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AN EVALUATION OF ROAD ROUGHNESS AND THE EFFECTS ON RIDING COMFORT AND VEHICLE DYNAMICS

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The purpose of this paper is to evaluate the road roughness, its influence on riding comfort and to point out possible methods for understanding a correlation between road roughness and the resulting vehicle dynamics. First, statistical measurements of actual road roughness in summer and that in winter are carried out and its effect on riding comfort is discussed in comparison with ISO standard 2631. Based on the measurements, the road roughness characteristics can be represented by road roughness model functions. Second, regression analysis is used to investigate a linear relationship between the road profile elevation spectral density and the equivalent acceleration excitation to a vehichle. In addition, vibration source contribution method is applied to the prediction of the vibratory response of the vehicle from road roughness. As a result, significant results are obtained.

1. INTRODUCTION

The measuring of road roughness is important in terms of road serviceability, vehicle operating costs, highway safety and the riding quality to the highway user.

The developments of various methods for measuring the road roughness have been taken place so far[1),2)].

The statistical characteristics of the road surface has been often described by the power spectral density (PSD) since Walls, Houbolt and Press[3)] used it in order to determine quantitatively the road roughness. Many studies in Japan have been done also by automotive engineers[4),5)].

However, The method has been rarely applied to investigations on road roughness in winter and the paucity on the effective method used for understanding the road roughness conditions affecting various vehicle motions has prompted us to investigate it[6),7)].

In addition to these published reports, as regards road roughness, we investigated the effect on riding comfort in comparison with ISO vibration standard 2631, which provides a common measure for human vibration levels, and developed the road roughness model function for the purpose of representing its wavy characteristics and analyzed the correlation between the road roughness and motor vehicle acceleration response at the natural frequency of the vehicle vibration mode.

Furthermore, the vehicle used throughout this investigation, was a typical passenger car and was regarded as a multiple input-single output linear system. Accordingly, by applying vibration source contribution method, the effect of the road roughness to the vehicle vibratory system was discussed on the basis of the characteristics of frequency response and coherency functions.

2. ROAD ROUGHNESS MEASUREMENT

In regard to road roughness measurement, the influence on vehicle motion and the actual conditions

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especially in winter were mainly chosen as the subject of the study.

Accordingly, from the point of view of measuring it easily at such a speed as not to disrupt normal traffic flow and establishing general roughness rather than specific roughness, we used an analytical method which utilizes vehicle frequency response characteristics. In this case, the road roughness can be expressed quantitatively as the road elevation power spectral density (PSD).

The fundamental of the method is illustrated below,

$$P_a(f)=|A(f)|^2 \cdot P_r(f) \cdots\cdots\cdots\cdots\cdots\cdots (1)$$

In which

$P_a(f)$=the PSD of acceleration at arbitrary location of a vehicle;

$P_r(f)$=the PSD of road surface;

$A(f)$=the frequency response function of a vehicle.

To begin with, $P_r(f)$ was calculated by the profile leveling results on tangential section of Hokkaido Development Bureau Ebetsu Test Circuit and $P_a(f)$ was calculated by the measurement of the normal acceleration at the center of gravity (C.G.) of a vehicle when the vehicle had travelled on the Circuit.

Table 1 Details of Test Routes in Summer.

Ref. Code	Location	Measurement Speed	Note
SR1	Kita 20-Nishi 4 (Nishi 4-Chome St.)	40km/h	Manhole, vehicle rolling
SR2	Kita 34-Higashi 9 (Sapporo Shindo Highway)	40km/h	Extrmely smooth
SR3	Kariki O-hashi Bridge	40km/h	Irregular surface, vehicle pitching
SR4	Shin-Ishikari Bridge	50km/h	
SR5	Intersection (Route No.12(NH) to Route No.274(NH))	40km/h	
SR6	Shiroishi-Hondori 13 (Route No.12(NH))	40km/h	
SR7	Misono 8-7 (Kanjo St.)	40km/h	
SR8	Under Misono Pedestrian Bridge	40km/h	Relatively smooth
SR9	Minami 1-Nishi 1	30km/h	Underpass
SR10	Shinkawa 1-Jo St.	40km/h	Patched bituminous overlay, vehicle rolling

NH = National Highway

Table 2 Details of Test Routes in Winter.

