COMPUTATIONAL CONTINUUM MECHANICS

ВЫЧИСЛИТЕЛЬНАЯ МЕХАНИКА СЛОШНЫХ СРЕД

Computational Continuum Mechanics. 2021. Vol. 14. No. 1. pp. 91-101 DOI: 10.7242/1999-6691/2021.14.1.8

ANALYSIS OF SEISMIC VIBRATIONS EXCITED BY A MOVING RAILWAY CONSTRUCTION

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The paper presents a theoretical analysis of seismic vibrations generated by a fast moving train. The possibility of using seismic vibrations of a technogenic nature, created by the vehicle itself and recorded by the equipment used in seismic exploration of the subsoil, to detect and localize areas of the geomedium under the tracks and in its vicinity, prone to karst phenomena, where the risk of accidents is increased, is investigated. The main physical mechanisms for the excitation of seismic waves traveling along the free surface and going deep into the earth are listed. The main attention is paid to Rayleigh surface waves, which dominate at small and medium distances from the path at frequencies up to the first tens of hertz. The calculation of the spectrum of the surface Rayleigh wave, prevailing in the seismic response recorded at the indicated distances, has been performed. The amplitude-frequency characteristics and their dependence on the speed of movement, on the difference in the speed of propagation of elastic waves in the sedimentary strata are considered. The graphs of the seismic wave response spectrum at several values of the velocity of movement and parameters of the upper layer of the sedimentary strata are shown as a relief on the plane of arguments: frequency - distance along the perpendicular. The effect of the frequency dispersion of the velocity of propagation of surface waves in a layered structure under the mainline on the spectrum of the wave response is analyzed. The characteristic features in the relief, depicting the spectrum in two-coordinate representation, are considered as informative features that are laid down in the algorithms for monitoring the layered structure of the soil, as well as the basis for the operation of diagnostic systems for local anomalies caused by karst phenomena under the highway.

Key words: seismic vibrations, wave excitation, elastic half-space, moving vibration source, lower structure of the railway track, ground monitoring

1. Introduction

Currently, increased interest is shown in the study of seismic vibrations created as a result of dynamic impacts on the earth's surface by a train moving along the tracks at a speed of 30-50 m/s. The rapid movement of a constant thousand-ton load along the free surface is accompanied by the response of the generated quasi-static deformation field, the leading edge of which moves synchronously with the load and causes shaking and high-intensity vibration not only of the upper and lower structures of the railway track, but also of the adjacent infrastructure (structures, buildings, traffic lights signaling, electrification system and all kinds of communications that ensure the conditions and normal operation of the railway). The contact interaction of wheels with rails is a source that causes intense shaking of the roadbed, which is difficult to extinguish at distances close to the track. In this case, technogenic disturbances excited at infrasonic frequencies propagate further along the earth's surface and deep into the soil in the form of seismic waves (ground vibration). The analysis of seismic waves emitted by a rapidly moving complex source formed by a multitude of elementary ones connected in a long chain, and an adequate interpretation of the spectrum of the resulting seismic response are the subject of this work. Based on the results obtained, a prerequisite for solving the problem of reducing the level of vibrations and eliminating their negative consequences is created. Monitoring and diagnostics of violations due to natural influences on the entire complex that forms the railway track is facilitated.

Numerous studies can be divided into two parts. Some of them are aimed at finding ways to create "barriers" that screen the propagation of elastic waves along the ground generated by a train moving rapidly within densely populated areas [1, 2], others are devoted to monitoring the roadbed and sediment in the soil near the track and are related to diagnostics of possible anomalies (sinkholes, voids of karst origin, zones with low bearing capacity of the soil directly under the tracks) [3–6]. The specified direction is also of interest in the framework of this work. At the same time, it should be noted that in the territories covered by the railway network, careful systematic control is carried out on an ongoing basis through engineering seismic survey, which is associated

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with the need to comply with the conditions for the trouble-free operation of the rolling stock of railway transport, to eliminate the risks of emergencies due to untimely response to the negative impact of natural factors that can cause failures in the operation of transport infrastructure (rail track, technical devices for ensuring traffic, etc.). However, along with traditional methods of engineering seismic prospecting, which make it possible to monitor the state of the railway track, it is also possible to use for these purposes our own seismic fields generated by a moving train, which implies the registration of the corresponding seismic responses and requires a thorough study of their characteristics. A number of works are devoted to this matter, in which the results of the analysis of seismic vibrations and deformations of the structure of the medium observed when the train moves under the track, near the track and in some of its vicinity are presented. The fixed responses are characterized by a wide frequency band. The limit at the bottom corresponds to "a few seconds", and at the top - to a few tens of hertz. On evaluating the data obtained, it is usually concluded that for diagnostics and identification of localization sites of the most "weakened" soils, low-frequency signals of the first tens of hertz and even lower (~ 0.5 Hz) have the maximum information content.

