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SOME FEATURES OF TRANSIENT PULSES FORMS ON A WEIGH-IN-MOTION SYSTEM SENSOR INPUT

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Some individual distinctions are considered in the transient responses forms from small-buried seismic sensors excited by a car tyre interaction with asphalt-concrete road pavement. A refined model of the response is proposed having taken into account a wind velocity component oriented along the road centreline. The model is based on conception that a tyre footprint is acceptable to consider as some array of point sources of Raleigh waves. Asymmetries in transients are analysed using decomposition of them on even-odd components, and an idea is proposed to describe a response as some probability density function. These examinations have realized with modelled transients and experimentally registered optical sensor responses. The set of Matlab codes is worked out for seismic transients modelling and processing.

Keywords: weigh-in-motion system, sensor transient response modelling, road pavement reaction, pulse forms.

1. Introduction

The progress in automotive load transportation is determined predominantly by road net system conditions. Degree of road deterioration depends on traffic activity and gross weight of trucks with loads. In accordance with the international agreements, an every axle loading of a motor car has to be restricted to some maximally allowable value. Weigh-in-motion (WIM) systems application is the promising way to estimate an axle loading without car stoppage [1].

The WIM sensors are responded to seismic or acoustic waves initialised by the travelling car. There are some versions of WIM using small-buried subsurfaced seismic sensors mounted within road pavement. The optic fibre sensors have taken the leading place among them. Output signal of that sensor is a time series of some transient pulses. The quantity of them is equal to the motor car axle's number. At first sight all the pulses appear to be similar one another in average.

However, just the individual distinctions in the forms of pulses have to serve as some measures of axle loadings. From theoretical point of view the every separate transient is some superposition of two pulses. The first from them is resulted by vertical loading from motor car parts and cargo weight quota fallen on given axle. It has to be symmetrical (even) along the tyre footprint, or in time. The second pulse reflects the interaction of the wheel with the road pavement and has to be a non-symmetrical (presumably odd) function [2, 3]. It is obvious that this second pulse form has to depend on great many accidental factors. Summation of such the even and odd pulses gives some non-symmetrical transient form, which is well observed everywhere in practical measurements. In this paper is supposed that the degree of asymmetry in sensor transient forms may be consider as an evaluation of road pavement contribution to the WIM measurement. For successful designing a WIM system the nature of these delicate features ought to be discovered and interpreted. The goal is to work out a method to filter individual differences in the pulses on the sensor output.

The organization of the paper is as follows. In Section 2 the algorithm is developed based on modelling of a small-buried seismic sensor response excited by forces distributed along a car tyre footprint to asphalt-concrete road pavement. It is supposed that a seismic wave perceived by the sensor is the vertical component of surface Raleigh wave [4, 5] propagating in a pavement top layer. In contrast to [6], in the new model it is taken into account a car velocity, as well as a wind pressure component oriented along the road centreline. The calculation is kept out to a pulse basic form excited by a unit point mass body moving with some friction along a horizontal road. In Section 3 the model of a transient pulse is investigated when a footprint is excited by forces distributed along it. In this case the footprint is considered as some discrete dynamic array of Raleigh waves sources. Asymmetry of the transients is studied in Section 4. It is supposed the pulse from WIM sensor is a positive definite single-mode function. If the same pulse is decomposed to the even and the odd parts, the measure of asymmetry may be the ratio of energies contained in these parts. On other hand, it can be seen that this pulse is analogous to a distorted probability density function of some normally distributed random quantity. Thus, the third central momentum, or the skewness, may be served as a measure of pulse asymmetry. Some experimental results are discussed in Section 5.

Results of modelling and processing of real optic sensor response transient forms have been found based on the set of Matlab programs worked out to illustrate the algorithms considered in this work.

2. Modified Response on a Point Mass Movement with the Regard for Friction Coefficient

The problem described in this part is derivation of a seismic pulse form excited by a unit point mass body moving with certain friction along a smooth horizontal road. In contrast to [6], in this model an attempt makes to take into account some changes in friction coefficient depended on the velocity of the body as well as a wind velocity component oriented along the road centreline.