Ref. Code	Location	Measurement Speed	Note
WR1	Kita 20-Nishi 4 (Nishi 4-Chome St.)	30km/h	
WR2	Kita 26-Nishi 4 (Nishi 4-Chome St.)	20km/h	
WR3	Route No.371(HPH)	40km/h	Compacted snow surface
WR4	Intersection (Route No.371(HPH) to Route No.214(HPH))	50km/h	Compacted snow surface
WR5	Intersection (Route No.214(HPH) to Route No.12(NH))	50km/h	Compacted snow surface
WR6	Sumikawa 6-Nishi 5	20km/h	Cul-de-sac, vehicle rolling
WR7	Kita 26-Nishi 7	20km/h	Slushy road, extremely rough, vehicle bouncing
WR8	Intersection (Route No.5(NH) to Shinkawa 1-Jo St.)	30km/h	Rutted surface
WR9	Shinkawa 1-Jo St. (200m north from WR8)	20km/h	Rutted surface
WR10	Shinkawa 1-Jo St. (100m north from WR9)	20km/h	Slushy surface, extremely rough, vehicle bouncing

NH = National Highway, HPH = Hokkaido Prefectural Highway

From the relationship given by (1), $A(f)$ was calculated[7]. Accordingly, when the PSD of road roughness, $(P'_r(f))$ is unknown and the same vehicle travels on that road, the PSD of acceleration at C.G. of the vehicle $(P'_a(f))$ is measured.

Therefore, $P'_r(f)$ can be obtained from the relation $P'_r(f)=P'_a(f)/|A(f)|^2$.

In this study, we investigated the PSDs of the roads in Sapporo city and on the outskirts of it in summer and in winter. Using the same vehicle, the investigation was carried out at such constant speeds as the tire was held in contact with the road surface. Measured sites and road surface conditions are shown in Table 1, 2.

3. EVALUATION OF ROAD ROUGHNESS AND ITS INFLUENCE ON RIDING COMFORT BY ISO STANDARD

(1) Road Roughness Evaluation

For riding comfort considerations, the frequency range of interest is 0.5~50 Hz.

In addition, for the vehicle speed range of 20~100 km/h, the range of wavelengths can be calculated to be 0.1~55.5 m.

From the purpose of evaluating the PSDs of previous measured road surfaces, we applied International Standard (ISO 2631, Proposals for Generalized Road Input to Vehicles)[8] which had been developed by Technical Committee ISO/TC 108.

Using a two-exponential representation, the Standard defines and gives the PSD function because the change in the slope at 6 m wavelength is significant :

$$P(n)=P(n_0)(n/n_0)^{-w_1} \quad \text{for} \quad n \leqq n_0$$
$$P(n)=P(n_0)(n/n_0)^{-w_2} \quad \text{for} \quad n \geqq n_0 \qquad (2)$$

where

$P(n)$=the PSD function, mm²/cycle/m (10^{-6}m³)

n=spatial frequency, cycle/m (1/m)

$n_0=1/2\pi$. reference spatial frequency, cycle/m (1/m)

w_1, w_2=exponent of slope.

Table 3 Proposed Road Surface Classification.

	Subjective Road Classification	10^{-6} m³	w_1	w_2
A	Very good motorways	2-8	2	1.5
B	Good principal roads	8-32	2	1.5
C	Average principal roads	32-128	2	1.5
D	Poor minor roads	128-512	2	1.5
E	Very poor minor roads	512-1024	2	1.5

Using this function, road surfaces are classified into five classes as shown in Table 3. A few typical classification examples of the PSDs of measured road surfaces are illustrated as in Fig. 1, 2.

Upper classification line in figure indicates the upper limit of "Very poor minor roads" and lower one indicates the lower limit of "Very good motorways". From Fig. 1, the PSDs of summer road surfaces rank "Good principal roads" and the results agree with those which has been obtained[5].

From Fig. 2, in regard to snow road surfaces, even compacted snow surfaces which are considered to be good roads, belong to "Average principal roads" and a few roads exceed the upper classification line. In addition to this, it has been confirmed that upper classification line implies the critical condition that you can drive at a velocity of 40 km/h.

Therefore, these results prove that you oblige to drive at a slow speed in winter.

(2) Evaluation of Riding Comfort by ISO Standard

Special features of the method of measuring road roughness used in this study are as follows : the acceleration at arbitorary location of a vehicle is measured and it can be applied to the evaluation of riding comfort.

The evaluation method of riding comfort has been studied by many researchers[9]. To facilitate the evaluation and comparison of data gained from continuing research in this field, we applied the ISO standard 2631 (Guide for the Evaluation of Human Exposure to Whole body Vibration[10),11)] to the acceleration data at C. G. of a vehicle (passenger car) exerted from the previous measured roads.

The ISO standard proposes a criteria with respect to a vibration on longitudinal and transverse (fore and aft, lateral) directions respectively. The standard defines and gives physical factors of primary importance in determining the human response to vibration as follows : vibration frequency, acceleration magnitude, exposure time and the direction of vibration.

Furthermore, the magnitude of a vibration, that is, the acceleration, is expressed as a root-mean-square (rms) value in third octave frequency band. We will introduce a few typical examples of application of ISO standard to normal acceleration data of the vehicle as in Fig. 3.

As in evident from the figure, there is a peak between 10 and 15 Hz on both roads in summer and those in

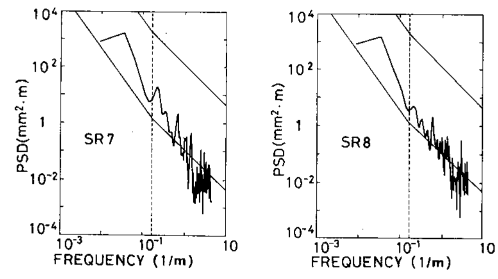


Fig. 1 Typical PSDs of Summer Road Surface.

