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DEVELOPMENT OF A SOFTWARE FOR MODELING OF VEHICLE EXCITATION DUE TO THE ROAD ROUGHNESS

UDK: 683.3.06:629.114.6

INTRODUCTION

The road roughness induces oscillatory processes of a motor vehicle. The intensity of oscillations depends on statistical characteristics of the road, design parameters of the vehicle and vehicle speed. Investigation of dynamic response of the vehicle to the influence of road roughness has special importance during the solving of the problems of dynamic endurance of elements and structures, oscillatory comfort, steering control and stability of motion, loads and durability of the road. It is for these reasons that recording of road roughness, and mathematical interpretation of its excitation effects and interaction with motor vehicles, were the subjects of a great number of specialist in the past. Accordingly, we underline four papers /1/ - /4/ from previous period, which results had important influence on later theoretical-experimental investigations in this field.

Investigations of vehicle excitations due to road roughness were initiated at Laboratory for motor vehicles of the Faculty of Mechanical Engineering in Kragujevac with cooperation of Automobile Institute "Zastava", in 1972., within the framework of scientific-investigative project "Investigation and classification of the road according to the roughness of the longitudinal road profile". In previous period, a continuation of investigations in this field was kept through continuation of cooperation between the Faculty of Mechanical Engineering and Automobile Institute and the same can be concluded from the short review of references which follows. Our own methodology for identification of basic statistical characteristics of the road and forming of equivalent excitations of a two axle vehicle is given in paper /5/. The behavior relations of a passenger automobile during the simultaneous influence of the road roughness and the driver through the steering wheel are presented in paper /6/.

The problem of modeling of the vehicle excitation form due to the road roughness and investigation of their coupling is considered in paper /7/. In paper /9/, additional criteria for checking the homogeneity and isotropy of road surface random field of the roughness were formed and some mutual foundations in identification of excitation forces of road- and rail- vehicles were pointed out. Possibilities of simulation of the excitations due to the road roughness for laboratory investigations of vehicles and structures are presented in paper /10/.

Some current problems in this field should be pointed out. The quality of the road and its excitation effects on the vehicle are the subject of activities of working groups and technical comity for international standards ISO/TC108/SC2. This means the engagement of greater number of experts, investigation-development institutions and associations /11/. In the area of scientific-investigative and development work, hypothesis of homogeneity of a random field of the road roughness, presented in paper /4/, is acceptable with some modifications of statistical characteristics of excitation /12/ and the use of modern measuring systems /13/, /14/.

Considering the previous discussions, we tried to develop a procedure for forming the equivalent vehicle excitations on the basis of starting data of recording the individual profiles or standard characteristics of individual road categories. A short review of investigations is given in following chapters.

TO POINT OUT THE PROBLEM

Based on excitation model of the two axle vehicle /7/, shown in Fig. 1, a spectrum corresponding to the observed point of the system can be determined.

$$S_{kk}(f)=\sum_{i=1}^{4}\sum_{j=1}^{4} H_i^{*}(f)\,H_j(f)\,S_{ij}(f) \qquad (1)$$

where $H_i^{*}(f)$ and $H_j(f)$ are characteristics of the transfer structure of the vehicle and $S_{ij}(f)$ are the excitation spectra due to the road roughness. According to Fig. 1, in general case of the two axle vehicle excitation, 16 individual components of excitation, $S_{ij}(f)$ should be known. In order to simplify the problem, the demands which should be taken into account during definition, identification and the use of the basic statistical characteristics of the road will be pointed out.

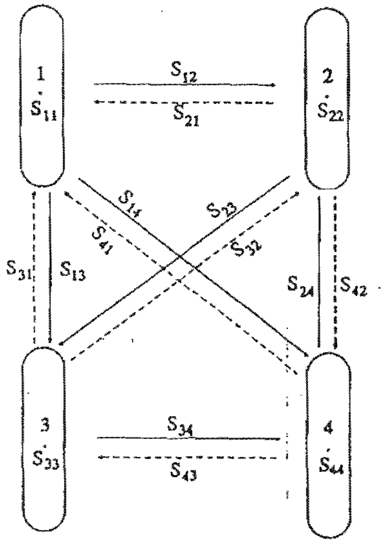

FIGURE 1.: MODEL OF EXCITATION OF TWO AXLE VEHICLE DUE TO ROAD ROUGHNESS /7/

MATHEMATICAL BASICS FOR DESCRIPTION OF ROAD SURFACE

The road surface is considered to be a random function of two independent variables, of length and of width, x, y. According to the assumption of homogeneity, correlation function of the road surface roughness does not depend on coordinates x, y, but only on correlation steps, $\delta_x = x_{i+k} - x_i$, $\delta_x = x_{i+k} - x_i$:

$$R(\delta_x,\delta_y)=\dot{E}\left[\,z(x,y)\,z(x+\delta_x,y+\delta_y)\,\right] \qquad (2)$$

Appropriate two-dimensional power spectrum density is determined as a Fourier transform of expression (2):

$$S(\Omega_x,\Omega_y)=\int_{-\infty}^{\infty}\!\int_{-\infty}^{\infty} R(\delta_x,\delta_y)\,e^{[-i2\pi(\Omega_x\delta_x+\Omega_y\delta_y)]}\,d\delta_x\,d\delta_y \qquad (3)$$

Statistical characteristics of individual longitudinal or lateral profiles (sections) can be determined from statistical characteristics of the surface, (2), (3), for fixed value of independent variables, δ_x = const and δ_y = const , that is $\delta_x = 0$, $\delta_x = 0$. Based on this assumption, a relation between power spectrum density of the roughness of the individual profile and the power spectrum density of the road surface roughness is established:

$$S(\Omega_x)=\int_{-\infty}^{\infty} S(\Omega_x,\Omega_y)\,d\Omega_y \qquad (4)$$

Assumption on homogenous and isotropic random road surface means the circular symmetry of two-dimensional power spectrum density, $S(\Omega_x,\Omega_y)$ in relation to the origin, and it corresponds to the presentation in polar coordinates:

$$S(\Omega\phi)=\int_{-\infty}^{\infty}\!\int_{0}^{\pi} |\delta|\,R(\delta,0)\,e^{[-i2\pi(\Omega\delta)]}\cos(0-\phi)\,d\theta\,d\delta \qquad (5)$$

where Ω,ϕ and δ,θ are polar coordinates of the power spectrum density, and correlation function, respectively. Expression (5) can be reduced to the following form:

$$S(\Omega\phi)\equiv S^{*}(\Omega)=2\pi\int_{0}^{\pi}\delta R^{*}(\delta)\,J_o(2\pi\Omega\delta)\,d\delta \qquad (6)$$

where symbol $J_o(2\pi\Omega\delta)$ denotes the first kind, zero order Bessel function, and $S^{*}(\Omega)$ and $R^{*}(\delta)$ are the power spectrum density and correlation function of the road surface independent from angle coordinates ϕ and 0, respectively.

Based on previous relations, an algorithm of possibilities for describing the relations of relevant statistical characteristics of the road surface from measured, that is available characteristics of road roughness longitudinal profile.

According to block-scheme in Fig. 2, auto-correlation function, 1, and power spectrum density, 2, are determined for measured amplitudes of longitudinal profile of the road roughness, z(x). These two characteristics are coupled by direct, 3, and inverse, 4, Fourier transform. For known auto-correlation function of longitudinal profile of homogenous and isotropic road surface, $R(\delta)$, a cross-correlation function $R_k(\delta_x, 2s)$, 5, of parallel longitudinal profiles with track, 2s, and corresponding cross-spectrum, $S_k(\Omega)$, 6, are determined. Alternative procedures are marked with numbers 7 and 8 in Fig. 2.