Figure 1 shows the sketch of the task. An omni directional (isotropic) seismic sensor is placed on some depth h from road surface and it is superposed with the origin O of Cartesian coordinates system. A point body moves from initial position t = 0, $x = x_0$ from the left to the right along the plain pavement surface with constant velocity $\boldsymbol{V}$**.** It is supposed that x_0 is a negative value. The body experiences an influence both force of weight $\boldsymbol{W}$ and friction force $\boldsymbol{F}$ too. The force $\boldsymbol{F}$ is caused by two main reasons: 1) body – pavement interaction, and 2) horizontal loading from a wind component blown along the road centreline.

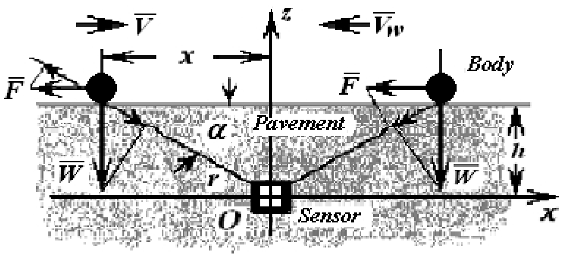

Figure 1. Excitation of seismic sensor by a unit point mass body movement (adapted from [2])

Instantaneous position of the body concerning the sensor describes by distances x, r and an angle α where

$$\boldsymbol{x} = \boldsymbol{x}_0 + \boldsymbol{V}\boldsymbol{t}, \quad \boldsymbol{r} = (\boldsymbol{x}^2 + \boldsymbol{h}^2)^{1/2}, \quad \sin\alpha = \boldsymbol{h}/\boldsymbol{r}, \quad \cos\alpha = \boldsymbol{x}/\boldsymbol{r}. \tag{1}$$

Movement of this body excites seismic oscillations in pavement layer propagating along the road surface as the Raleigh type waves with velocity $\boldsymbol{V}_{\mathbf{R}}$. The current pressure $\boldsymbol{P}$ perceived by the sensor depends on the instantaneous sum of projections onto running radius – vector $\boldsymbol{r}$ of the forces $\boldsymbol{W}$ and $\boldsymbol{F}$.

It is seen from Figure 1 that projections of $\boldsymbol{W}$ would be altering their directions as soon as the sign of x is changed. Hence, one can describe

$$\boldsymbol{P} = (\boldsymbol{W}\sin\boldsymbol{\alpha} - \boldsymbol{F}\cos\boldsymbol{\alpha})/\sqrt{\boldsymbol{r}} \tag{2}$$

where it has been taken into account the reverse squared root dependence of Raleigh surface wave intensity from distance [4, 5]. If a sensor has to response on normal, or z, component of force $\boldsymbol{P}$ only, then it is necessary to project the force in Eq. (2) to z-axis. Allowed for (1), the result can be written as

$$\boldsymbol{P}_z = W\left(1 + \frac{k_F x}{h}\right)\frac{h^2}{r^{5/2}} \tag{3}$$

where the value of $k_F = F/W$ may be considered as a rolling friction coefficient. If the velocity V of a body is no more than about 10 m/s it is possible to consider this coefficient as a constant k_{F0}. As $\boldsymbol{V}$ is extended, this coefficient should be noticeably influenced. It is interconnected with internal friction in tyres and hysteresis effect in outer tyre layer as a case of motor car is considered. In the absence of wind it had been found empirically that

$$k_F = k_{F0}(1 + a_F V^2). \tag{4}$$

For asphalt-concrete road pavement $k_{F0} = 0.01 \div 0.02$, $a_F = (0.45 \div 0.7)\times10^{-4}$ [2]. But if it is a need to take into account wind influence then a value of k_F has to be modified. Namely,

