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IMPACT EXCITATION OF A SMALL-BURIED SUBSURFACED SEISMIC SENSOR

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The aim of this paper is to work out a model of small-buried seismic sensor transient response excited by an impact of a car tyre footprint pressed down to asphalt-concrete road pavement. It is supposed that a seismic wave perceived by the sensor is the vertical component of surface Raleigh wave. The algorithm is based on supposition that a tyre footprint is acceptable to consider as some array of point sources of these waves. The proposed model permits to vary different parameters of excited seismic pulses, as to footprint dimensions, load distribution along a footprint, motor car velocity and others. The set of Matlab codes for seismic transient pulses modelling and processing is worked out.

Keywords: weigh-in-motion system, tyre footprint, impact, road pavement reaction, sensor response modelling

1. Introduction

Economic situation in every country is visibly affected by range of automotive load transportation, and, therefore, by condition of road networks. In many respects degree of road deterioration is determined by traffic activity and gross weight of trucks with loads. In accordance with present standards, loading for a single axis of a motor car has to be restricting to some maximun allowable value. Exceeding of it draws proper sanctions. Very promising way to estimate the loading on certain axis is application of weigh-in-motion (WIM) systems [1]. There are many versions of WIM using small-buried subsurfaced seismic sensors mounted within road pavement [2, 3].

Output response of that sort of sensor is a time series of some non-stationary transient signals (or video-pulses). Their number is equal to the number of axes of the motor car which is positioned over the sensor at that time. At first sight all the pulses appear to be similar one another. However, some theoretical considerations, as well analysis of experimental data, demonstrate that certain delicate differences exist among them. For successful designing a WIM system the nature of these differences ought to be discovered and interpreted.

The aim of this paper is to work out an approach to filter individual differences in features of those pulses by digital signal processing methods. The algorithm is based on modelling of a small-buried seismic sensor response excited by forced impact of 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 .the top layer of pavement.

It is assumed the tyre footprint should to be considered as some discrete array of sources of surface Raleigh waves each with own exciting loading distributed along the footprint.. A signal created by interferences of these waves is received by the seismic sensor. If a sensor depth position (that is a distance of it from pavement top surface) and tyre footprint dimensions are assigned as some initial conditions the proposed model permits to:

a) vary the function which describes tyre contact pressure distribution along the footprint,
b) specify an automobile velocity,
c) match a rolling road resistance coefficient,
d) take into account of wind velocity component oriented along the road, etc.

Results of modelling are sensor response forms which ought to comply with conditions specified above. These forms may be used as a starting material for formulation of the target inverse problem namely estimation of loads on axes of a motor vehicle passed through WIM.

The organization of the paper is as follows. The problem discussed in Section 2 relates to calculating of a seismic pulse basic form excited by a unit point mass body moving with certain friction along a horizontal road. In Section 3 the model of a seismic pulse excited by tyre-road contact footprint is suggested. The tyre footprint is considered to be some discrete array of sources of surface Raleigh waves each with own exciting loading distributed along the footprint. In Section 4 some potentials of that model are demonstrated with examples. Features of Matlab programs worked out to illustrate resources of the models considered in this paper are briefly discussed.

2. Response on a Unit Point Mass Movement

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. 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 $t = 0$, $x = x_0$ to 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.

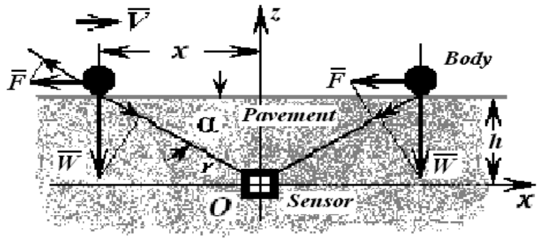

Figure 1. Excitation of seismic sensor by a unit point mass body movement

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

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

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 W and F.

It is seen from Figure 1 that projections of $\boldsymbol{W}$ would be alter 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 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

$$\boldsymbol{P}_z = \boldsymbol{W}\,(1 + \boldsymbol{k}_F\boldsymbol{x}/\boldsymbol{h})\boldsymbol{h}^2/\boldsymbol{r}^{5/2} \ , \tag{3}$$

where the value of $k_F = F/P$ may be considered as a rolling friction coefficient.

