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DRIVING SIMULATOR EXPERIMENT ON THE BEHAVIOR OF AUTOMOBILE DRIVERS UNDER SEISMIC MOTION

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ABSTRACT : Japan Highway Public Corporation (JH) has developed the new seismometer networks along the expressways since the 1995 Kobe earthquake. Using earthquake information from these instruments, JH closes the expressways if the peak ground acceleration (PGA) is larger than or equal to 80 cm/s^2 is recorded or reduces the maximum speed limit if the PGA is larger than or equal to 50 cm/s^2 is observed. However, recent studies have revealed that highway structures will not be seriously damaged under such level of seismic motion. Moreover, the highway structures are being retrofitted now. Therefore, we may think of relaxing the regulation of expressway closure. In order to do so, we must examine the effects of seismic motions to the automobile drivers on expressways since they may encounter difficulties in keeping the safety driving and traffic accidents may occur. In this study, the model of a vehicle with six degrees of freedom was made and its responses under several seismic motions were calculated. Then, in order to conduct a series of virtual tests of driving on a highway during earthquakes, the response of a vehicle under seismic motion was applied to the driving simulator. This driving simulator has six servomotor-powered electric actuators and they control its motions. We carried out several types of tests for examinees. In the near future, intelligent transportation system (ITS) will be realized. In that case, we must stop vehicles automatically if a large earthquake occurs. This research is also helpful for such systems.

KEYWORDS : driving simulator, expressway, seismic motion, drivers' response, intelligent transportation system (ITS)

1. INTRODUCTION

In Japan, after the 1995 Kobe earthquake, higher priority has been given for the countermeasures against earthquakes than before. Thousands of strong motion seismometers were installed and a number of damage assessment systems were also developed by different organizations [1]. 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 [2]. 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. [3] 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.

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Yamanouchi and Yamazaki [4] 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 [5]. 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 while controlling the simulator under seismic motion with good reality.

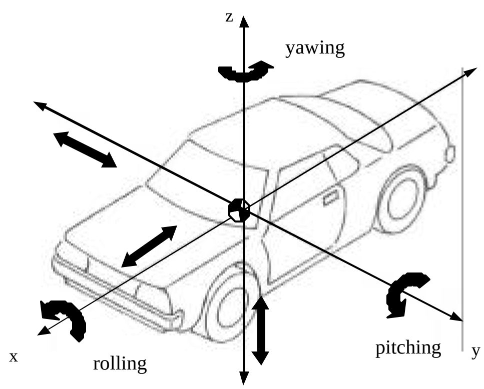

Figure 1. Fundamental motions of a vehicle

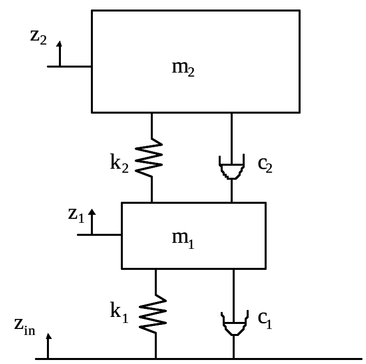

Figure 2. Quarter vehicle model

In this study, a vehicle model with six degrees-of-freedom was considered, and its responses under seismic motions were obtained. Based on the results, the effects of seismic motion to the dynamic response of a vehicle were analyzed. In order to investigate the drivers' responses and their feelings, a series of virtual tests using the driving simulator were also conducted.

2. SEISMIC RESPONSE ANALYSIS OF A RUNNING VEHICLE

Figure 1 shows the fundamental motions of a vehicle. 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. The model has three translation motions (longitudinal, transverse, and vertical) and three rotational motions (rolling, pitching, and yawing). The equations of motion of a vehicle to the longitudinal and transverse direction are described as follows:

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

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

where u and v are the velocities in the x and y directions, respectively and r is the angular velocity of yawing. d 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 and pitching angles are described by Eq. (3) and (4), respectively.

$$f(K_f - mgh) = m(\dot{v} + ur)h \tag{3}$$

$$qK(l_f{}^2 + l_r{}^2) = m(\dot{u} - vr)h \tag{4}$$

where f is the roll angle and q is the pitch angle. K_f is the rolling stiffness, K is the suspension stiffness and h is the height of the center of the gravity. As shown in Eq. (5), yaw angle can be obtained by integrating yaw angular velocity, r.

