot{z}_{in}) + c_2(\dot{\zeta}_2 - \dot{\zeta}_1) + k_2(\zeta_2 - \zeta_1) = 0 \tag{7b}$$

where z_{in} is the vertical displacement of the ground. $\zeta_1 (= z_1 - z_{in})$ and ζ_2 $(= z_2 - z_{in})$ are the relative vertical displacement of m_1 and m_2, respectively.

By solving Eq. (7), the transfer function between z_{in} and z_2 can be derived. The transfer function used in this study is shown in Fig. 2. The predominant frequency is observed around 1.2 Hz. In order to check this modeling, the measurements of acceleration were conducted using an actual car (Honda Civic). The calculated Fourier spectrum for the vertical component of acceleration is also shown in Fig. 2. In the figure, the predominant frequency is observed around 1.5-2.2 Hz. However these characteristics are, of course, depend on cars.

3 SEISMIC RESPONSE ANALYSIS OF A VEHICLE

3.1 *Magic Formula Model*

In order to conduct seismic response analysis of a vehicle, we have to calculate the force acting on each tire. In this study, the Magic Formula Model (Bakker et al. 1989) was employed. Equation (8)

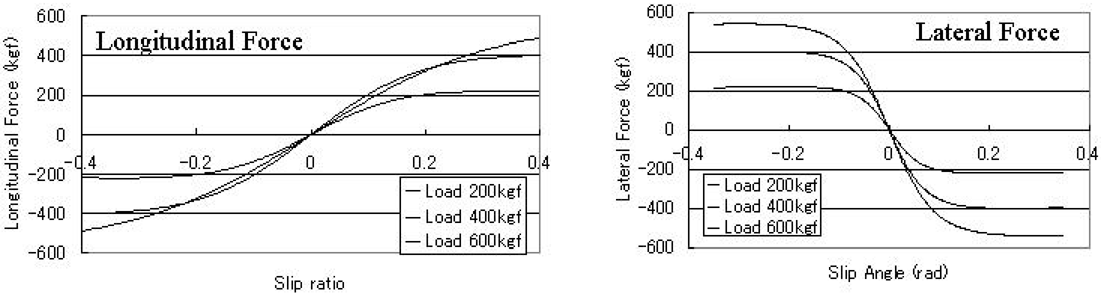


Figure 3. Characteristics of the Magic Formula Model.

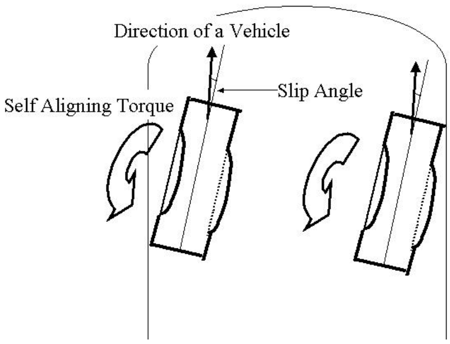


Figure 4. Self aligning torque acting on each tire.

shows the fundamental equation used in the Magic Formula Model. All coefficients used in this equation are determined by experiments because this model was made empirically.

$$y(x) = D\sin\left[C\arctan\left\{Bx - E\left(Bx - \arctan(Bx)\right)\right\}\right] \tag{8a}$$

$$Y(x) = y(x) + S_v \tag{8b}$$

$$x = X + S_h \tag{8c}$$

where B, C, D and E are the stiffness, shape, peak and curvature factors, respectively. S_h and S_v are the amount of the horizontal and vertical shifts. In the model used in this study, both shifts are set to be zero.

Y(x) in Eq. (8b) is the output force (longitudinal or lateral) of the Magic Formula Model. For calculating the lateral force, F_y, the slip angle is used as the input value X in Eq. (8c). For the longitudinal force, F_x, the slip ratio is used as the input value. The characteristics of the Magic Formula Model used in this study are shown in Fig. 3.