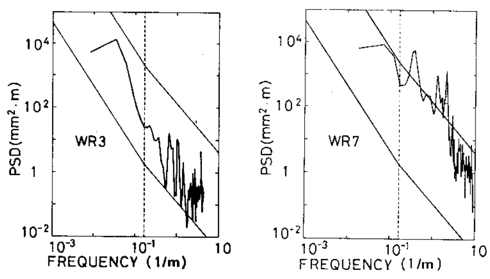


Fig. 2 Typical PSDs of Winter Road Surface.

winter. And the results agree with the natural frequency range of the vehicle unsprung mass vertical vibration.

Further, the values of summer road reach "8 hr Exposure Limit" and it is related to the criterion of the preservation of health or safety against 8 hour exposure time. The values of winter road reach "1~4 min Reduced Comfort Boundary" and it is related to the criterion of the preservation of comfort and related to difficulties of carrying out such operation as eating, reading, and writing against short exposure time.

In regard to lateral acceleration data of the test vehicle, as in Fig. 4, the rms values of acceleration have a tendency to increase with frequency and the influence on riding comfort is shown in a frequency range of 1 to 2 Hz which agrees with the natural frequency range of a body bounce and roll motions.

Furthermore, the values of summer road reach "8 hr Reduced Comfort Boundary". The values of summer road reach "8 hr Reduced Comfort Boundary". The values of winter road reach "8 hr Fatigue-Decreased Proficiency" and it is related to the criterion of the preservation of working efficiency against 8 hour exposure time. From the results obtained agree approximately with those expected.

4. ROAD ROUGHNESS CLASSIFICATION BY USE OF ITS MODEL FUNCTION

It is important to understand the characteristics of road roughness from the point of view of its maintenance and repair besides the riding comfort[12),13)]. In this case, the PSD of road roughness model function is very helpful to obtain the information about the wave length and amplitude of road roughness.

The PSD of road roughness, $P_r(n)$ has been expressed as a exponential function and can be described with

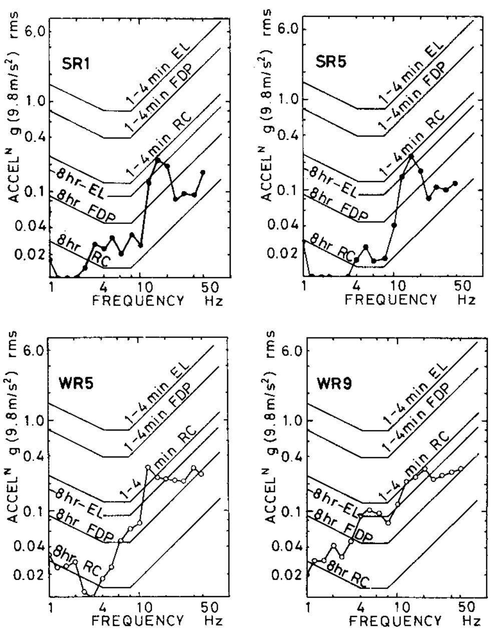
$$P_r(n)=an^{-w} \quad \cdots\cdots (3)$$

where

n=spatial frequency, cycle/m (1/m) ;

a=the parameter concerned smoothness of the road surface, mm²/m/cycle (mm²/m) ;

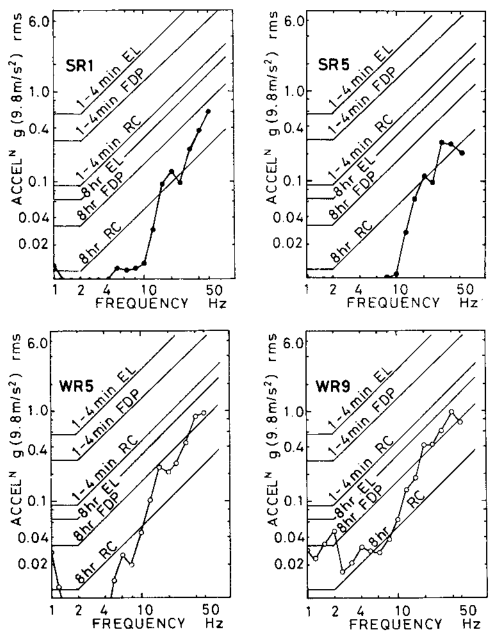
w=the exponent which indicates the power distribution in the subjective frequency.



EL=Exposure Limit

FDP=Fatigue-Decreased Proficiency

Fig. 3 Typical Normal Acceleration at C. G. of a Test Vehicle.



RC=Reduced Comfort

Fig. 4 Typical Lateral Acceleration at C. G. of a Test Vehicle.