$$y = \int r dt \tag{5}$$

For the vertical motion, a quarter vehicle model (Fig. 2) is employed in this study. 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

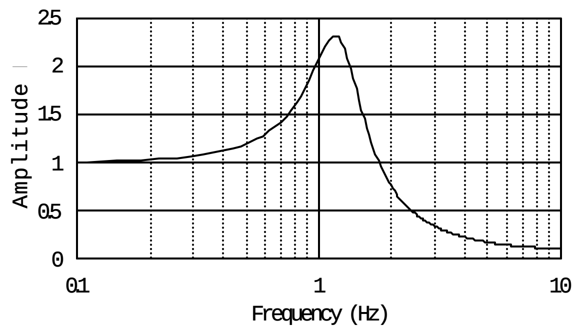

Figure 3. Response characteristics of a vehicle to vertical motion

$$m_1(\ddot{z}_1 + \ddot{z}_{in}) + c_1\dot{z}_1 + c_2(\dot{z}_1 - \dot{z}_2) + k_1 z_1 + k_2(z_1 - z_2) = 0 \tag{6a}$$

$$m_2(\ddot{z}_2 + \ddot{z}_{in}) + c_2(\dot{z}_2 - \dot{z}_1) + k_2(z_2 - z_1) = 0 \tag{6b}$$

where z_{in} is the vertical displacement of the ground. $z_1 (= z_1 - z_{in})$ and z_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 (Fig. 3). The predominant frequency is observed around 1.2 Hz.

In order to calculate the force acting on each tire, the Magic Formula Model [6] was employed in this study. The lateral force, F_y, is described as the function of the slip angle. The longitudinal force, F_x, is described as the function of the slip ratio. In the calculation, the slip ratio is set to be zero because it is assumed that a vehicle is running without accelerating or deaccelerating.

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

$$\begin{aligned} m_2(\dot{u} - vr + \ddot{x}\cos y + \ddot{y}\sin y) &= \sum_j \sum_i (F_{xij}\cos d_{tij} - F_{yij}\sin d_{tij}) = \sum_{i,j} F'_{xij} \\ m_2(\dot{v} + ur - \ddot{x}\sin y + \ddot{y}\cos y) &= \sum_j \sum_i (F_{xij}\sin d_{tij} + F_{yij}\cos d_{tij}) = \sum_{i,j} F'_{yij} \end{aligned} \tag{7a,b}$$

where $\ddot{x}$ and $\ddot{y}$ are the ground accelerations of longitudinal and transverse directions to the vehicle. For the vertical component, the ground acceleration due to the earthquake was substituted as $\ddot{z}_{in}$ in Eq. (6).

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 [7], the filtered motions with the range of 0.2-10 Hz were employed as input motions. Figure 4 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 1 Hz compared with those of the other records.

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 5 shows the relationship between the PGA and the maximum lateral velocity of the vehicle for the five sets of acceleration time histories. The initial running speed of a vehicle was set 100 km/h. According to the figure, these

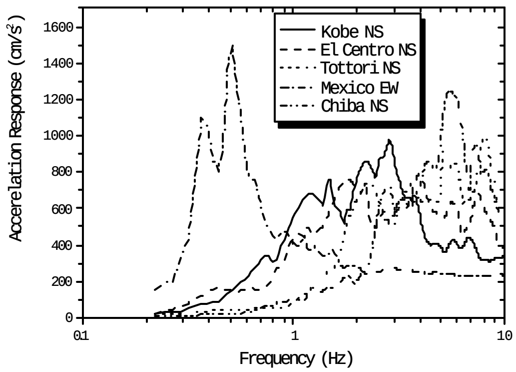

Figure 4. Acceleration response spectra (5 % damping) of five records scaled to PGA=300cm/s^2 applied to the transverse direction to the vehicle