At the same time, it is obvious that the signals correspond to the region of the near, non-wave zone of non-radiated oscillations created in the medium under the source and in the immediate vicinity of it. A similar "low-frequency" region with the involvement of impedance characteristics has its own analogue used in acoustic flaw detection. Similar studies on the deformation field of the medium at frequencies close to the above are also carried out in studying phenomena associated with the interaction, for example, the foundation of a structure with the enclosing soil mass under seismic impacts of natural earthquakes, for which modern computational methods and tools are used [7].

The problem of calculating the field of deformations that appear not under the influence of radiation, that is, not carrying away energy from the source, but caused by a moving (oncoming) constant load distributed along the boundary of a semi-infinite strip, is considered in [8] (two-dimensional case). Its solution, as well as the results from the publications listed above, are of interest in the formulation of features that need to be taken into account for remote diagnostics of local inhomogeneities in the bulk soil mass under the tracks.

In this work, the main focus is on the spectral characteristics of seismic wave responses at frequencies above 0.5 Hz radiated and carried away energy away from a rapidly moving oscillation source, and their features are supposed to be used as the basis for creating algorithms for the operation of environmental monitoring devices under railway tracks.

2. Problem statement. Explanation of approaches to the solution

To analyze the spectral composition of seismic waves, one should determine the main sources of wave excitation. The reasons for the emergence of variable forces localized at the wheel-guide contact have already been considered earlier [9-12], therefore, limiting ourselves to only mentioning the main ones, we then turn to the theoretical analysis of the characteristics of elastic wave fields of the prevailing level propagating near the earth's surface.

Let us outline several dominant physical mechanisms leading to the appearance of a force reaction, which is a source of excitation of seismic vibrations. In terms of importance, the prevailing ones are: oscillations of the center of the car mass of noticeable amplitude along the vertical, generated during its translational motion due to incomplete damping in the suspension system (springs) (1st mechanism); similar longitudinal-axial vibrations of the center of the car mass (2nd mechanism); self-oscillating mode of returnable lateral, in other words, perpendicular to the car body (along the traverse), displacements of the wheelset (and the carrier bogie) within the standard permissible interval - gap between the rail and the flange on the wheel rim (3rd mechanism). Its simplified model can be a continuous (without slippage) rolling of a heavy polished sphere along a rectilinear polished groove, laid on the boundary of an elastic half-space, with a constant average speed, but with "yaw or wobble" along the course. Due to lateral cyclic or return movements accompanying rolling with a constant (on average) axial velocity, a variable force acts on the walls of the groove (and the opposite reaction force returns the deflected ball to the longitudinal axis), while surface and bulk waves are excited in the half-space surrounding the groove. Figure 1 shows diagrams illustrating the above-mentioned physical mechanisms of variable force action on the ground and the radiated waves of the prevailing level are conventionally designated. The arising quasi-periodic oscillating force effects on rails and sleepers (accompanied by their deformation) are transmitted to the bulk (gravel or crushed stone) cushion and further to the underlying soil and excite seismic waves that are formed and propagate deep into it and along the earth's surface.

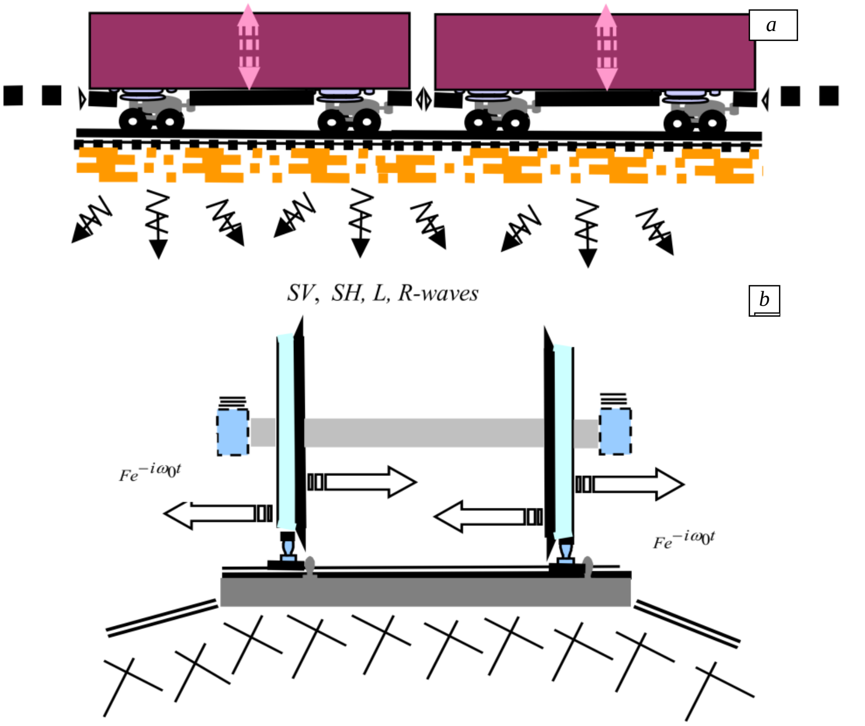

Fig.1. The scheme of the impact on the ground and the waves prevailing in the radiation during the oscillation of the center of the car mass (a), during the return lateral (traverse) displacements of the wheel pairs (b).

