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EXPERIMENTAL INVESTIGATION INTO THE ONE-DIMENSIONAL CALCULATED MODEL OF WAVE PROPAGATION IN BLOCK MEDIUM

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The strain wave propagation in the one-dimensional block medium is experimentally studied. The experimental and calculated data are compared. It is shown that the proposed model provides satisfactory description of low-frequency pendulum wave propagation at the proper selection of the model parameters.

Block medium, interlayers, viscoelastic deformation, impact, low-frequency pendulum strain waves

The rock mass at different scale levels consists of separate blocks, fairly homogenous in their physical properties bound with relatively weak joints [1]. The joints influence on wave propagation in such a medium [2]. Besides longitudinal and transverse waves, slow pendulum wave propagation is also induced [3 – 5]. To study pendulum waves in a block medium experimentally, a physical model constructed of lime-and-sand bricks was used [4]. Here, the relationship between the acceleration and spectral distribution of oscillations during wave propagation in physical model is studied. In [6,7] the problem of strain wave propagation in a chain of masses connected by elastoplastic elements is theoretically examined, and the calculated scheme is developed and compared with the experimental data obtained in impact loading of the strain wave in a chain of steel bars separated by rubber interlayers.

In the present paper a model of block media made of bricks was used. The researches aim at obtaining data on the velocity of pendulum wave, attenuation of its magnitude with distance depending on the presence of rubber interlayers, and comparing with the data of theoretical calculations [7].

The scheme of the physical models is shown in Fig. 1. We used 8 bricks with the size of $250\times120\times85$ mm and weight of 5.2 g at a density of 2040 kg/m^3 and a longitudinal wave velocity of 3100 m/s. To record the process of the wave propagation in this model, accelerometers GT-200 were attached to the lower edge of the bricks by a plasticine layer 1 mm in thickness. To arrange free areas for mounting sensors, six upper bricks were advanced for 25 mm out of the system, each to its own side in turn (Fig. 1). The model was mounted on a laboratory bench. The lowest natural frequency of the system amounted to 90 Hz.

As a wave exciter, a hammer was used with its impacting part in the form of a steel cylinder 13.8 mm in diameter and 43 mm in length, with accelerometer 9803 (“Brüel&Kjær”) to measure force and duration of an impact. In Fig. 2 the specific oscillograms of separate blocks are shown. They demonstrate peculiarities of a signal induced by the impact action of the hammer on the upper brick, that propagats along the system of 6 bricks with the damping interlayers.

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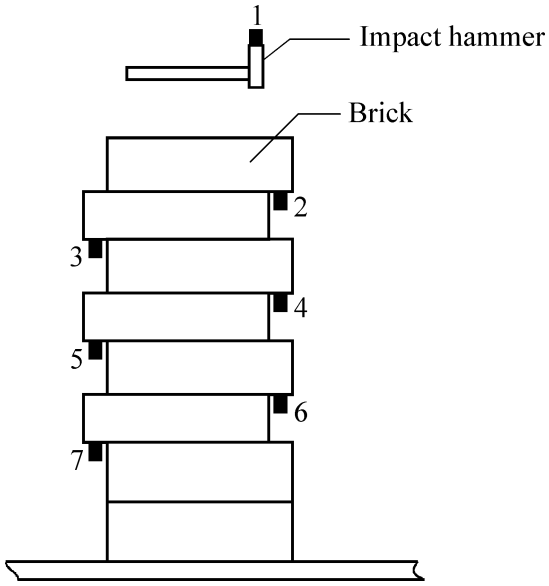

Fig. 1. Arrangement of bricks and accelerometers in physical model (■ — accelerometers)

Curve *1* shows the impact force, whereas curves *2 – 7* are the accelerograms of the blocks (Fig. 2). The numbers to the right of the plot correspond to the sensor numbers (Fig. 1). The numbers to the left are the signal magnitudes.