3.2 *Seismic Response Analysis*

In order to conduct the seismic response analysis, Eq. (1) is modified as

$$m_2\left(\dot{u} - vr + \ddot{x}\cos\psi + \ddot{y}\sin\psi\right) = \sum_j \sum_i \left(F_{xij}\cos\delta_{tij} - F_{yij}\sin\delta_{tij}\right) = \sum_{i,j} F'_{xij} \tag{9a}$$

$$m_2\left(\dot{v} + ur - \ddot{x}\sin\psi + \ddot{y}\cos\psi\right) = \sum_j \sum_i \left(F_{xij}\sin\delta_{tij} + F_{yij}\cos\delta_{tij}\right) = \sum_{i,j} F'_{yij} \tag{9b}$$

where $\ddot{x}$ and $\ddot{y}$ are the ground accelerations of longitudinal and transverse directions to the vehicle. For vertical component, the vertical ground acceleration, $\ddot{z}_{in}$, due to an earthquake was substituted in Eq. (7). Then the height of the center of gravity is changed when the vertical motion occurs. The height of the center of gravity is described as

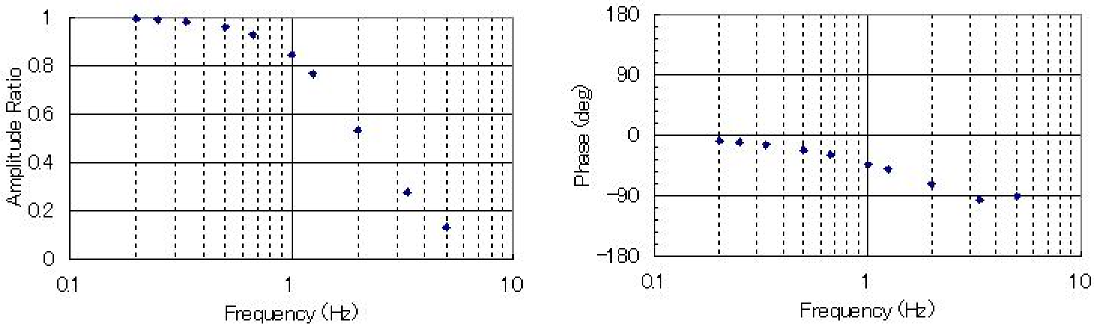


Figure 5. Amplitude ratio and phase delay between input and response accelerations under harmonic excitation.

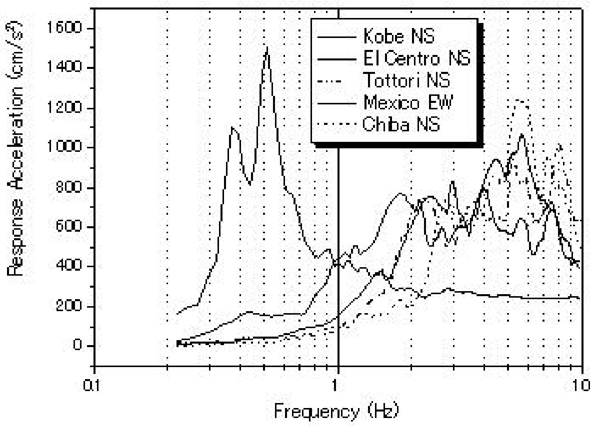


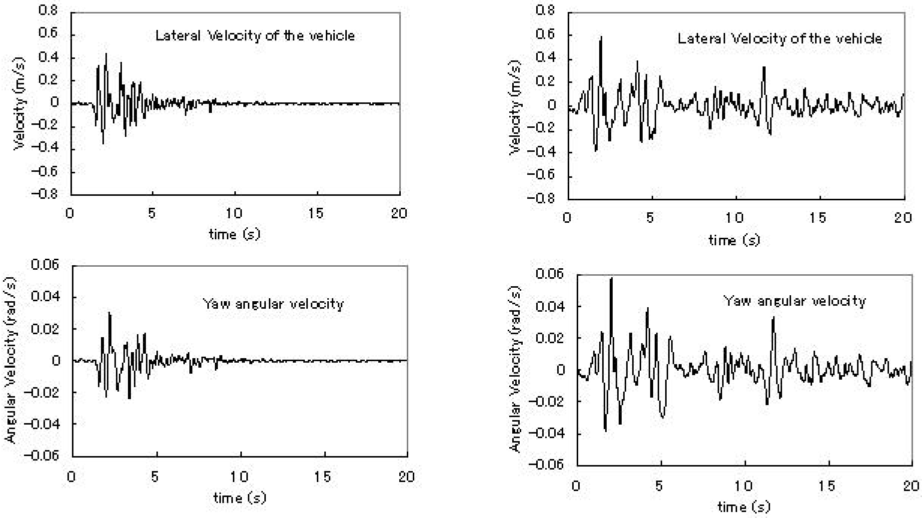
Figure 6. Acceleration response spectra (5 % damping) of five records scaled to PGA=300cm/s^2 applied to the transverse direction to the vehicle.

$$h = h_0 + \zeta_2 \tag{10}$$

The moment called the self aligning torque shown in Fig.4, which reduces the slip angle of each tire, is also considered. This moment reduces the lateral displacement generated by seismic motion.