Due to the fact that seamless joining of rails is widely used on modern railways, the article does not further mention seismic vibrations caused by the passage of a wheel along the weld between the rails. It should be noted that the analysis of seismic vibrations is becoming most requested in the case of swampy areas (with weak loose soils, where the wave velocity of propagation is $c_R = 150...250$ m / s) and in connection with the increasing speeds of transport ($V \approx 50$ m / s), at which the Mach number reaches values of $\sim M = V/c_R = 0,3$, and seismic radiation turns out anisotropic and acquires a pronounced directionality. Variable loads arise during the translational movement of the train, and each car (or wheelset) is a discrete source of seismic radiation. A railway train in the form of wagons connected in a chain forms a multi-link seismic source. To assess the maximum achievable level of the useful signal, the assumption is used that the oscillating force effects are in-phase (coherence) along the chain of discrete sources as the most preferable in comparison with the model of independent sources, and in relation to all the above mechanisms. In this case, there is a synchronous oscillating effect of sources on the flat boundary of a continuous medium, moving translationally at a speed at which the Mach number is noticeably different from zero. The Doppler shift caused by the movement of the train (as a whole) disrupts the in-phase of the waves going to the receiver from each elementary source, which leads to a decrease in the level of the total signal and an expansion of the frequency band of its spectrum.

A general analysis of the excitation of seismic waves of various types (natures) in relation to moving sources of different types was carried out earlier [9, 10]. In particular, seismic waves generated by vehicles moving along highways have been studied theoretically and experimentally. There is some commonality in the mechanisms of excitation, but there are also significant physical differences that determine the features of the wave characteristics corresponding to railway transport. One of the main mechanisms is the "technologically flat" rail surface, in contact with which the car wheel rim is located and which allows reaching the level of seismic vibrations caused by the irregularities of the rail contact surface, which is minimal in comparison with the excitation on the irregularities (micro-profile) of the road surface. In addition, the train, if compared with a vehicle, is characterized by a significant excess by several orders both in mass and in linear dimensions. Air-acoustic noise caused by flexural deformations of cars during train movement can also contribute to the seismic response. All these differences cause different spectral and wave composition of seismic vibrations.

3. Derivation of design ratios

Referring to the general characteristics of seismic radiation generated by the physical mechanisms described above and taking into account the results of previous studies, it can be noted that in the case of the 1st and 2nd mechanisms, seismic responses will appear in the range of several hertz, moreover, in the form of surface R and L -waves and volumetric transverse SV and SH -waves (the contribution of longitudinal waves is insignificant). Oscillatory reciprocating lateral displacements of wheelsets together with bearing bogies when acting on rails also represent an oscillating shear source of body and surface waves (3rd mechanism). The seismic responses corresponding to it (conventionally) fall into the frequency interval up to ten - twenty hertz. The waves generated by this mechanism are likely to dominate the entire set of recorded responses against the background of microseisms from the distances closest to the roadbed and up to several hundred meters from it.

According to the above, further discussion concerns the surface Rayleigh waves excited by the 3rd physical mechanism. Conditions are assumed in the form of flat terrain and straight sections of track with rails laid along a low embankment. Therefore, in the analysis and quantitative assessments, one should turn to an approximate (semi-empirical) approach, in which the real substructure (subgrade) is modeled as a homogeneous half-space with a flat upper horizontal boundary. The calculation of the spectral amplitude of the seismic response (in the laboratory system associated with the receiver) due to the aggregate source is performed using wave displacements in the surface Rayleigh wave. In this case, the wave is generated at the boundary of a homogeneous elastic half-space by a moving elementary source of variable force, oscillating at a frequency ω_0, and has horizontal polarization perpendicular to the motion of the source. When deriving the calculated relations, taking into account the above simplifications, the formulas obtained in [9, 10] are used, which describe the elastic vertical displacements of particles at the free boundary $z = 0$ in a Rayleigh wave excited by a moving source. In principle, the same apparatus can be applied to the surface Love wave [11], taking into account the fact that its amplitude maximum is oriented in the longitudinal direction, that is, it is parallel to the main line and coincides with the direction of the velocity vector, as well as to body waves going deep.