In addition to this, $P_r(n)$ on bridge has been studied by Kobori et al. in relation to the dynamic response analysis of highway bridge[14),15)] and the parameter (β), which is dependent on the results of measurement and the distribution forms of $P_r(n)$, has been introduced[16)] and shown by the following equation.

$$P_r(n)=a/(n^w+\beta^w) \quad \cdots\cdots (4)$$

We have classified also $P_r(n)$ by use of these equations[7)]. Furthermore, from the facts described above and the results of measurement in this study, we developed a new road roughness model function and describe as follows :

$$P_r(n)=C_1 n^{-w}+C_2[1/\{(n-f)^w+\beta^w\}+1/\{(n+f)^w+\beta^w\}] \quad \cdots\cdots (5)$$

where

C_1, C_2=constant which is equivalent to the smoothness parameter in equations (3), (4), $mm^2/m/cycle$ (mm^2/m)

f=excellent spatial frequency, cycle/m(1/m).

The vehicle ride can be said to be affected mainly by roughness and waviness characteristics of the road surface because roughness waves produce an excitation in the vehicle at one of the vehicle's resonant frequencies.

The model function in equation (5) is a improvement type of those in equation (3), (4) and suited to express the characteristics of undulating road. In this case, it is considered that $P_r(n)$ includes largely the component of wave length at the frequency f.

The model function approximation to the PSD of previous measured road was considered and the non-linear least-square error method for selecting parameters of the functions is used and modefied Marquardt method is adopted here.

We examined then the fittest type among model functions for the measured PSDs of road roughness.

The degree of fitness was evaluated by two estimates : minimum RSS (Residual Sum of Squares) estimate and minimum AIC (Akaike's Information Criterion) estimate.

AIC is proposed by Akaike for the purpose of evaluating fitness of statistical model to the observations and defined as follows :

$$\text{AIC}=(-2)\log_e \text{(logarithmic likelihood)} + \text{(the number of parameters)} \quad \cdots\cdots (6)$$

For further details, the reader should refer to other paper[17)].

From the form of the PSD of road roughness, it is considered that the application of type Ⅱ model function to the PSDs of road roughness in summer is inadequate. Accordingly, in regard to application to summer road PSDs, type Ⅰ, Ⅲ models were used. The results are shown in Table 4, 5 and 6. In case of summer road and road on bridge, these are in agreement with the published results[15)]. The results of road roughness classification are shown

Table 4 Comparison of Road Roughness by Type Ⅰ.

	a	w	RSS	AIC
SR 1	0.71	1.56	6.2577×10^6	2.6800×10^3
SR 2	0.06	1.92	3.5583×10^3	1.4023×10^3
SR 3	1.32	1.41	5.6686×10^6	2.6631×10^3
SR 4	0.04	2.75	1.1042×10^9	3.5646×10^3
SR 5	0.33	1.84	7.4822×10^8	3.4981×10^3
SR 6	1.02	1.44	4.5990×10^7	3.0211×10^3
SR 7	0.36	1.55	2.5644×10^6	2.5275×10^3
SR 8	0.12	2.24	1.7931×10^7	2.8600×10^3
SR 9	1.72	1.33	3.3248×10^6	2.5719×10^3
SR 10	0.65	1.29	1.3920×10^7	2.8168×10^3
WR 1	1.29	0.87	3.0932×10^7	2.9533×10^3
WR 2	2.45	1.29	8.5007×10^6	2.7324×10^3
WR 3	0.82	1.01	2.1105×10^8	3.2817×10^3
WR 4	1.25	1.29	1.3112×10^{10}	3.9878×10^3
WR 5	0.81	0.97	1.9536×10^8	3.2685×10^3
WR 6	2.49	1.07	4.9414×10^6	2.6396×10^3
WR 7	1.31	2.42	5.2600×10^{10}	4.2253×10^3
WR 8	1.63	1.04	1.0355×10^6	2.3724×10^3
WR 9	25.94	3.67	4.8862×10^{15}	6.1814×10^3
WR 10	2.13	0.97	1.7282×10^5	2.0663×10^3

Table 5 Comparison of Road Roughness by Type Ⅱ.

	a	w	ß	RSS	AIC
WR 1	4.73	2.44	0.47	3.0942×10^7	2.9553×10^3
WR 2	2.62	1.38	0.07	4.4716×10^6	2.6246×10^3
WR 3	0.83	1.01	-2.95×10^{-4}	2.1214×10^8	3.2845×10^3
WR 4	1.56	2.69	0.55	1.3202×10^{10}	3.9909×10^3
WR 5	1.30	1.77	-0.85	1.9710×10^8	3.2720×10^3
WR 6	265.48	5.53	-1.93	5.4705×10^6	2.6590×10^3
WR 7	11.16	2.29	0.51	1.4483×10^6	2.4318×10^3
WR 8	1.65	1.04	5.50×10^{-4}	1.0385×10^6	2.3749×10^3
WR 9	42.56	4.04	-1.11	1.6375×10^5	2.0589×10^3
WR 10	48.36	4.25	1.55	2.2688×10^5	2.1148×10^3