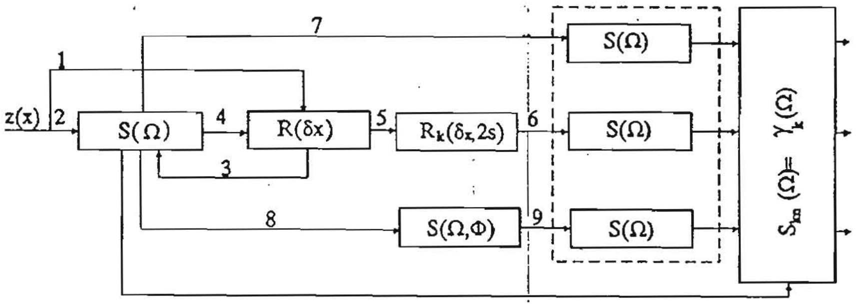

FIGURE 2.: THE COUPLINGS BETWEEN STATISTICAL CHARACTERISTICS OF LONGITUDINAL SECTION ROUGHNESS AND ROAD SURFACE ROUGHNESS

In first case, 7, power cross-spectrum, $S_k(\Omega)$, of parallel tracks on distance 2s is determined directly:

$$S_k(\Omega)=\int_{|\Omega|}^{\infty}\left[\frac{d\,S\,\Omega_1}{d\,\Omega_1}\right]J_o\left(4\pi s\sqrt{\Omega_1^2-\Omega^2}\right)d\,\Omega_1 \qquad (7)$$

In second case, 8, a two-dimensional power spectrum density of the road surface, $S(\Omega,\phi)$ is determined :

$$f(\Omega)=\int_{o}^{\pi}S(\Omega,\phi)\,|\Omega|\,d\,\Omega=-\frac{d}{d\,\Omega}\int_{\Omega}^{\infty}S(\Omega_1)\frac{\Omega_1 d\,\Omega_1}{\sqrt{\Omega_1^2-\Omega^2}} \qquad (8)$$

In each of tree cases (4, 7, 8), the available power spectrum of longitudinal profile of the road roughness, $S(\Omega)$ is the input characteristic and normalized power cross- spectrum $S_{nk}(\Omega)=\gamma_k(\Omega)$, that is, coherence function, $\gamma_k(\Omega)$, is the output characteristic. With available characteristic $S(\Omega)$ and characteristic $\gamma_k(\Omega)$ determined by $S(\Omega)$, equivalent excitations of the motor vehicle due to road roughness can be determined.

a) Vertical oscillation excitation:

$$S_{zz}(\Omega)=\frac{1}{4}S(\Omega)\left[1+\gamma_k(\Omega)\right]\left[1+\cos(l\,\Omega)\right] \qquad (9)$$

b) Excitation of angular oscillations about vehicle lateral axis:

$$S_{\alpha\alpha}(\Omega)=\frac{1}{l^2}S(\Omega)\left[1+\gamma_k(\Omega)\right]\left[1-\cos(l\,\Omega)\right] \qquad (10)$$

c) Excitation of angular oscillations about vehicle longitudinal axis:

$$S_{\psi\psi}(\Omega)=\frac{1}{4s^2}S(\Omega)\left[1-\gamma_k(\Omega)\right]\left[1+\cos(l\,\Omega)\right] \qquad (11)$$

d) Excitation of torsional oscillations of vehicle suspended mass:

$$S_{\xi\xi}(\Omega)=\frac{1}{4s^2}S(\Omega)\left[1-\gamma_k(\Omega)\right]\left[1-\cos(l\,\Omega)\right] \qquad (12)$$

For determination of coherence function of parallel road roughness sections, we used, in this paper, a procedure from Fig. 2 marked by numbers 2-4-5-6.

SELECTION OF A MODEL FOR DESCRIPTION OF THE ROAD ROUGHNESS

Trying that suggested procedure has a practical use, we paid special attention to the selection of mathematical model for description of power spectrum density of longitudinal roughness section. For different kinds of the roads and terains, a model for auto-correlation function of longitudinal roughness section in general form, can be used:

$$R(\delta)=\sum_{i=1}^{m}A_i e^{-\alpha_i|\delta|}+\sum_{k=1}^{r}A_k e^{-\alpha_k|\delta|}\cos\beta_k\delta \qquad (13)$$

Direct Fourier transform of the expression (13) gives the power spectrum density of appropriate roughness section in the form of rational-fractioned function:

$$S(\Omega)=\frac{D}{\pi}\left[\sum_{i=1}^{m}A_i\alpha_i\frac{1}{\Omega^2+\alpha_i^2}+\sum_{k=1}^{r}A_k\alpha_k\frac{\Omega^2+\alpha_k^2+\beta_k^2}{(\Omega^2+\alpha_k^2+\beta_k^2)-4\,\Omega^2\beta_k^2}\right] \qquad (14)$$