Since the spectral (and angular) characteristics of the wave (dependence on the frequency at the receiving point) are of interest, the numerical coefficients taking into account the amplitude of the variable shear force (horizontal polarization in the direction perpendicular to the motion) and the parameters of the density and elasticity of the medium in the formula for vertical wave offsets are omitted. Thus, the following "shortened" expression is used for the calculation:

$$u_{zj}^{Rayl}\Big|_{z=0} \sim \sqrt{\frac{\omega_0}{r_j\left(1-\left(V/c_R\right)\cos\varphi_j\right)}}\sin\varphi_j \exp\left(-i\frac{\omega_0\left(t-\left(r_j/c_R\right)\right)}{1-\left(V/c_R\right)\cos\varphi_j}-\frac{\omega_0\Theta r_j}{2c_R\left(1-\left(V/c_R\right)\cos\varphi_j\right)}\right)$$

Here: c_R - speed of the Rayleigh wave; V - speed of translational motion of the source; Θ - damping (absorption) decrement of the Rayleigh wave; $r_j = \sqrt{h^2 + x_j^2}$, $x_j = j \cdot d$, where d is the conditional distance between the "emitting links", h is the distance between the railway track and the receiver located abeam; $\sin\varphi_j = h \big/ \sqrt{h^2 + x_j^2}$, where j is the summation index numbering the links along the length of the chain from $-L$ to L, while L is the length of that part where the excess of the useful signal over microseisms is achieved, and it is also assumed that the frequency ω_0 of the prevailing oscillations in each elementary source is known (see Fig. 2).

Note that, in order of magnitude, the amplitude of the oscillatory action of the force F on the rails from the moving source reaches the order of $\sim 10^3\,\mathrm{N}$, (where is the number of elementary sources in the chain). This remark is of interest when searching for and clarifying the conditions for reducing the technogenic seismic or vibration impact on the surrounding infrastructure.

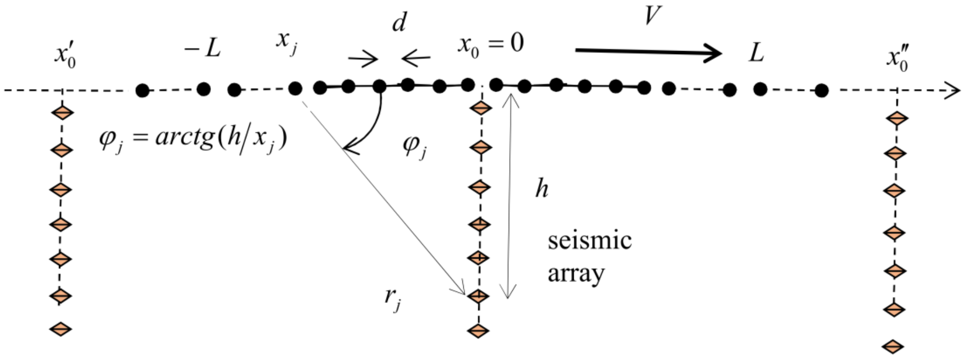

Fig.2. General schematic view of a multi-link source and a receiving seismic spit; ●●- a source link (car), ◈ - a spit element (receiver).

We will consider a coherent multi-link source (composition) with in-phase force effects along its length at a time moment that corresponds to its symmetrical location relative to the central registration line, perpendicular to the mainline. Seismic receiver systems like streamer are installed on several of these lines. Of interest is the time t dependence of the spectral characteristics of the signal in the region at a distance h from the receiver. In this case, for the total seismic response at the free boundary in the form of Rayleigh surface waves generated by a train moving at a speed along the highway past the streamer, it is easy to write the following expression:

$$U(t) = \sum_{j=-L}^{L} \frac{\sqrt{\dfrac{(\omega_0 h/c_R)}{\left(1-(V/c_R)\cos\phi_j\right)}}}{\sqrt[4]{\left(1+\left(x_j/h\right)^2\right)^3}} \exp\left(-i\frac{\omega_0\left(t-(h/c_R)\sqrt{1+\left(x_j/h\right)^2}\right)}{1-\dfrac{(V/c_R)\cdot\left(x_j/h\right)}{\sqrt{1+\left(x_j/h\right)^2}}} - \frac{\omega_0\left(\Theta h/2c_R\right)\sqrt{1+\left(x_j/h\right)^2}}{1-\dfrac{(V/c_R)\cdot\left(x_j/h\right)}{\sqrt{1+\left(x_j/h\right)^2}}} \right)$$

Summation is assumed only for the part of the chain of the total length $2L$ at which the useful signal exceeds the level of microseisms. The length of this part in the accepted conventional units due to the two support bogies that fall on the length of the car is equal to half the length of the car. When writing the formula for the total response, the Doppler frequency shift that occurs in the radiation of an elementary source in a moving composition and comes to the receiver from each of them is taken into account.

The superposition of the contributions of all sources is performed by passing to the dimensionless variables $\zeta = h/d$, $\tau = c_R t/h$, $\varpi = \omega_0 d/c_R$, $\omega_0 h/c_R = \varpi\zeta$ (ω_0—the frequency of oscillations in the system associated with the source) using the replacement of discrete summation by j integration by $\xi = x_j/d$, which is an idealization that simplifies the calculations. Taking this into account, we come to the following entry for the total response:

$$U(\tau,\zeta)=\int_{-L}^{L}\left(\left(\sqrt{\varpi\zeta\Big/\left(1-\frac{M(\xi/\zeta)}{\sqrt{1+\xi^2/\zeta^2}}\right)}\right)\Big/\left(\sqrt[4]{\left(1+\xi^2/\zeta^2\right)^3}\right)e^{\left(\left(-i\varpi\zeta\left(\tau-\sqrt{1+\xi^2/\zeta^2}\right)\right)-\varpi\zeta(\Theta/2)\sqrt{1+\xi^2/\zeta^2}\right)\Big/\left(1-\frac{M(\xi/\zeta)}{\sqrt{1+\xi^2/\zeta^2}}\right)}\right)d\xi$$

where $M = V/c_R$.