Table 6 Comparison of Road Roughness by Type Ⅲ.

	c_1	c_2	f	w	β	RSS	AIC
SR 1	0.78	-0.06	2.40	1.53	0.42	6.2845×10^{6}	2.6868×10^{3}
SR 2	2.80×10^{-4}	1.12×10^{-4}	0.19	3.94	0.09	7.7755×10^{7}	3.1169×10^{3}
SR 3	0.61	0.10	1.03	1.87	0.13	1.4223×10^{7}	2.8264×10^{3}
SR 4	0.05	1.76×10^{-4}	0.89	2.43	0.01	5.7143×10^{7}	3.0642×10^{3}
SR 5	0.40	-187.00	62.22	1.57	359.41	7.7735×10^{8}	3.5106×10^{3}
SR 6	0.71	9.57×10^{-3}	1.10	1.88	0.03	4.8087×10^{7}	3.0347×10^{3}
SR 7	2.67	-1.64	0.47	0.71	0.39	3.1163×10^{6}	2.5668×10^{3}
SR 8	0.55	-0.21	0.43	1.21	0.54	2.5416×10^{6}	2.5320×10^{3}
SR 9	0.49	0.02	1.45	1.55	0.03	3.7700×10^{5}	2.2056×10^{3}
SR 10	0.50	0.01	1.13	1.53	7.58×10^{-3}	1.2555×10^{7}	2.8051×10^{3}
WR 1	0.49	0.33	1.26	1.11	-0.04	3.0940×10^{7}	2.9593×10^{3}
WR 2	7.69×10^{-10}	1.87	1.39	32.95	-0.99	7.2370×10^{75}	2.9879×10^{4}
WR 3	0.22	7.12×10^{-3}	1.04	3.21	-0.10	7.4018×10^{11}	4.6835×10^{3}
WR 4	0.87	0.10	0.88	1.49	-2.41×10^{-4}	1.1887×10^{10}	3.9770×10^{3}
WR 5	1.26	-2.00	18.59	0.70	-5.26	1.9632×10^{8}	3.2753×10^{3}
WR 6	0.65	1.24	1.25	1.71	0.18	4.2376×10^{6}	2.6194×10^{3}
WR 7	1.06	1.21	1.52	2.12	5.50×10^{-4}	4.0525×10^{7}	3.0055×10^{3}
WR 8	1.10	0.42	0.79	1.31	-4.35×10^{-4}	1.1573×10^{6}	2.3974×10^{3}
WR 9	0.01	15.92	0.26	3.78	0.72	1.8159×10^{9}	3.6557×10^{3}
WR 10	0.12	1.92	1.01	2.25	0.58	7.7282×10^{5}	2.3284×10^{3}

Table 7 Road Roughness Classification by the Model Function.

	Type		Type
SR 1	I	WR 1	I
SR 2	I	WR 2	II
SR 3	I	WR 3	I
SR 4	III	WR 4	III
SR 5	I	WR 5	I
SR 6	I	WR 6	III
SR 7	I	WR 7	II
SR 8	III	WR 8	I
SR 9	III	WR 9	II
SR 10	III	WR 10	I

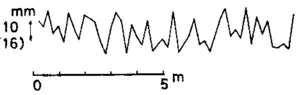


Fig. 6 Road Surface Simulation.

in Table 7.

Based on the results, a few typical application examples of classified model functions to actual PSDs of road roughness are shown in Fig. 5. In addition to this, the road roughness is simulated for the purpose of investigating the applicability of type Ⅲ model function.

The method used in this simulation is based on the assumption that the road surface wave can be expressed by combining several components with different frequencies. In this method, the road roughness at time t is simulated in the following form ;

$$x(t)=\sum_i X_i \cos(2\pi f_i t+\phi_i) \cdots\cdots\cdots\cdots\cdots\cdots (7)$$

the PSD of $x(t)$ is expressed as the equation

$$P(f)=\sum_i (1/4) X_i^2 \delta(f-f_i) \cdots\cdots\cdots\cdots\cdots\cdots (8)$$

Therefore, on condition that arbitorary $P(f)$ is given, the amplitude X_i, for certain frequency band $(f_i-\varepsilon_i<f<f_i+\varepsilon_i)$ can be obtained as follows :

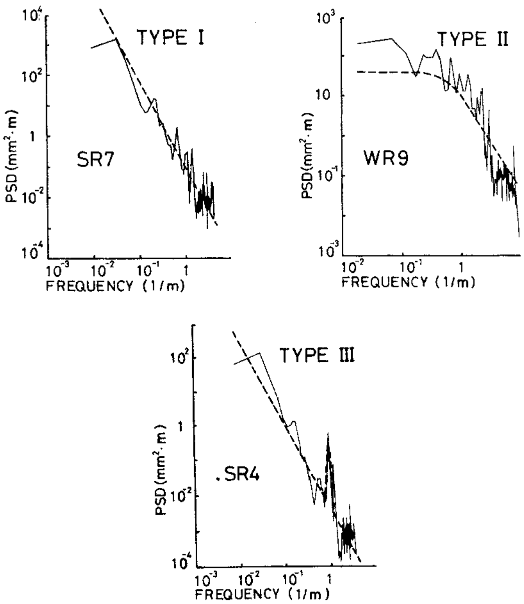


Fig. 5 Typical PSD Types of Road Surface.