Exponential model of the power spectrum density has often used for modeling roughness in low frequency area /1/:

$$S(\Omega)=\begin{cases}S(\Omega_o)(\Omega/\Omega_o)^{-w_1}, & \Omega\le\Omega_o\\ S(\Omega_o)(\Omega/\Omega_o)^{-w_2}, & \Omega\ge\Omega_o\end{cases} \qquad (15)$$

where $S(\Omega_o)$ is a measure of road roughness, w_1, w_2 are waviness coefficient of the road roughness. For a greater number of contemporary roads, good approximation of the power spectrum density of longitudinal roughness section is achieved by using the model:

$$S(\Omega)=S(\Omega_o)\,\Omega^{-w}=C\,\Omega^{-w} \qquad (16)$$

Exponential form (16) was more acceptable than rational function form (14) in regard to given demand for compatibility of results with the base of normalized data according to ISO standards /11/. In expression (9), $S(\Omega)$ is appropriate one-sided power spectrum density and C and W, are parameters of the road characteristics.

According to algorithm in Fig. 2, for known spectral characteristic of one longitudinal section, $S(\Omega)$, auto-correlation function, $R(\delta_x)$; determined by inverse Fourier transform, in accordance with expression (17):

$$R(\delta)=\int_{-\infty}^{\infty} S(\Omega)e^{i2\pi\Omega\delta}d\Omega \tag{17}$$

$$R(\delta)=\int_{0}^{\infty} S(\Omega)\cos 2\pi\Omega\delta \, d\Omega \tag{18}$$

Cross-correlation function of parallel tracks is calculated by interpolation of independent variable:

$$R_k(\delta_x, 2s)=\int_{0}^{\infty} S(\Omega)\cos(2\pi\Omega\sqrt{\delta_x^2+4s^2})\,d\Omega \tag{19}$$

and, in the next programming step, appropriate cross-spectrum, too:

$$S_k(\Omega)=4\int_{0}^{\infty} R_k(\delta_x, 2s)\cos 2\pi\Omega\delta \, d\delta \tag{20}$$

In the following, a descrete form of expression (20) is used:

$$S_k(\Omega)=S_k\left(\frac{k\Omega_g}{m}\right)=\frac{1}{\Omega_g}\left[R_k(0)+2\sum_{r=1}^{m-1}R_k(r)\cos\frac{\pi r k}{m}+(-1)^k R_m\right] \tag{21}$$

$$k=0, 1, 2, \ldots, m$$

where $S_k(\Omega)$ is an estimate of the spectral density value of the k-th harmonic with appropriate frequency $\Omega=\frac{k\Omega_g}{m}$.

Final estimate of the power spectrum density is determined with further frequency equalizing according to following algorithm:

$$\begin{aligned} &S_o = 0.5\,S_o + 0.5\,S_1\\ &S_k + 0.25\,S_{k-1} + 0.5\,S_k + 0.25\,S_{k+1}\\ &S_m = 0.5\,S_{m-1} + 0.5\,S_m\ , \ k=1,2,\ldots,m-1 \end{aligned} \tag{22}$$

which is in accordance to the use of Hanning lag weighting function D(r):

$$\begin{aligned} &D(r)=\frac{1}{2}(1+\cos\frac{\pi r}{m})\ , \quad r=0,1,2,\ldots,m\\ &D(r)=0 \qquad\qquad\qquad\ , \quad r>m \end{aligned} \tag{23}$$

and the forming of appropriate model for determination of power cross-spectrum of two longitudinal sections of road roughness:

$$S_k(\Omega)=S_k\left(\frac{k\Omega_g}{m}\right)=\frac{1}{\Omega_g}\left[R_k(0)+2\sum_{r=1}^{m-1}R_k(r)D(r)\cos\frac{\pi r k}{m}\right] \tag{24}$$

$$k=0, 1, 2, \ldots, m$$

Finally, normalized cross-spectrum, that is, coherence function is calculated according to the model:

$$S_{kn}\left(\frac{k\Omega_g}{m}\right)=\left[\frac{S_k\left(\frac{k\Omega_g}{m}\right)}{S\left(\frac{k\Omega_g}{m}\right)}\right] \tag{25}$$