When calculating the signal spectrum, it is assumed that the levels of the detected useful signal and microseisms when the middle of the composition passes the registration line they are in a certain relative ratio (with the maximum level on the traverse exceeding the microseisms by several times; then 20 dB is assumed), which, in addition to the decline in wave propagation, limits the duration the "audibility" of the useful signal (against the background of noise), and therefore, is included as a determining factor in the spectral relations calculated further. The level of microseisms depends on the weather conditions, and the level of the useful signal depends on the degree of congestion of the cars in the train. The spectrum of the total signal is calculated as its Fourier transform at the time interval (symmetric with respect to zero due to the uniformity of motion), at which the signal exceeds the level of microseisms:

$$S(\nu,\zeta)=\int_{-L}^{L}\frac{\sqrt{\varpi\zeta\Big/\left(1-\frac{M(\xi/\zeta)}{\sqrt{1+(\xi/\zeta)^2}}\right)}\sin\varpi L\left(\nu-1\Big/\left(1-\frac{M(\xi/\zeta)}{\sqrt{1+(\xi/\zeta)^2}}\right)\right)}{\sqrt[4]{\left(1+(\xi/\zeta)^2\right)^3}\left(\nu-1\Big/\left(1-\frac{M(\xi/\zeta)}{\sqrt{1+(\xi/\zeta)^2}}\right)\right)}e^{\left(-\varpi\cdot\zeta\cdot\Theta\sqrt{1+(\xi/\zeta)^2}\right)\Big/\left(2\left(1-\frac{M(\xi/\zeta)}{\sqrt{1+(\xi/\zeta)^2}}\right)\right)}d\xi \quad (1)$$

where $\nu=\omega/\omega_0$, $\varpi=\omega_0 d/c_R=1$ ($f_0\approx 1...20$ Hz, $\varpi L\approx\frac{2}{\Theta}\ln\left(\frac{u_0}{u_{micr}}\right)$). The expression (1) determines the frequency drop in the response spectrum. In addition, it includes as a parameter the ratio of the signal level in the maximum u_0 to the signal level of the microseims u_{micr}, which sets the "effective length" of the part of the composition: $L\approx\frac{2}{\varpi\Theta}\ln\left(\frac{u_0}{u_{micr}}\right)=\frac{20}{\varpi\Theta\cdot 4,36}\lg\left(\frac{u_0}{u_{micr}}\right)$, discrete elementary sources of which create a useful signal on the sensors at points on the central line of registration (if it coincides with the center of the composition) with a level exceeding the level of microseisms by a specified amount.

4. Spectral amplitudes of signals

The results of calculating the spectral amplitude $S(\nu,\zeta)$ when the midpoint of the composition coincides with the central line of registration are shown in Fig. 3. One half of the elementary sources corresponds to a positive frequency shift, and the other half corresponds to a negative one. Therefore, the spectrum of the total signal has a distribution relative to the central traverse that is close to symmetric. The effect of increasing the speed of translational motion, at which the Mach number $M = V/c$ takes the values $M = 0,1$ (Fig.3a) and $M = 0,3$ (Fig.3b), is considered. The spectral amplitude is represented by a two-dimensional relief as a function of two arguments, one of which is the dimensionless frequency ν in the spectrum of seismic vibrations of the receiver, normalized to the central frequency ω_0 of the oscillations (measured in the system of the source itself). Another argument is $\zeta = h/d$ the distance h from the receiving point to the railway track along the traverse line, also normalized by the "link length" d. The cross-section of this relief at some ζ is the amplitude spectrum of the total seismic response at a fixed distance from the highway. The relief representing the spectral amplitude is presented in relation to a medium with a low value of the attenuation decrement, namely $\Theta = 0,2$, at the ratio $u_0/u_{micr} = 20$ dB. The maximum in the frequency distribution of spectral amplitudes is reached at a small distance ($h \sim 35...50$ m) from the main line, after which, as the registration points move away from it, the amplitude level decreases. The frequency bandwidth also narrows when the registration points are removed, which is due to the competing influence of the wave excitation factor and the wave dissipation factor during propagation.