As the Raleigh surface wave propagates along the r from the point of instantaneous position of the moving body to the sensor it should be delayed in time on $t_R = r/V_R$. Temporal scale of sensor has to take it into account. Therefore, "sensor time" t_s has to look as

$$\boldsymbol{t}_s = (\boldsymbol{x} - \boldsymbol{x}_0)/\boldsymbol{V} + (\boldsymbol{r} - \boldsymbol{r}_0)/\boldsymbol{V}_{\mathrm{R}} \ , \tag{4}$$

where $r_0 = (x_0^2 + h^2)^{1/2}$. Equations (3) and (4) may serve as a basis for modelling of sensor responses time forms initiated by a moving body. Some results are presented on Figure 2 with some variations of k_F.

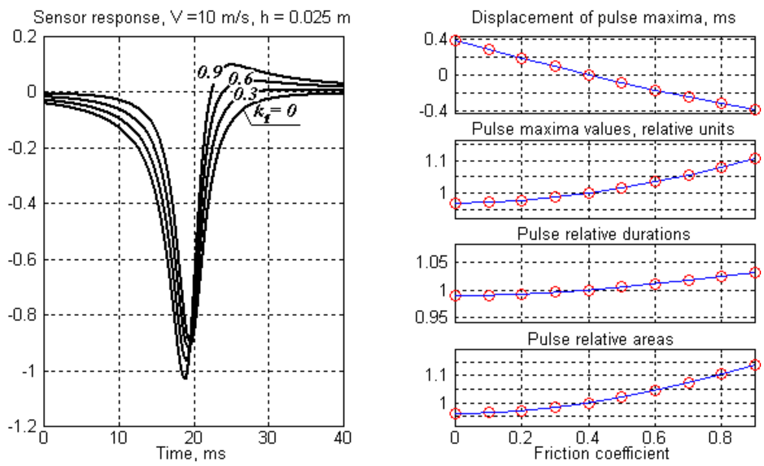

Figure 2. Pressures pulses forms versus rolling friction coefficients

It should be noted that in accordance with Eqs. (1) and (4) the distance x and sensor time t_s are in nonlinear relation due to second item in (4). It is especially significant in a region of small times.

The plots on Figure 2 represent the results of seismic wave propagation in asphalt-concrete road pavement. The exact value of Raleigh wave velocity is unknown but it perhaps is about $V_R = 400$ m/s [6]. It is seen from the left plot of Figure 2 that the growth of friction coefficient leads to certain asymmetry of sensor response with respect to maximum value of it. It is accompanied by increasing of pulse amplitudes, durations and areas. In the same time the maximum of the pulse is shifted with some lag in opposition to direction of motion.. These features are shown on graphs placed in right panel of Figure 2.

3. Seismic Pulse Excited by Tyre-Road Contact Footprint

The model described in the previous part permits to derive a seismic pulse form excited by a unit point mass. Essentially, solution of this task should be considered as a certain Creen's function. Hence, it may be used to find a form of response caused by motion of some finite-dimensional body with known distribution of mass along it. Such the solution is reduced to modelling of interaction of seismic pulses excited by different parts of the moving body taking into account the lags.

This approach may be conformable with the problem of seismic sensor response excited by forced impact of a car tyre footprint to road pavement. Unfortunately, any analytical definitions, neither of mass distribution along a footprint, nor normal component of road reaction on pressure acting, are not discovered in accessible reference sources. In this paper, the normalized function

$$\boldsymbol{W}(\boldsymbol{x}) = \begin{cases} \sin(\pi \boldsymbol{x} / 2\boldsymbol{x}_{\max}), & \boldsymbol{x} \in [0,\ \boldsymbol{x}_{\max}] \\ \cos[\pi(\boldsymbol{x} - \boldsymbol{x}_{\max}) / 2(\boldsymbol{l} - \boldsymbol{x}_{\max})], & \boldsymbol{x} \in [\boldsymbol{x}_{\max},\ \boldsymbol{l}] \end{cases} \qquad (5)$$

is proposed to describe the distribution above as a piecewise smooth approximation where l is the footprint length, x is the current coordinate along footprint. The value of $x_{\max}$ is the position of maximum pressure point. It is depended both on a car velocity and a rolling friction coefficient. That maximum is displaced from the point of footprint centre in the direction of motion of the car. The value of this shift would be associated with friction coefficient and depends on road rolling resistance, car velocity, aero-dynamical factors, etc.