$$k_{\mathrm{F}} = k_{\mathrm{F0}}(1 + a_{\mathrm{F}}V^2) + k_{\mathrm{W}}F_{\mathrm{W}}V^2/W = k_{\mathrm{F0}}[1 + (a_{\mathrm{F}} + k_{\mathrm{W}}F_{\mathrm{W}}\,/\,k_{\mathrm{F0}}W)V^2] \tag{5}$$

where $k_{\mathrm{W}} \approx 0.25$ is an air resistance coefficient, F_{W} is a mid-length section of the body. The product k_{W} F_{W} may be referred as a fairness factor. The multiplier in round brackets of (5) determines the velocity correction for the rolling friction coefficient. It can be found that the spherical body with unit mass has to possess of the mid-length section value

$$F_{\mathrm{W}} = \pi(3/4\pi\rho)^{2/3}$$

where ρ is specific gravity of a material of the sphere. In other cases, e.g., for a truck, $F_{\mathrm{W}} = BH$, where B is the wheel rut, and H is the height of the car. For heavy trucks – $F_{\mathrm{W}} \approx 7 \div 10$ m^2.

As the Raleigh surface wave propagates along the r from the point of instantaneous position of the moving body to the sensor with velocity V_{R}, it should be delayed in time on $t_{\mathrm{R}} = r/V_{\mathrm{R}}$. It may be necessary to take into account when a temporal scale of sensor is fixed. Therefore, "sensor time" t_{s} has to look as

$$t_s = (x - x_0)/V + (r - r_0)/V_{\mathrm{R}} \tag{6}$$

where $r_0 = (x_0^2 + h^2)^{1/2}$. Equations (3) - (6) may serve as a basis for modelling of sensor responses time forms initiated by a moving body. Certain results are presented in Figure 2 *a* with some variations of V.

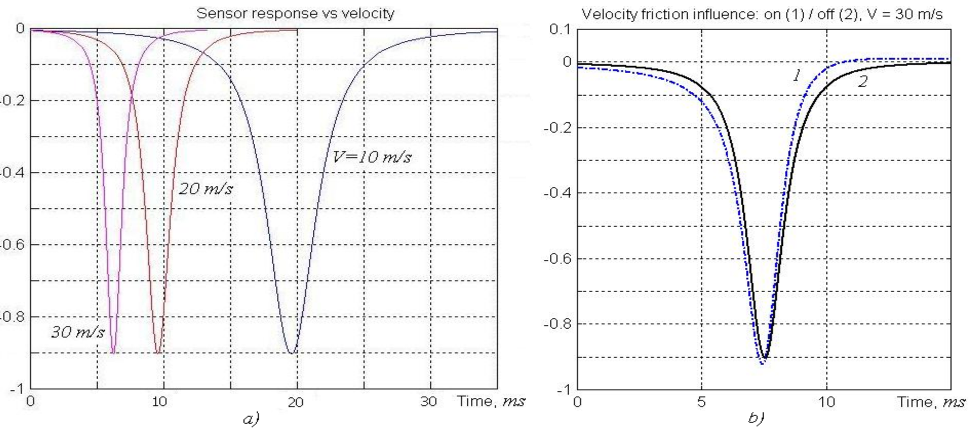

Figure 2. Influence of velocity on pulses forms: *a*) $a_{\mathrm{F}} = 0$, $k_{\mathrm{W}} = 0$; *b*) 1 - k_{F} has found from (5); 2 – friction is ignored

It should be noted that in accordance with Eqs. (1)-(5) the distance x and sensor time t_{s} (6) are in nonlinear relation due to second items in (4)-(5). It is especially significant in a region of small times.

As a rule, the exact value of Raleigh wave velocity V_{R} is unknown, since it is influenced by a concrete mix inside pavement upper layer. Most likely, it is about 400 ÷ 700 *m/s* [7]. It is seen from the right panel of Figure 2 that in accordance with (5), the growth of friction coefficient leads to some asymmetry of the transient pulse relative to maximum value of it. It depends on velocity V of motion. It is important that the maximum of this pulse is shifted with some lag s in the opposite direction relatively of motion vector. It is agreed with [2, 3]. Hence, this lag should be served as a measure of asymmetry, or a rolling friction coefficient again.