4.1. Accounting for the dispersion of the surface wave propagation velocity

The spectral characteristics described above, calculated under the assumption of the simplest model of a homogeneous continuous medium with a flat boundary, must be transformed due to the fact that the real structure of the underlying soil thickness is more complex because it has a layered character. The need to take into account the complicated structure also meets the initial goal — to analyze the possibility of detecting signs in the wave response (or in its spectrum) that indicate the presence of heterogeneity. Consider the simplest case in which the inhomogeneity is a layer covering a homogeneous half-space with an underlying medium. The layer parameters differ from the underlying environment. In typical flat conditions, an elastic layer lying on an elastic half-space is characterized by a reduced density and velocity of propagation of transverse waves relative to the underlying medium. In such a structure, the surface wave becomes "quasi-Rayleigh", that is, a set of wave modes arises, the branches of which originate at critical frequencies (if we resort to estimated calculations): $f_n = (c_{t1}/2\pi h)(n)$, where c_{t1} is the velocity of the shear waves in half — space. At low frequencies adjacent to zero and extending to the next number in order, the first mode is excited $n = 0$; at higher frequencies, modes with increasing values *n* gain an advantage in amplitude. Taking as an example a layer with a thickness of $h = 3$ m, at a shear wave velocity of $c_{t1} = 200$ m/s, we obtain as a frequency interval in which only the first mode is excited, and the higher modes are not present, the following value: $\Delta f \cong 0...20$ Hz. The specified interval presumably corresponds to the first-fundamental mode of surface waves of the Rayleigh type and the physical mechanism of vibration excitation of the ground considered here. On the graph of dispersion curves-the dependence of the phase velocity on the frequency, this mode is represented by a branch falling from $c_{\max}$ at $f = 0$ to $c_{\min}$ at $f \to \infty$.

To account for the effect of dispersion in the medium, the following simplest approximation of the propagation velocity dependence c_R, now expressed in relative frequencies ν, is proposed:

$$c_R(\nu) = \hat{c}_R - \Delta c \frac{2}{\pi} \operatorname{arctg} \nu = \hat{c}_R \left(1 - \frac{\Delta c}{\hat{c}_R} \frac{2}{\pi} \operatorname{arctg} \nu\right) = \hat{c}_R \left(1 - \beta \cdot \operatorname{arctg}(\nu)\right), \ \beta \le \frac{2}{\pi}, \qquad (2)$$

where $\hat{c}_R = c_{\max}, \Delta c = c_{\max} - c_{\min}$ is the difference in the values of the phase velocity of surface waves at low and high frequencies of the dispersion curve of the first mode, which is used in calculating the spectral amplitude when substituting expression (2) for $M = V/c_R(\nu)$ in formula (1).

The magnitude of the phase velocity decline with increasing frequency varies by the choice of the parameter β, and an increase in its value corresponds to an increase in the contrast of shear elasticity in the layer and the underlying half-space, and by $\beta = 0$ – the transition to the previously considered case of the absence of velocity dispersion in the wave, when the medium does not contain a subsurface boundary and a layer. Further studies are expected to identify and analyze signs of the presence of surface inhomogeneities that are not infinitely extended, but rather limited laterally – in the directions along the railway track.

Fig. 3c shows a relief that shows the two-dimensional dependence of the spectral response amplitude $S(\nu,\zeta)$ in the presence of dispersion in the surface wave and corresponds to the case of the movement of the composition with an increased speed ($\hat{M}=0{,}3$, $V\approx 50$ m/s, $\hat{c}_R\approx 150...200$ m/s). It is easy to see that in this case, a local side maximum is formed in the terrain area that corresponds to the distance close to the highway, which is then replaced by a sharp maximum of the prevailing level. With an increase in the contrast of elastic parameters, as well as with an increase in the speed of movement at distances close to the highway, the frequency band expands and the spectral amplitude increases in it, leading to the formation of a side maximum. This transformation is explained by the Doppler shift of the frequency of the spectral amplitudes. There is interference and redistribution of components that occur at both lower and higher wave propagation speeds. The formation of a local maximum is a distinctive feature of the movement of a multi-link source at an increased speed along the boundary of the medium with the layer and indicates a difference from the already considered case of movement along the boundary of a homogeneous medium. The presence of local maxima is one of the diagnostic signs of the layered structure. Note that such a maximum in this part of the spectrum is not formed when moving at low speeds, including in the presence of dispersion at the wave velocity.