However, the modelling practice have been demonstrated that more promised results have to take place with upgraded formulation of (5), namely

$$\boldsymbol{W}_{\mathrm{M}}(\boldsymbol{x}) = \boldsymbol{W}^{\alpha}(\boldsymbol{x}), \qquad \alpha < 1 \,. \qquad (6)$$

It has been established with numerical experiments that more pertinent values of α should be situated about 0.3 – 0.5. Behaviour of distribution (6) under different α with the regard for Eq. (5) is illustrated on Figure 3 where the length of car tyre footprint in (5) is taken as l = 0.3 m with $x_{\max} = 0.21$ m. It is conformed approximately to friction coefficient value nearly 0.3.

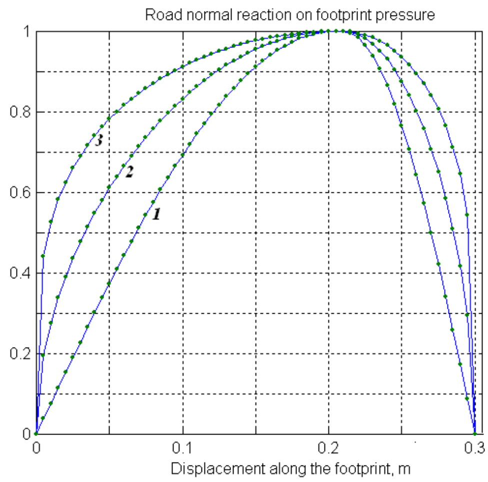

Figure 3. Supposed normal road reaction distributions: 1) $\alpha = 1$; 2) $\alpha = 0.5$; 3) $\alpha = 0.25$

The curves on Figure 3 are not contrary to proper graphs, which have been given in some reference sources (see, e.g., [7]) to explain nature of road reaction on a footprint contact at least in qualitative sense.

In order to calculate seismic sensor response initiated by a body with finite sizes it is advisable to replace the body by equivalent source of seismic wave in the form of some one-dimensional discrete array. The array is oriented in the direction of supposed motion of the body. It consists of well-defined number of point sources of surface Raleigh waves each with own exciting loading. These loadings are distributed along the body, for example, some footprint, in accordance with Eqs. (6) and (5). Every element of the array excites own Raleigh wave and makes contribution into summarized normal pressure component influenced on a sensor.

The described approach permits to find a sensor response on short-term impact under simultaneous contact of tyre footprint with a road pavement. Symmetric load distribution along the footprint is shown on Figure 4 above. The middle panel presents relative contribution into total pressure from different elements (i.e. footprint parts located along a road pavement surface) of an equivalent array.

It is supposed the sensor is situated on the depth h = 0.025 m from the surface. Coordinates along footprint are counted from sensor position (as x on Fig. 1).The reaction of sensor in those conditions is, in essence, the pulse response of the process in consideration. Such the response after normalization is plotted on Figure 4 below.

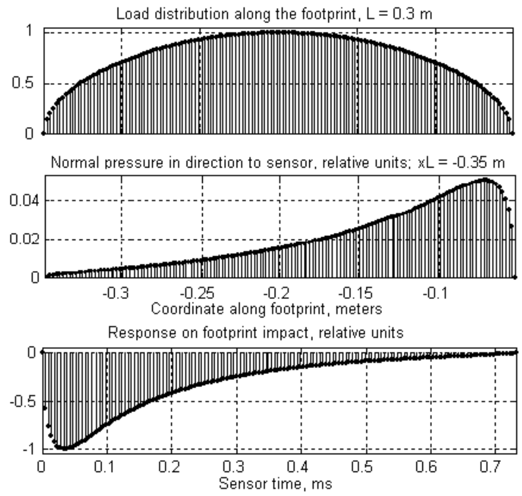

Figure 4. Pulse response initiated by tyre footprint contact with a road

It should be noted that natural experiment consisting in direct instrumental measurement of pulse response is rather difficult in realization. It is possible that computer modelling is only one the way to decide this problem by relatively inexpensive tools.