$$X_i=\left[4\int_{f_i-\varepsilon_i}^{f_i+\varepsilon_i} P(f)df\right]^{1/2} \cdots\cdots\cdots\cdots\cdots\cdots (9)$$

where

ϕ_i=random variables identically distributed with uniform density between 0 and 2π ; independent of $\phi_j(i \neq j)$ and of frequency f_j.

After all, $x(t)$ is given by substituting X_i into the equation (7). As a simulation example, the comparison of the road type I with the road type Ⅲ is shown in Fig. 6. In the figure, the value in parenthesis represents I type's.

As a result, there is a possibility that the road roughness may be overestimated in case of I type's compared with Ⅲ type's. Therefore, in case of using the road roughness model function, as a basic data for investigating the road maintenance or its repair, it is necessary to consider the applicability of the function carefully.

5. CORRELATION BETWEEN VEHICLE VIBRATION MODE AND ROAD ROUGHNESS

As is stressed in Chapter 3, in regard to riding comfort, it is necessary to make clear the vibration condition at the natural frequency of a vehicle vibration system.

We therefore analyzed correlation between the PSD of road roughness and PSD of acceleration of the vehicle at the natural frequency for each vibration mode. Mass-sprung model of a passenger car with 7 degree of freedom, which takes into account the suspension system of the vehicle and rotational vibration, is employed. The model of the vehicle is shown in Fig. 7.

The equations of motion of the model for the free vibration of an undamped system are given as follows :

$$\left.\begin{aligned} &m\ddot{Z}=Pf_1+Pf_2+Pf_3+Pf_4\\ &m_1\ddot{Z}_1=P_1-Pf_1\\ &m_2\ddot{Z}_2=P_2-Pf_2\\ &m_3\ddot{Z}_3=P_3+P_4-Pf_3-Pf_4\\ &I_y\ddot{\theta}_y=(Pf_1+Pf_2)l_1-(Pf_3+Pf_4)l_2\\ &I_x\ddot{\theta}_x=(Pf_1-Pf_2)s_1+(Pf_3-Pf_4)s_3\\ &I_3\ddot{\theta}_3=(P_3-P_4)s_2-(Pf_3-Pf_4)s_3 \end{aligned}\right\} \quad \cdots\cdots (10)$$

where

m=sprung mass

m_1, m_2=front unsprung mass

m_3=rear unsprung mass

I_x=roll moment of inertia of sprung mass

I_y=pitch moment of inertia of sprung mass

I_3=roll moment if inertia of rear unsprung mass

l_1=distance from C. G. to line between front sprung units

l_2=distance from C. G. to rear sprung unit

s_1=distance from longitudinal axis to front tire

s_2=distance from longitudinal axis to rear tire

s_3=distance from longitudinal axis to rear spring

P_1, P_2, P_3, P_4=spring force of each suspension (spring constant=K_{tf}, K_{tr})

Pf_1, Pf_2, Pf_3, Pf_4=spring force of each suspension (spring constant=K_{Sf}, K_{Sr}).

The natural frequencies for various vibration modes of the vehicle are given by computing the eigenvalue of equation (10). We computed the natural frequencies of the vehicle in Chapter 2, 3 by use of its specifications.

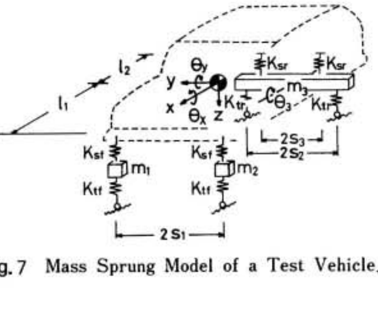


Fig. 7 Mass Sprung Model of a Test Vehicle.

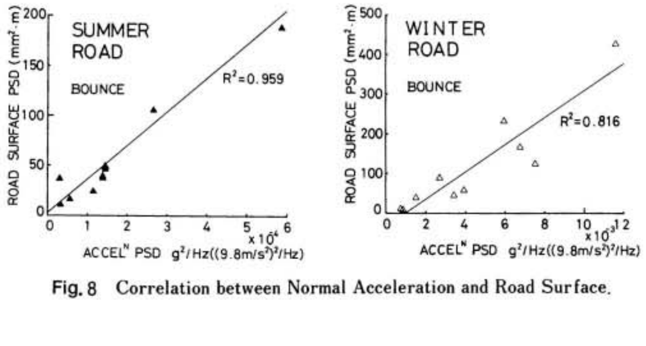


Fig. 8 Correlation between Normal Acceleration and Road Surface.