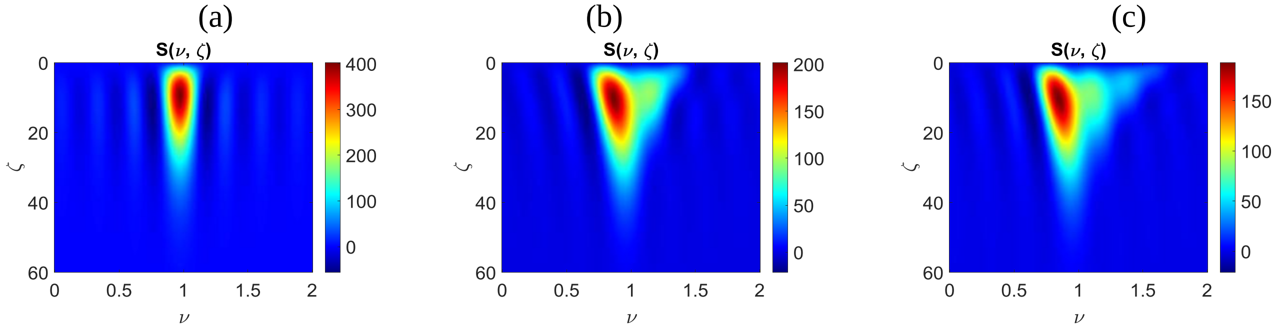

Fig. 3. The spectral amplitude $S(\nu,\zeta)$ of the seismic responses recorded at the central traverse lines at $\Theta=0{,}2$, $\varpi=1$, $u_0/u_{micr}=10$ and different values of the Mach number M and parameter β: $M=0{,}1$, $\beta=0$ (a); $M=0{,}3$, $\beta=0$ (b); $M=0{,}3$, $\beta=0{,}3$ (c).

In experimental studies on ground vibration generated under field conditions during the movement of a railway express train at a speed of 300 km / h, the integral level of vibration (vertical vibrations) of the ground surface was recorded [6]. The integral level of the signal with an increase in the distance from the path to the receiver is mainly characterized by a decline, with the exception of a local rise and a maximum (in the interval $15...30$ m), followed by a further decline with the distance from the path of the measuring points. When describing the experimental results, as a rule, there is no data on the features in the distribution of spectral components over frequency, in contrast to the demonstrated level dependence, which does not allow us to compare them with the obtained theoretical ones. The further decline in the level after the local maximum is explained by the predominance of the near field of vibration and deformations accompanying the moving load. However, the presence of the above-mentioned local maximum observed in the experiment can be explained by the dominance of the contribution of surface waves in the seismic response over a certain range of distances under conditions of "high-speed" movement, which confirms the theoretical justification outlined above. At the same time, the image of the spectral amplitude in the form of a relief on the plane of two variables ν, ζ allows us to consider in more detail its frequency dependence at different distances, which is important for diagnosing the presence of a subsurface boundary. In particular, according to the estimates of the data from Fig. 3, the maximum of the spectral amplitude should be reached at a distance from the main line $\zeta=7...15$ ($h\sim 35...50$ m). The theoretical value of the distance interval, which is more significant than the experimentally observed one, is associated with an underestimated value of the wave attenuation decrement taken as an estimate. The use of the assumption of a single excited Rayleigh wave and the coherence of the vibration sources also leads to the fact that the presented mathematical model does not fully describe the vibration response of the ground in the problem of wave excitation.

4.2. Seismic response spectra in front of the approaching and leaving railway construction

The results presented above correspond to the response recorded in the steady-state mode of translational uniform movement of an extended multi-link source, and its reception is performed at the moment when the sensor line intersects with the midpoint along the length of the train. As already mentioned in section 1, the approach and crossing by the head of the moving train of the boundary of the "undisturbed" area of the highway and its vicinity causes transients processes in the near field of deformations of the soil environment and leads to specific effects.

Similar features should be expected in seismic radiation, so it is interesting to perform a comparative analysis of the spectral characteristics of seismic responses when registering in three cases: at points on the line preceding the arrival of the head part of the train through the point x_0''; when the point in the middle of the length of the train coincides with the central line with the coordinate x_0; behind the tail part of the train, which corresponds to the point with the coordinate x_0' (see Fig. 2). In the case of a single source (a local object of motor transport), a similar analysis was previously performed in [12].

Next, we present two-dimensional reliefs of the amplitude spectra of the signals recorded in the three specified situations, which in practice can be simplified by using two spatially spaced braids.

The calculation of the amplitude spectrum for these cases is performed according to the formula (1) for the receiving line on the traverse $x_0 = 0$, as well as for the lines shifted to the left ($\xi' = x_0'/d = 30$), or to the right ($\xi'' = x_0''/d = 30$). Such parameters are selected to place the receiving array beyond the zone of the “audibility”of the useful signaland outside the length of the train: both in front of the head and behind the tail part of it.

The spectra of the signal generated by a train moving along the boundary of a half-space having an upper covering layer (contrast indicator $\beta = 0.3$) at an increased speed of movement $\sim V = 50$ m/s are considered, which corresponds to $\hat{M} = 0,3$. Fig. 4a shows the case of reception on a line with a coordinate x_0'', Fig. 4b – on a line $x_0 = 0$, Fig. 4c – on a line x_0'. In the first and last cases, there should be a shift in the center frequency of the total signal spectrum along with a broadening of the spectral distribution. From their comparison, it is easy to see that on the line x_0'' from the approach of the head of the train to the traverse, the frequency in the maximum of the spectrum is higher than in the maximum of the spectrum of the signal on the traverse x_0, which, in turn, is higher than on the line x_0'. It should also be noted that the spectral amplitudes of the signal recorded at points on both sides of the central traverse have a significantly lower level relative to those that correspond to reception when the midpoint of the train is located above the central registration line, that is, at the moment of its symmetrical location relative to the receiver lines in front of and behind the train, and a higher level is recorded behind the tail of the train.