3. Seismic Pulse Excited by Tyre-Road Contact Footprint

The model described in the Section 2 has been derived for a solitary pulse excited by a unit point mass. For more complicated problem it would be considered as a certain Green's function. For instance, it is a need to search a response caused by motion of a finite-dimensional body with known distribution of load over the footprint on pavement boundary surface. This footprint would be held as a discrete dynamic array of Raleigh waves' sources [6]. The solution is reduced to modelling of interaction, or interference, of seismic pulses excited by different parts of the moving body taking into account the lags. Mathematically, it can be realised as Green's function de-convolved with some load distributed function.

In this paper, the one-dimensional normalized function

$$W_{\mathrm{M}}(x) = \begin{cases} \sin^{\alpha}(\pi x / 2x_{\max}), & x \in [0,\ x_{\max}] \\ \cos^{\alpha}[\pi(x - x_{\max})/2(l - x_{\max})], & x \in [x_{\max},\ l] \end{cases} \tag{7}$$

is proposed to descript the distribution above as a piecewise smooth approximation where l is the footprint length, x is the current coordinate along it. The index α in (7) has an influence on deceleration of the distribution $W_M(x)$ toward to the edges of a footprint. In common case it should be described by a certain two-dimensional function $W_M(x, y)$. Certain numerical modelling practice have been demonstrated that value of α would be within the bounds of $0.5 \div 2$.

The value of x_{max} in (7) is the position of maximum pressure, or maximum road reaction, or else a shift $s = x_{max}/l$. It is associated with friction coefficient (5) which depends on rolling resistance, car velocity, aerodynamic factors, wind vector etc.

Behaviour of distribution (7) under different α is illustrated on Figure 3 *a* , where the length of car tyre footprint in (7) is taken as $l = 0.4$ *m* with $x_{max} = 0.28$ *m*. It is conformed approximately to friction coefficient value nearly 0.3.

In order to simulate a seismic pulse form at the WIM sensor input it is necessary to convolve the unit pulse P_z represented by (3) with the suitable distribution (7). Namely,

$$P(x) = \int_{-\infty}^{\infty} P_z(x-\xi) W_M(\xi) d\xi \tag{8}$$

The results are plotted on Figure 3 *b*. Evidently, it is easy to evaluate the $P(x)$ as a function of time too.

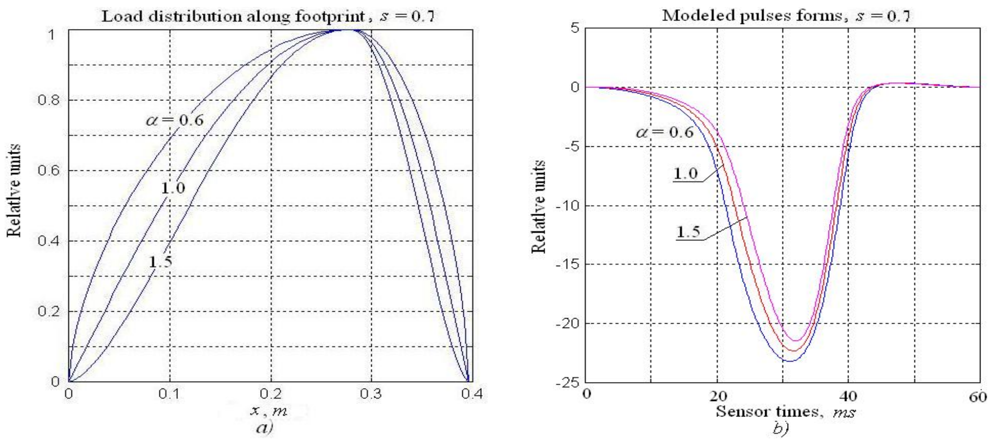

Figure 3. Road reactions and pulses forms: *a*) load distribution; *b*) deconvolution of *a*) with the pulse from Fig. 1 *a* (V = 10 m/s)

The curves on Fig. 3 are not contrary to proper graphs which had been given in some reference sources [2, 3] to explain nature of road reaction on a footprint contact at least in qualitative sense.