4. Variations of Seismic Pulse Forms

As a function of weight, a form of seismic pulse in WIM applications can be described by many features. Being realized as Matlab codes the models considered above allow to analyse relative influence of some factors on inherent structure of the pulse and pick out the most correlated with WIM aims. In computational sense, finding of a pulse form excited by a moving array with N elements reduces to calculation of some matrix. Every string in it is an elementary pulse. It is conformed to appropriately delayed motion of an individual element of the array (see Eqs. (1–4)). That matrix is

$$\boldsymbol{P} = \begin{bmatrix} \boldsymbol{P}_{11} & \boldsymbol{P}_{12} & \dots & \boldsymbol{P}_{1\mathrm{K}} & 0 & 0 & \dots & 0 \\ 0 & \boldsymbol{P}_{21} & \boldsymbol{P}_{22} & \dots & \boldsymbol{P}_{2\mathrm{K}} & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & \dots & 0 & \boldsymbol{P}_{\mathrm{N}1} & \dots & \dots & \boldsymbol{P}_{\mathrm{N,K-1}} & \boldsymbol{P}_{\mathrm{NK}} \end{bmatrix}, \tag{7}$$

where K is the prescribed number of array element positions, or shifts, along x-axis on Figure 1. Every string in (7) is completed by zeroes in start and finish points in order to equalize the lengths. Current position of the element P_{NK} determines the total length of any string. As sensor time t_s depends on x nonlinearly plain addition by columns in (7) is not correct to have the right response form. Certain interpolation for every string has to be done preliminarily using the Raleigh wave minimal arrival time h/V_{R} as the step.

As a sounding example of this method it may be applied to the problem of correlation of pulse form with footprint length solved by computational experiments. In order to correspond with (7) it has been supposed the seismic signal is formed by linear combination of some delayed pulses. Each from them is excited by proper element of discrete array, which is some equivalent of the footprint. The vehicle velocity and position, or shift, of loading centre is treated as the constants. Results are shown on Figure 5.

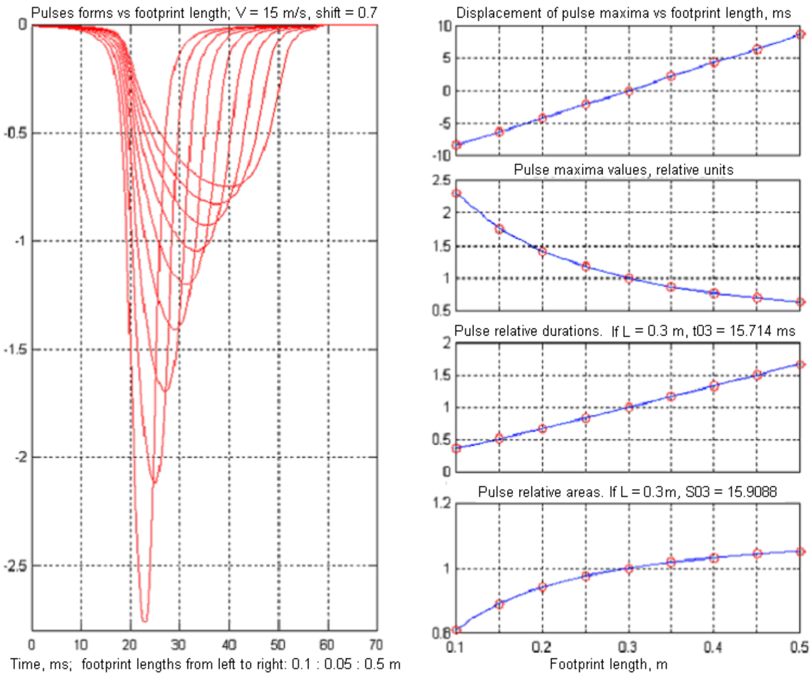

Figure 5. Forms of pulses vs footprint lengths

In particular, it is seen from the right panel of Figure 5 that duration of the pulses depends on footprint length rather linearly. This fact may be used in designing of WIM systems.

5. Conclusions

In this paper, the model of seismic sensor excitation by automotive tyre footprint pressure is suggested. It is based on replacement of a footprint by certain discrete array considered as an equivalent source of a transient seismic signal. It has been displayed, the temporal form of that pulse is described by a matrix reflected the interference of waves from different parts of the array. The appropriate computing procedures have been realized in Matlab. These forms may be used as a starting material for formulation of the target inverse problem in designing of WIM systems namely estimation of loads on axes of a car.

Acknowledgements

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