The detected differences in the spectral composition of the signal recorded in front of the head and behind the tail parts can be used in algorithms for remote monitoring and diagnostics of the parameters of the elasticity of the medium, taking into account the signs of the presence of a surface layer with a sharp contrast in the magnitude of the velocity of propagation of surface seismic waves. It can be assumed that the feature that characterizes the inhomogeneity in the form of a layer should also be considered as an indicator of the presence of a local subsurface anomaly, limited in size by horizontal coordinates.

An essential feature that occurs and is detected in the case of a noticeable contrast in the elastic parameters of the upper (shallow) layer relative to the underlying homogeneous medium and at an increased speed of movement is the presence in the two-dimensional terrain near the main maximum of another (local) maximum at distances close to the highway, which indicates the expansion of the frequency band of the spectrum. This feature is present in the spectrum of the signal recorded on the traverse and in its near vicinity. An increase in the spectral frequencies of the signal recorded on the line in front of the head of the train is characteristic. These features can be used in the development of algorithms for the reconstruction of the structure of the lower structure (groundbed) of the railway track, in the future they should also be considered as an informative feature in the remote diagnosis of local subsurface inhomogeneities under the main line.

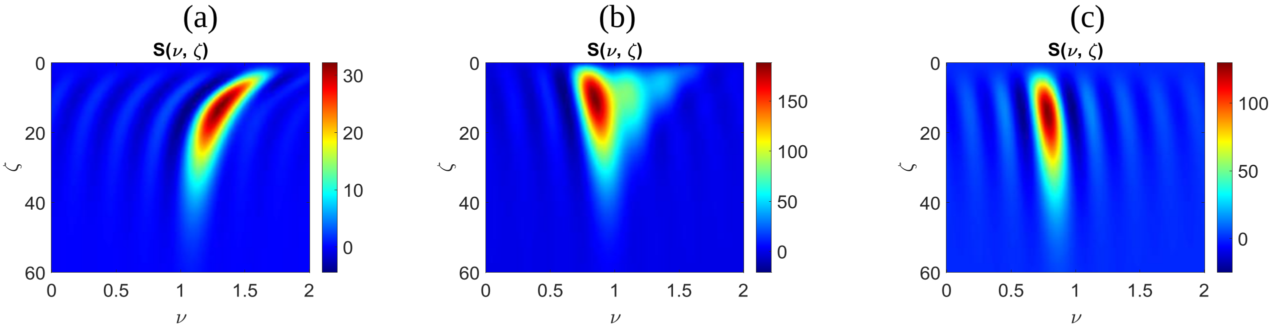

Fig. 4. The spectral amplitude of the seismic responses recorded at $\varpi = 1$, $M = 0,3$, $u_0/u_{micr} = 10$, $\Theta = 0,2$, $\beta = 0,3$ at different reception lines: at the approach of the composition $\xi'' = -30$ (a); at the traverse $\xi_0 = 0$ (b); behind the outgoing composition $\xi' = 30$ (c).

Note that the present review has not touched upon the analysis of volumetric shear waves (compression (P) and shear (SV and SH) waves excited by a rapidly moving train. These waves go deep into the earth's crust, then reflected and scattered by the boundaries of the layers of the lower structure of the path, which lie deep in the bowels, return to the free boundary. Their selective registration against the background of microseisms and other wave types can be used in seismic profiling in order to search for mineral deposits in areas adjacent to highways.

In conclusion, we will say that the above issues are relevant in connection with the prospect of implementing high-speed traffic on domestic railways. Recently, in the world practice, it is common to put into operation sections with high-speed train traffic at speeds of $V = 200...300$ km / h.

5.Conclusion

The calculated relations are obtained for the spectral amplitude of the seismic response that occurs when a railway train moves at distances from the track to the first hundred meters. The seismic response excited by the interaction in the "wheel pair – rails" system during the movement of the train at speeds up to ~50 m/s is considered. In this case, it is assumed that the Rayleigh-type surface wave dominates in the frequency range up to about two tens of Hertz, and the influence of the near-field strain on the response is not taken into account. For the medium on the surface of which the path is laid, a simplified model of the "layer – half-space" structure is used. The results are presented in the form of a two-dimensional relief on the plane of the variables "frequency-distance perpendicular to the highway". The calculated dependences of the spectral amplitude on the distance of the registration points (within the first hundred meters), on the speed of the train, and on the contrast of the elastic parameters in the layer and in the underlying thickness.

Based on the review of the response the possibility of current control of the depth of the interface between the layer and the medium, as well as the choice of the parameters of the elasticity of the material in the layer and in the half-space is discussed. It is assumed that the features in the response spectrum, which are manifested at high speeds, can be used in the construction of systems for monitoring the sediment of the ground layer under railway tracks, in the diagnosis of its structure, in identifying informative signs of the presence of local inhomogeneities, for example, karst origin.

The work is carried out within the framework of the state task of the IAP RAS (project 0030-2021-0018.

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The authors declare no conflict of interests.

The paper was received on 11.02.2021.
The paper was accepted for publication on 19.04.2021.