One should be seen that an axle point load $\boldsymbol{W}$ represented on Figure 1 is translated to a footprint as a nonuniformly distributed wheel pressure. If a wheel is in static position ($x_{max}= l/2$, $s = 1/2$), a pressure along footprint is described by a function (7), which is depended on tire elasticity forces depicted by certain *even modes* only.

On the other hand, as the wheel is in rolling motion along the axis x with some linear velocity $\boldsymbol{V}$ and angular velocity $\boldsymbol{\omega_w}$, some friction forces are added being caused by elements of a tire tread. Radial deformation of a tire is changed in time with a really complicated manner [2]. It is amplified in the tread front part, but it is reduced in the back of it. The maximum in (7) should be displaced due to friction forces from the footprint centre in the direction of motion in such a way as to $x_{max} > l/2$, or $s > 1/2$.

These reasons are reflected in (7) as the dominated *odd modes*. Evidently, named even and odd modes have to be observed in a resultant seismic pulse (8). It should be marked that any analytical definitions, neither of load distribution along a footprint, nor descriptions of these modes have not been discovered in accessible source of information.

It can suppose from previous discussion that the even modes generate due to car load, whereas the odd ones are a result of the road friction forces. Unequal contribution of these modes into an observed seismic pulse has an influence on the form of it acting as a symmetry-breaking factor. A numerical value of this factor would be served as a measure to odd modes and, consequently, friction forces. Thus, in WIM systems it should be given special consideration to even-odd modes extracting and processing.

4. Even-Odd Modes Decomposition of a Transient Pulse

This problem consists of two parts. Firstly, it is necessary to work out a procedure to decompose a seismic pulse into even and odd modes. The second part has to include an evaluation of a symmetry-breaking factor which would be in the best correlation with this pulse.

There are some methods to decide the first part of the task. The simplest way is as follows:

a) to invert the pulse $u(t)$ in time in order to obtain the auxiliary pulse $v(t)$;

b) to find the even and the odd components as

$$u_e(t) = [u(t) + v(t)]/2; \qquad u_e(t) = [u(t) - v(t)]/2. \tag{9}$$

Realization of that unsophisticated algorithm is extremely artless in every computing medium, including Matlab. But it suffers from serious disadvantage: resulting forms in (9) are depended rather noticeably from the choice of the origin point $t = 0$ in the function $u(t)$. In fact, this choice imposes virtually the position of a centre of symmetry, or the location of a maximum module point, for the even function $u_e(t)$ in (9). It leads to some uncertainties in estimations of $u_e(t)$ and $u_e(t)$.

The other opportunity to carry out the required expansion may be made based on the seismic pulse $u(t)$ presentation as a power-law series

$$u(t) = \sum_{n=0}^{\infty} a_n t^n . \tag{10}$$

In fact, an obtainable accuracy in estimation of coefficients a_n is restricted by potentialities inherent in the computer program employed. The result is

$$\tilde{u}(t) \approx \sum_{m=0}^{M} a_{2m} t^{2m} + \sum_{k=0}^{M-1} a_{2k+1} t^{2k+1} = u_e(t) + u_o(t) \tag{11}$$

where a maximally accessible number of the even coefficients a_{2m}, or M, is, as a rule, no more than several tens. For instance, proper Matlab routines allow a stable solution of Eq.(11) if only $2M < 40$.