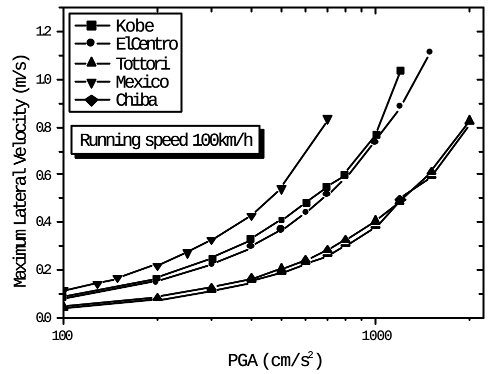

Figure 5. Relationship between the maximum lateral velocity of the vehicle and the peak ground acceleration applied to the transverse direction to the vehicle

relationships are almost linear. The variation of the maximum lateral velocity is seen from event to event even the same PGA value is applied. The Mexico record was associated by larger lateral velocity responses compared with those by the other records. Figure 6 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 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. 4, 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 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.

3. A SERIES OF VIRTUAL TESTS USING DRIVING SIMULATOR

Based on all the results of the seismic response analysis, the JMA intensity may be the most suitable index to express the severity of seismic motion from the viewpoint of vehicle response. However, in the calculations, the reaction of the driver is not considered. Hence, in order to investigate the effect of seismic motion in keeping safety driving, a series of virtual tests using the driving simulator (Fig. 7) were carried out. A scenario highway course is equipped on the simulator for the 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. Before conducting virtual tests, the sinusoidal waves with a certain frequency were applied to the actuators and the amplitude ratios between the motions produced by the actuators and those applied to the actuators were calculated (Fig. 8). The amplitude ratio is almost equal to 1.0 in the low frequency range and it becomes small in the high frequency range.

In order to conduct a series of virtual tests of driving on a highway during earthquakes, the response of a vehicle under seismic motion was applied to the actuators of the driving simulator. The longitudinal and transverse displacements applied to the actuators are shown in Eq. (8).

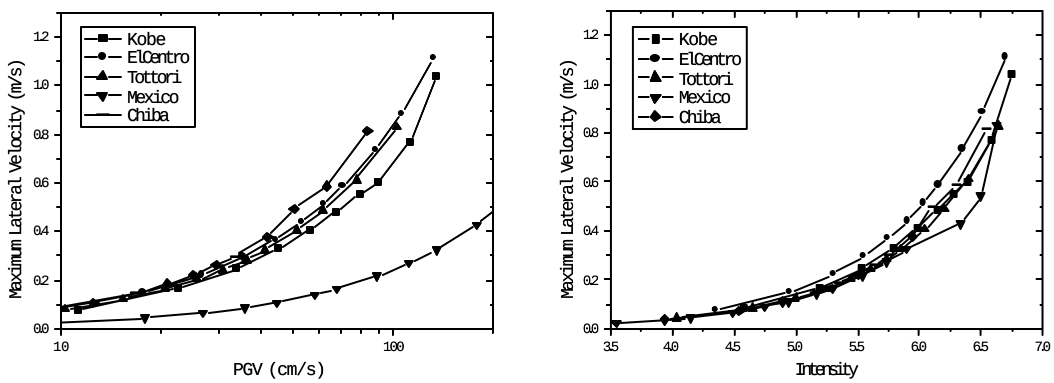

Figure 6. Relationship between the maximum lateral velocity of the vehicle and the peak ground velocity applied to the transverse direction to the vehicle (left) and the relationship between the maximum lateral velocity of the vehicle and JMA intensity (right)

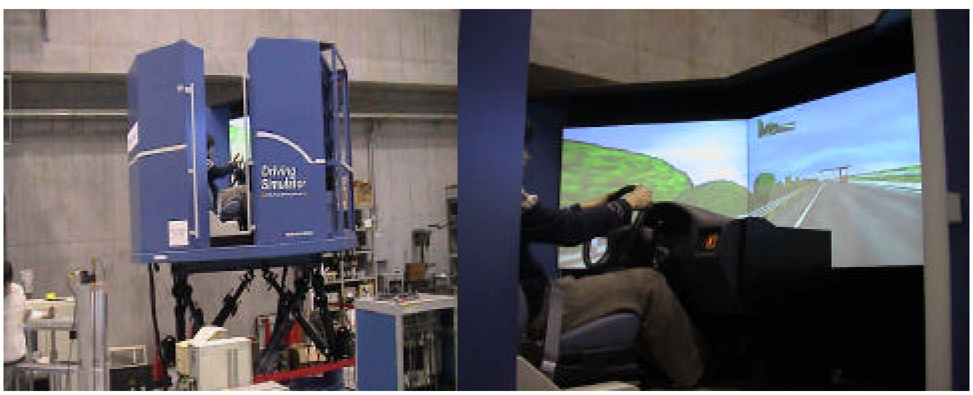

Figure 7. Driving simulator introduced to the Institute of Industrial Science, the University of Tokyo