Before conducting the seismic response analysis, the response characteristics of this vehicle model were investigated. The sinusoidal wave with a certain frequency was applied to the transverse direction of the vehicle model and then the absolute response acceleration to the transverse direction was calculated. Figure 5 shows the amplitude ratio and phase delay between input acceleration and response acceleration. In the figure, when the frequency of the input motion is low, the amplitude ratio between the input and response accelerations is close to 1.0. For higher frequencies, the model shows smaller amplitude ratios and large phase delay.

The seismic response analysis was performed using five sets of actual earthquake records. The acceleration records at the Kobe Marine Observatory of Japan Meteorological Agency (JMA) in the 1995 Kobe Earthquake, at the El Centro station in the 1940 Imperial Valley Earthquake, at the K-NET Kofu station in the 2000 Tottori-ken Seibu Earthquake, at SCT station in the 1985 Mexico Earthquake and at Chiba Experiment Station of Institute of Industrial Science, the University of Tokyo in the 1987 Chiba-ken Toho-Oki Earthquake were selected as typical examples of strong motion records. Considering the sensitivity of the model (Fig. 5), the filtered motions with the range of 0.2-10 Hz were employed as input motions. Figure 6 shows the acceleration response spectra with 5 % damping for the records (transverse component to the vehicle) scaled to PGA equal to 300 cm/s^2. The acceleration response spectrum of the SCT, Mexico record has much larger value in the frequency range smaller than 1Hz compared with those of the other records. It is also



(a) JMA Kobe (b) El Centro

Figure 7. Response of a vehicle due to the seismic motions recorded at JMA Kobe station and El Centro station scaled to PGA=800 cm/s^2. The initial running speed of the vehicle was set to be 100 km/h.

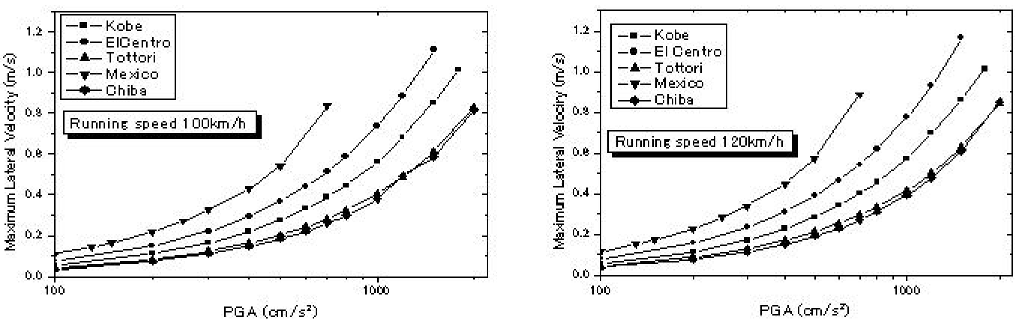


Figure 8. Relationship between the maximum lateral velocity and the peak ground acceleration applied to the transverse direction to the vehicle. The initial running speed of the vehicle is set to be 100 km/h (left) and 120 km/h (right).

observed that the acceleration spectrum of the El Centro record is larger than those of the JMA Kobe, Tottori and Chiba records in the frequency range smaller than 2Hz.

In order to apply the seismic motion to the vehicle model, the recorded seismic motions were scaled with respect to the peak ground acceleration (PGA). The three-component record was applied to the vehicle model in each case by scaling the records with respect to the PGA of the transverse component. The running speed of a vehicle was set to be 100 km/h. Figure 7 shows the response of a vehicle due to the seismic motions recorded at JMA Kobe station and El Centro station scaled to 800 cm/s^2. As the indices representing the vehicle responses to seismic excitation, the lateral velocity and yaw angular velocity were selected. According to the figure, the response of the vehicle under El Centro record is larger than that under JMA Kobe record though both PGA values are scaled to be same. This is mainly because of the response characteristics of the vehicle model shown in Fig. 5 and the acceleration response spectrum shown in Fig. 6.