As Eq. (11) is in work, it is convenient to reflect the refined signal onto a normalized compact carrier, e.g., $x \in [-1, 1]$. Some results have been demonstrated that in this case the choice of origin point in $u(t)$ is not so critical, and the power-law series decomposition is more preferable as compared with (9).

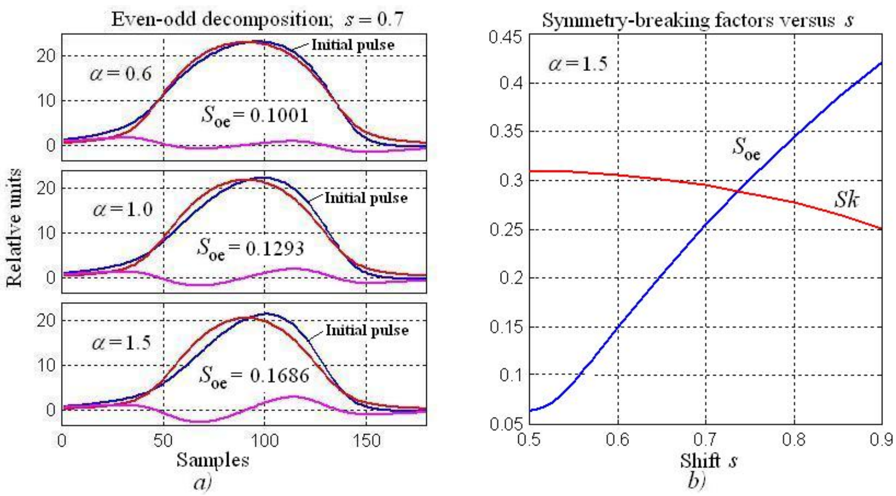

Figure 4. Some symmetry properties for modeled seismic pulses: *a)* influence of the road reaction form on even-odd decomposition results; *b)* dependence of the symmetry-breaking factors from the shift of road reaction maximum

Evidently, the even-odd decomposition outputs have to depend from the form of the pulse under operation. Figure 4*a* shows some results for the pulses from Figure 3*b*, which has to multiply by -1 to invert their signs for visuality. The original pulses are marked especially; shapes of even/odd components have no need any explanations. It is seen that sharpening, or faster drops of pulse edges towards the ends of the carrier domain, brings to growth of the odd component, and asymmetry is increased.

Now it is necessary to put into operation certain measures of asymmetry, or symmetry-breaking factors. A rather evident measure is the coefficient

$$S_{oe} = S_o / S_e \tag{12}$$

where S_o and S_e are the areas under curves describing the odd and even components, correspondingly. The values of it are indicated on Figure 4*a,* reflecting changes in road reaction forms. It has been determined that (12) demonstrates noticeable sensitivity to any pulse shape variations. As the convincing example, the substantial relation of the coefficient (12) with the shift s, or road friction, is deduced on Figure 4*b*.

Perhaps, some potential to estimate an asymmetry factor may be derived from representation of road reaction pulse shape as a probability density function f(x), or p.d.f., of a certain random process X. If it is consistent then the third central moment of p.d.f., namely

$$m_3 = \int_{-\infty}^{+\infty} (x-\mu)^3 \mathrm{f}(x) dx$$

would be computed where μ is the first central moment. The asymmetry coefficient, or skewness, is [8]

$$Sk = m_3 / \sigma^3, \tag{13}$$

where σ is a standard deviation of X. For discrete univariate data $x_1, x_2, ..., x_N$, the formula for skewness is:

$$Sk = \frac{1}{(N-1)\sigma^3} \sum_{n=1}^{N} (x_n - \mu)^3 \tag{14}$$

where N is the number of data points. The skewness for a normal distribution is zero, and any symmetric data should have a Sk near zero. Negative values for the Sk indicate data that are skewed left and positive values for the Sk indicate data that are skewed right.