Table 8 Analysis of Simple Linear Regression for Normal Acceleration at C. G. of a Test Vehicle.

Road Surface Condition	Mode of Motion	Regression Coefficient b	R-Square R^2	F Value	Significant at 5 per cent
Summer	Bounce	318277	0.9590	187.225	Yes
	Front Wheel Hop	22842	0.9702	260.163	Yes
	Rear Axle Hop	85631	0.9575	180.068	Yes
	Roll	363102	0.9763	330.158	Yes
	Pitch	444210	0.9931	1146.164	Yes
	Rear Axle Tramp	8953	0.4840	7.502	Yes
Winter	Bounce	312047	0.8160	35.480	Yes
	Front Wheel Hop	29385	0.7687	26.587	Yes
	Rear Axle Hop	28340	0.3858	5.024	No
	Roll	105625	0.1653	1.584	No
	Pitch	19432	0.0468	0.393	No
	Rear Axle Tramp	1358	0.1920	1.902	No

When a vehicle traverses the route at a constant velocity v and the profile has spatial frequency n, the frequency excited by road roughness, f is expressed as follows;

$$f = n \times v / 3.6 \quad (11)$$

Accordingly, if f coincides with the natural frequency of a vehicle vibration mode, then the amplitude of a related vehicle part increases resonantly. Therefore, simple linear regression analysis carried out in regard to the normal accelerations (rms values) of a vehicle sprung mass and PSDs of road roughness at the previous computed natural frequencies for each vibration mode. The used data are equal to previous measured ones in Chapter 2.

In general, linear regression function can be expressed as $y = a + bx$, in this case, y=PSD of road surface at the natural frequency of a vehicle vibration mode, x=PSD of acceleration at C. G. of a vehicle at the natural frequency of a vehicle vibration mode, a=regression constant and b=regression coefficient.

The existence of a statistically significant correlation between the variables of interest may be accomplished by testing the hypothesis that $b=0$. Table 8 show results of linear correlation analysis at the 5 per cent level of significance. In this case, F value with 1 and 8 degrees of freedom at the 5 per cent level of significance is 5.32.

As shown in Table 8, from the measurements in summer, it can be seen that PSDs of normal acceleration of the vehicle are significantly related to the PSDs of road roughness at the natural frequency for each vibration mode.

On the other hand, the relationships between them in winter are not significant at the 5 per cent level except front unsprung mass and sprung mass vertical motions. The typical examples of the analyses are shown in Fig. 8.

6. FREQUENCY RESPONSE FUNCTION ESTIMATES OF A VEHICLE VIBRATION SYSTEM

In the present paper, it is assumed that system, which is composed of the input road roughness and output vehicle vibration, is linear system. Based on this assumption, the PSD of road roughness can be obtained.

Therefore, in order to understand vehicle travelling condition, it is necessary to study vibratory response properties of the vehicle, which depend on road condition, traffic condition and driving condition of the vehicle.

For the purpose of predicting the vehicle response by analytical technique, we analyzed the response properties of vehicle viration according to road roughness conditions by application of vibration source

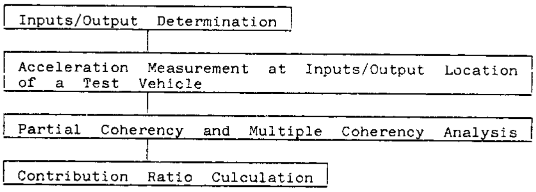


Fig. 9 Block Diagram for Analysis.

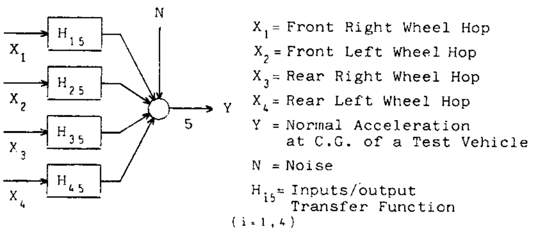


Fig. 10 Linear System of 4 Inputs and 1 Output.

contribution method[18] which is utilized for investigating noise and vibration problems of road vehicle by automotive engineers.

The analysis procedure of the method is shown in Fig. 9 and the vehicle is dealt with multiple input-single output linear system. In this study, it is assumed that inputs normal acceleration at each wheel of a vehicle exerted from road roughness are occuring with a single output normal acceleration at C. G. of the vehicle. The system is illustrated in Fig. 10.

The partial coherence function is used to understand the outline of contribution order to the output from inputs and the multiple coherence function is used to examine how closely an actual output can be predicted from linear operations using only the inputs of interest[19].

The examples of multiple coherence functions and partial coherence functions computed from previous observations are shown in Fig. 11. In addition to this, as noted in Chapter 5, it can be considered that a significant linear relationship between the PSD of normal acceleration at C. G. of the vehicle and PSD of road roughness was indicated and we computed the contribution ratio of each vibration components of inputs in vertical vibration at C. G. of the vehicle.