In accordance with the algorithm in Fig. 2 and formed mathematical model in relations (16) to (25), we developed appropriate software for identification of cross-coupling characteristics of longitudinal parallel tracks of road surface roughness, based on known characteristics of individual tracks (section). During this process, it has been shown that mathematical model given by expression (16) according to normalization /11/ is not suitable in its form for performing of direct operations in accordance with the algorithm in Fig. 2. In this sense, it was necessary to previously introduce boundary conditions in the domains of low and high wave frequencies of road roughness, Ω. Besides, the form of model (16) demands the introduction of numerical procedure of calculation already in programming step (4), which has an influence on stability of calculation results of entire cycle 4-5-6.

ANALYSIS OF THE RESULTS

As an example to illustrate the possibilities of the use of suggested procedure, model (16) is used with concrete parameters. As parameter C does not have an influence on values of normalized characteristics, in all calculations, only the influence of parameters of road waviness , w, is observed.

In Fig. 3, curves of normalized auto-correlation functions calculated for longitudinal tracks of road roughness with values of waviness w=2, 2.25, 2.5. Corresponding curves of normalized cross-correlation function for two parallel longitudinal tracks at the distance 2s=1.3m and given values of waviness, are shown in Fig. 4, "equivalent power cross- spectra" in Fig. 5 and normalized power cross-spectra, that is, coherence functions, in Fig. 6.

With the definition of "equivalent power cross-spectra", we normalized the absolute levels of cross-spectra with parameter C, and, by that, we eliminated its influence in analysis of relevant relations of individual road categories. In the case of "normalized power cross-spectra", the normalization is conducted with the power auto-spectrum of individual track and, hence, a data base for coherence function of parallel tracks has been formed. According to courses of the curves in Figs. 3 and 4, auto- and cross- correlation functions are monotonous decreasing function as the step δ_x increases. In both cases, the increase of the values of waviness coefficient of the road roughness has an impact on the increase of the correlation functions' levels. In that case, the frequency domain of characteristics, the road quality and the intensity of vehicle excitation can be interpreted on the basis of characteristic