Figure 8 shows the relationship between the PGA and the maximum lateral velocity for the five sets of acceleration time histories. The initial running speed of a vehicle was set as 100 km/h and 120 km/h. It is observed that the response of a vehicle with the initial speed of 120 km/h is a little larger than that of 100 km/h and these relationships are almost linear with to PGA. The variation of

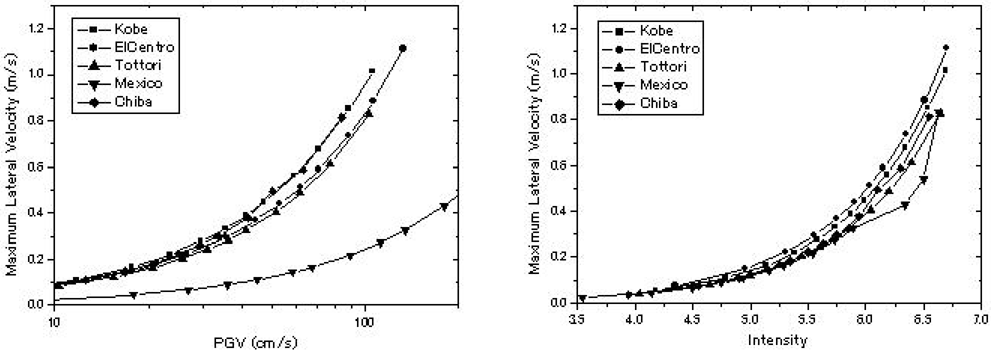


Figure 9. Relationship between the maximum lateral velocity of the vehicle and the peak ground velocity applied to the transverse direction to the vehicle (left) and the relationship between the maximum lateral velocity of the vehicle and JMA intensity (right) for the initial running speed 100 km/h.

Figure 10. Driving simulator introduced to the Institute of Industrial Science, the University of Tokyo.

the maximum lateral velocity is seen from event to event even the same PGA value is applied. The Mexico and El Centro records were associated by larger lateral velocity responses compared with those by the other three records.

Figure 9 shows the relationship between the peak ground velocity (PGV) and the maximum lateral velocity for the five sets of acceleration time histories and the relationship between JMA seismic intensity and the maximum lateral velocity. According to the figure, when the maximum values of lateral velocity are plotted as a function of PGV, the variation is not so large from event to event except for the response under the Mexico record. As shown in Fig. 6, the acceleration response spectrum of Mexico record is completely different from those of other four records. However, when they are plotted as a function of JMA seismic intensity, the results for the different input motions were very close including that for the Mexico record. The JMA seismic intensity is calculated through a frequency filtering of a three-component record. This process may have some similarity with the vehicle response model used in this study.

Based on all these results, the JMA intensity may be the most suitable index to express the severity of seismic motion from the viewpoint of vehicle response. However, a further study that considers wider variations in input motion and vehicle parameters may be necessary before the conclusion is made.

4 FURTHER STUDY USING DRIVING SIMULATOR

For a further study, we will conduct a series of virtual tests using the driving simulator shown in Fig. 10. A scenario highway course is equipped on the simulator for virtual driving and the front view from the driver's seat is realized by three large screens with LCD projectors. This simulator has six servomotor-powered electric actuators to simulate the motion of a vehicle.

Originally, they can only simulate the accelerations of a vehicle. We recently modified the control system of the driving simulator such that the seismic motion can be applied to the center of gravity of a vehicle model. Experiments using the driving simulator can evaluate human reaction to seismic motion properly as well as the vehicle dynamics studied in this paper. The virtual driving experiment is expected to give us useful information on the effects of shaking while driving the automobiles in high speed, and then it contributes to the promotion of highway safety in natural disasters.

5 CONCLUSIONS

In order to investigate the response of an automobile under seismic motion, a running vehicle model with six degrees-of-freedom was developed. The seismic response analysis was conducted using five sets of actual earthquake records. The vehicle responses for the different input motions were plotted as a function of peak ground acceleration (PGA). The response of a vehicle model became larger for the Mexico and El Centro records, since they have larger response spectrum amplitudes in the long period range compared with the other records though all records were scaled to have the same PGA value. When the relationships between the peak ground velocity (PGV) and the maximum lateral velocity or yaw angular velocity were considered, the relationships were distributed in narrow ranges except for that of the Mexico record. Similar relationships of the vehicle responses were also plotted for the JMA seismic intensity, and the results for the different input motions were very close including that for the Mexico record. According to these results, the JMA intensity may be the most suitable index to express the severity of seismic motion from the viewpoint of vehicle response. However, a further study that considers wider variations in input motion and vehicle parameters may be necessary before the conclusive observation is obtained.

In the near future, in order to investigate the drivers' responses and their feelings while driving automobiles in high speed under seismic motion, we will conduct series of virtual tests using a driving simulator. These experiments will contribute to the promotion of expressway safety in natural disasters.

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