By skewed left, the left tail is long relative to the right tail, and vice versa. Analysis of modelled pulse forms (e.g., Fig. 3 *b*) had displayed just the left tails in them. The module of the skewness (14) for modelled forms versus the road reaction maximum shift s is plotted on Figure 4*b*. It is seen the skewness shows rather weak sensitivity to pulse forms in comparison with the coefficient (12).

5. Some Experimental Results

The numerous experiments based on direct instrumental measurements of the seismic pulse responses in output of the optic fibre sensor have been carried out in WIM problem frames. As a function of weight and road conditions, a seismic pulse form has to depend on many factors. The experiment was executed for the two-axle truck with six-wheeler trailer. Velocities of the truck were selected from 20 up to 90 km/h. Experimental sensor responses were processed with certain computer codes in order to investigate some features of the pulse forms conformed to road reaction forces. Quality of symmetry has been examined too.

In particular, it had been ascertained that the left tails are predominant in these pulse shapes, as a rule. As it is determined above the skewness is not sufficiently sensitive measure to disturbances of pulse symmetry. Therefore, the relation (12) is more advisable to use as an asymmetry factor. It describes the ratio of areas under curves of the odd and the even components of a pulse investigated.

Some results are represented on Figure 5. The data used on Figure 5 are some arrays of observations. The ratio of areas S_{oe} (12) is displayed in it as a function of two variables: 1) truck velocity, 2) number of a wheel counted from truck front to back. The driving-wheels are signed as the wheels No 2.

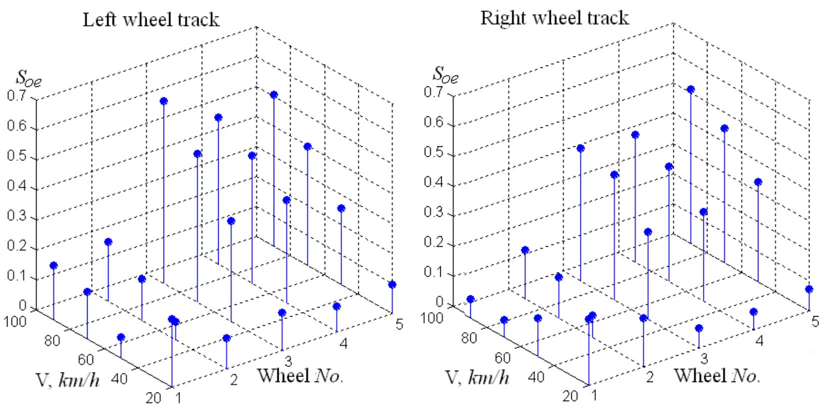

Figure 5. Two-dimensional representation of the relation (12)

The preview of Figure 5 detects some regularities in behaviour of these data: 1) most ordered data field is generated in truck trailer wheel domain (wheels No 3-5); 2) the coefficient S_{oe} (12) in that domain increases definitely as the truck velocity goes up; 3) as this velocity is constant then the values of (12) from the wheels with No 3-5 depend rather weakly; 4) the data for the driven wheel (No1) and the driving wheel (No2) display a certain disorder but the values of the coefficient (12) are noticeably smaller than it is observed for the back wheels.

If the modelled results from Figure 4*b* may be considered to be true then the conclusions above can be extended to influence of a road reaction to seismic pulse forms. In that case the data from Figure 5 would be considered as some preliminary estimates for friction forces exerting on truck motion.

6. Conclusions

In this paper, the model of seismic sensor excitation by automotive tyre footprint pressure is modified. It takes into account an influence of the motorcar and wind velocities to road friction forces. The model is displayed the temporal form of the pulse, which is described interference of Raleigh waves from different parts of a wheel footprint. Proclaimed structure of the model is not contrary to widespread ideas of a motorcar wheel interaction with a road pavement. The supposition is considered that asymmetry of seismic pulse forms has to be closely related with road pavement reaction. Some methods are proposed to measuring of symmetry-breaking factors. It is verified by modelling as well as natural experiments. The appropriate computing procedures have been realized in Matlab. Results of this work may be used in designing of WIM systems.

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