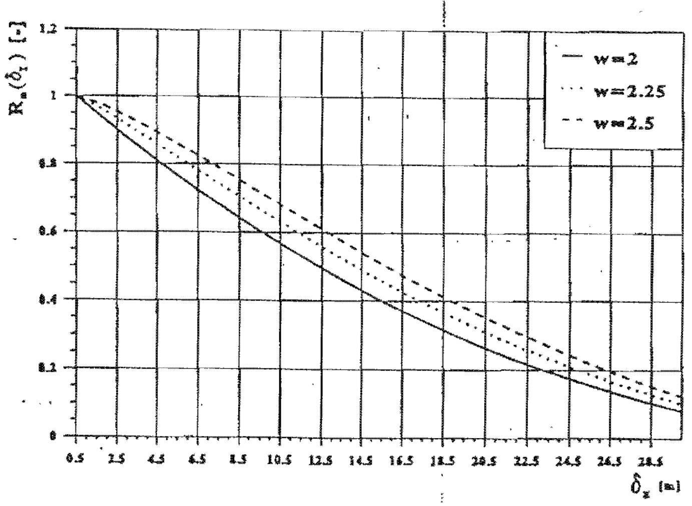

FIGURE 3.: NORMALIZED AUTO-CORRELATION FUNCTIONS OF INDIVIDUAL LONGITUDINAL ROAD ROUGHNESS TRACKS

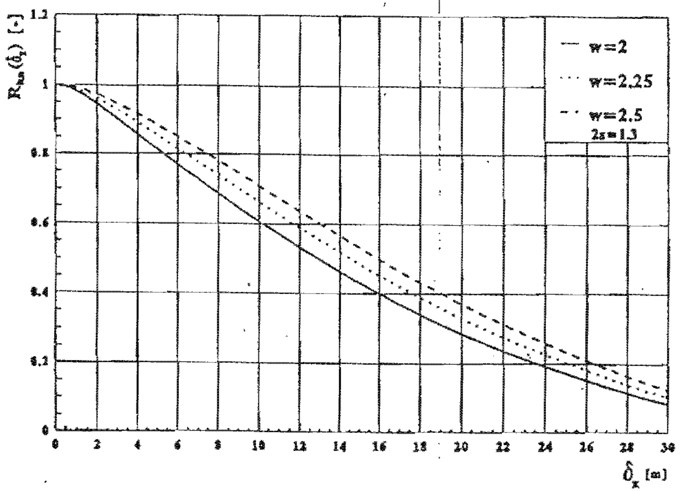

FIGURE 4. NORMALIZED CROSS-CORRELATION FUNCTIONS OF PARALLEL LONGITUDINAL ROAD ROUGHNESS TRACKS

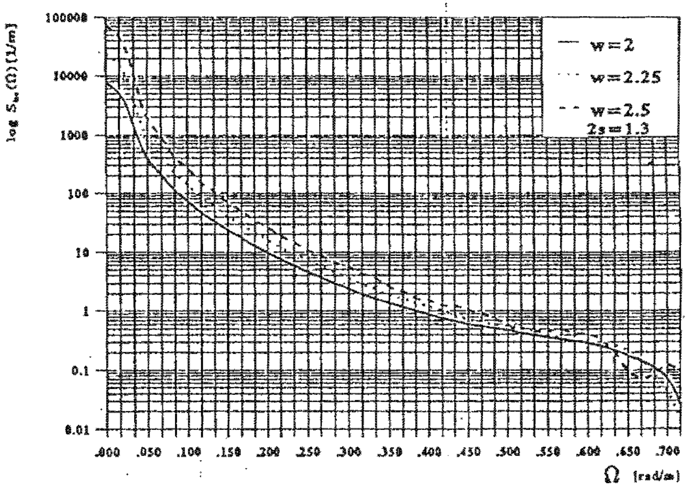

FIGURE 5. EQUIVALENT POWER CROSS-SPECTRA OF PARALLEL LONGITUDINAL ROAD ROUGHNESS TRACKS

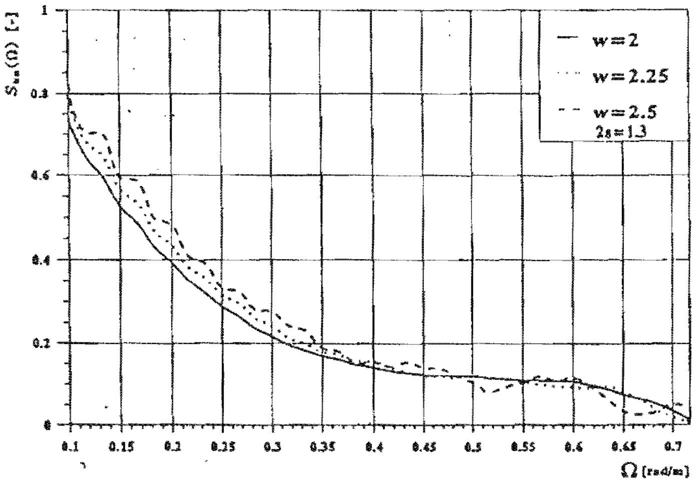

FIGURE 6. NORMALIZED POWER CROSS-SPECTRA OF PARALLEL LONGITUDINAL ROAD ROUGHNESS TRACKS

parameters of correlation functions, therefore in time domain. Observed in frequencies domain, the increase of the road roughness waviness by lower frequencies, increases the levels of parallel tracks cross-spectra, Fig. 5, and increases the coupling between their excitations according to Fig. 6. These presentations are also formed for tracks at the distance of 2s=1.3m. According to Fig. 6, statistical coupling is getting weaker with the increase of the distance between tracks and vice versa.

CONCLUSIONS

In relation to traditional method of presentation of longitudinal section characteristics in frequency domain (16), suggested procedure enables the broadening of the model and forming of characteristics of coupling between parallel tracks in time (Figs.. 3 and 4) and frequency domains (Figs. 5 and 6) in accordance with demands for modeling the vehicle excitation due to road roughness. Basic data are available bases of experimental results of measurement of the road roughness in one track, as well as normalized models in the structure of ISO-standards /11/.

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