The results are shown in Fig. 12. From Fig. 11, for measurement of summer road, it is seen that the multiple coherence function is quite high at about 8 and 12 Hz which coincide with the natural frequency of rear axle vertical vibration and that of front wheel vartical vibration respectively.

Hence, selected inputs to the output are adequate at these frequencies. The road surface used for this measurement is SR 1, where irregularities occur only under the travelling wheels on right side and it can be considered that vertical vibration of right wheel is highly coherent with sprung mass vertical vibration.

This is clearly shown in Fig. 12 and the high relative contribution of

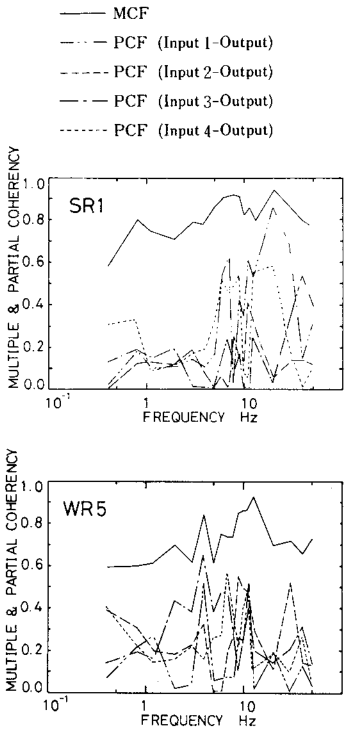


Fig. 11 Examples of Multiple Coherency and Partial Coherency between Inputs and Output.

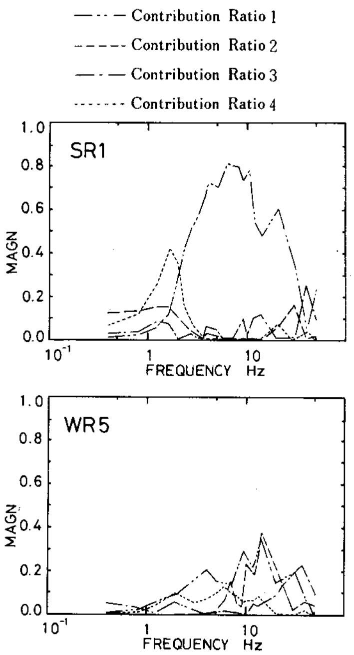


Fig. 12 Contribution Ratio of Inputs to Output.

the input front right wheel vertical vibration is indicated at the natural frequency range of unsprung mass system. Accordingly, the effects of different track profiles can be confirmed. The front wheels of the vehicle are independently sprung mass system.

In regard to winter road, from Fig. 11, it is seen that the multiple coherence function is high (0.60 to 0.93) over the entire frequency range. In addition, contribution of front wheels vertical vibrations to the output is high at the natural frequency of front wheel vertical vibration mode, as illustrated in Fig. 12.

7. CONCLUSION

Several important results in the present paper are summarized as follows :

(1) Based on measurements of road roughness PSDs, the actual state was clarified by ISO proposal and poor road condition in winter, which has not been published to date sufficiently, was studied.

(2) From the results of vehicle riding comfort evaluation in comparison with ISO vibration standard, for motions in longitudinal and lateral axes, it became clear that road surfaces in winter are in a bad condition in terms of riding comfort compared with those in summer. In case of a physical description of the human response to vibration, it was found that the levels of longitudinal vibration exerted from road roughness in winter reach "1-4 min Reduced Comfort Boundary" and the levels of lateral vibration exerted from those in winter reach "8 hr Fatigue-Decreased Proficiency Boundary".

(3) When developing the model function of undulating road and applying it to actual road, a good fitness was obtained compared to other road model functions which had been used. Therefore, more detailed characteristics of road surface can be analyzed by new road model function and the function can be also applied to the evaluation of pavement serviceability.

(4) When a vehicle traversing the road roughness, vibration frequency affecting riding comfort coincide with the natural frequency of a vibration mode of the vehicle.

(5) In regard to vertical vibration of a vehicle, a significant linear relationship between the PSD of road roughness at the natural frequency of the vehicle vibration mode and PSD of acceleration at C. G. of the vehicle was indicated in the measurement of summer road surface.

On the other hand, in regard to the measurement of winter road surface, there is moderate linear correlation between them in vertical vibration modes compared to rotational vibration modes.

(6) As a result of applying the vibration source contribution method to a multiple input-single output linear system for vehicle-road surface system, in regard to normal acceleration at C. G. of a vehicle as a single output, we can predict contribution ratio to the output from each input and the frequency range which has an effect on the linear relationship of the system. In addition, it was found that the vehicle motion corresponding to road roughness condition could be satisfactory predicted by the method.

The greater parts of analysis procedure and theory used in this paper have been studied in the field of automotive engineering, bridge engineering, highway engineering and so forth.

We consider that it is necessary to understand quantitatively the road roughness from the synthetic viewpoint. Based on this idea, this paper is presented. Suggestions and criticisms from readers will be welcomed and will be carefully considered.

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