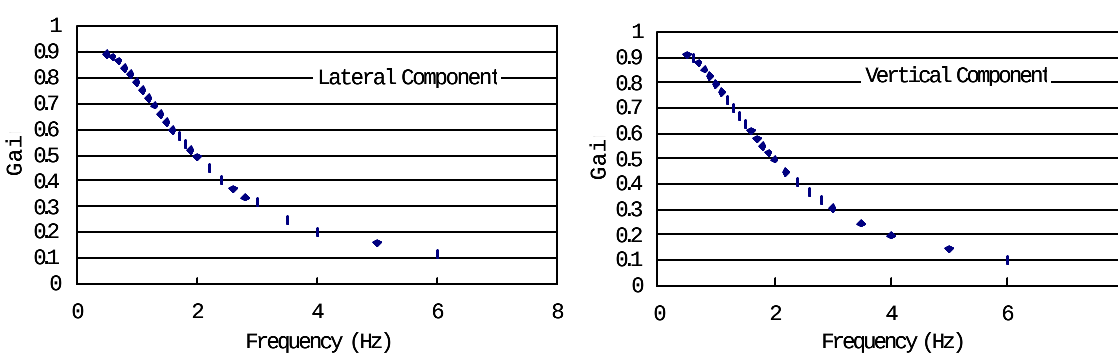

Figure 8. Amplitude ratio between the motion produced by the actuators and the motion applied to the actuators

$$D_{LT} = \int (u - v_0) dt$$
$$D_{TR} = \int v dt \qquad (8a,b)$$

where v_0 is the initial running speed of the vehicle. The vertical motion applied to the actuators is z_2 shown in Eq. (6). Roll, pitch and yaw angles are also applied to the actuators. All parameters that are used in the driving simulator are set to be the same as those used in the calculation of the dynamic vehicle response. The results of the simulator experiments will be presented in separate papers in the near future.

4. 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 record, since it has 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 relationship between the peak ground velocity (PGV) and the maximum lateral velocity was considered, the relationship was distributed in a narrow range 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.

A series of virtual tests driving on an expressway during an earthquake using the driving simulator were conducted. In the near future, intelligent transportation system (ITS) will be realized. In that case, we must stop vehicles automatically if a large earthquake occurs. We intend to apply the result of this research to such systems.

5. REFERENCES

[1] Yamazaki, F., Meguro, K. and Noda, S., "Developments of early earthquake damage assessment systems in Japan", *Structural Safety and Reliability*, 1998, pp. 1573-1580.

[2] Maruyama, Y., Yamazaki, F. and Hamada, T., "Microtremor measurements for the estimation of seismic motion along the expressways", *Sixth International Conference on Seismic Zonation*, 2000, pp. 1361-1366.

[3] Shibata, H., Ishibatake, H., Fukuda, T. and Komine, H., "Human operability under strong earthquake condition", *Proceedings of the 8th World Conference on Earthquake Engineering*, Vol. V, 1984, pp. 1109-1116.

[4] Yamanouchi, H. and Yamazaki, F., "Experiments on the behavior of automobile drivers under seismic motion using driving simulator", *Proceedings of 5th U.S. Conference on Lifeline Earthquake Engineering*, 1999, pp. 8-16.

[5] Hiramatsu, K., Satoh, K., Uno, H. and Soma, H., "The first step of motion systems realization in the JARI driving simulator", *The International Symposium on Advanced Vehicle Control*, 1994, pp. 99-104.

[6] Bakker, E., Pacejka, H. B. and Linder, L., "A new tire model with an application in vehicle dynamics studies", *Society of Automotive Engineers*, 1989, No. 890087.

[7] Maruyama Y. and Yamazaki F., "Dynamic response of a vehicle model with six degrees-of-freedom under seismic motion", *Proceedings of ICOSSAR 2001 Structural Safety and Reliability*, 2001.