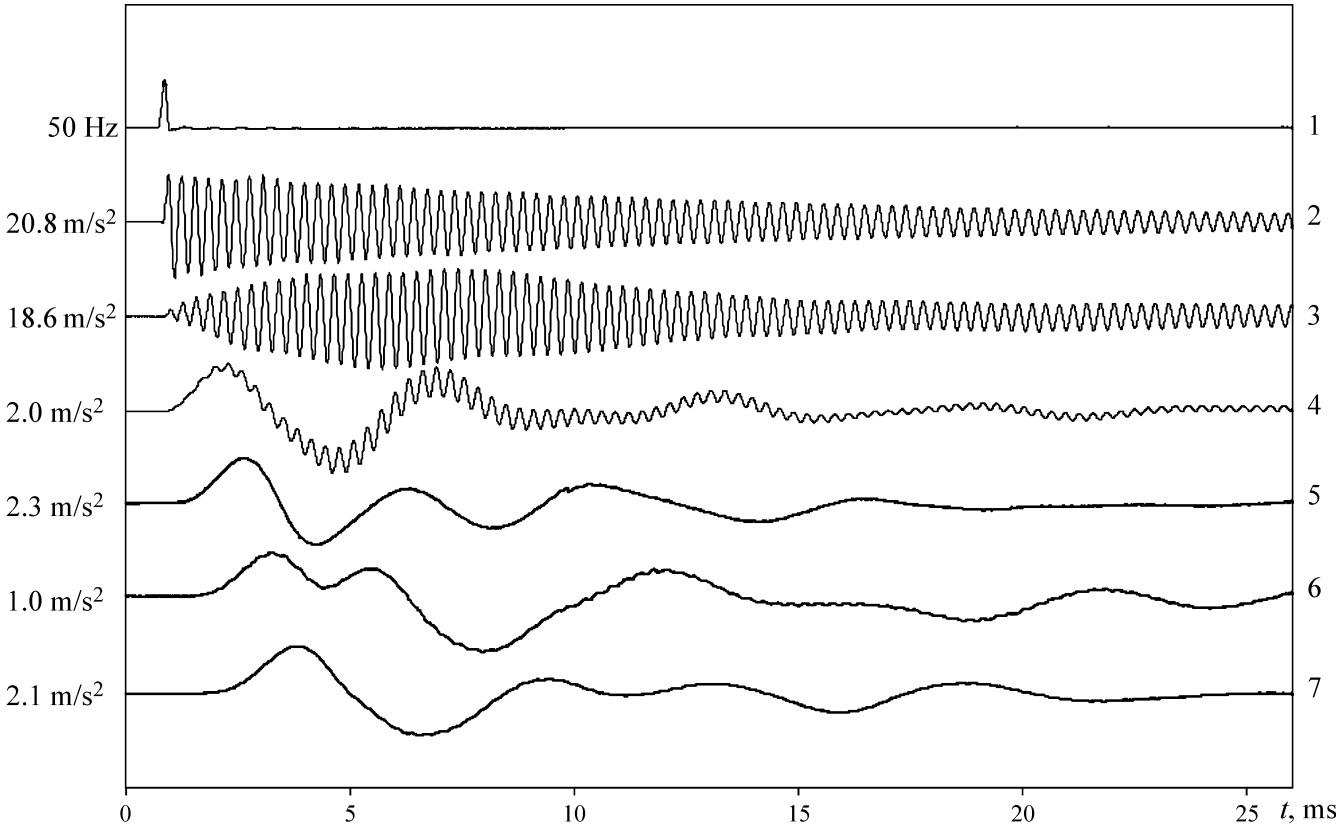

Fig. 2. The wave propagation in bricks separated by rubber interlayers 1 mm thick; low-frequency wave velocity is 164 m/s; impact duration is 0.21 ms

An elastic wave generated by the hammer impact on the surface of the upper brick is perceived by the sensor attached to this brick as a packet of attenuating high-frequency waves with a period of about 300 μs. The higher frequency waves corresponding to natural frequencies of a separate block with a period of 55 μs, have substantially less magnitude and are hardly noticeable. After passing the first interface between the blocks, high-frequency signal magnitude lowers. The second brick accelerometer records the wave of much longer period. On the next bricks, the lower frequency component of a signal is sharply revealed. The acceleration magnitude recorded by each following brick sensor is always higher than that on the preceding brick. As the calculated results show, it is an after-effect produced by high compliance of a brick having a modulus of subgrade reaction equaling approximately $13.3 \cdot 10^6$ N/m, inducing high acceleration of the last brick upon the wave reflection.

To expand the distance range between the wave generator and the sensors, we added some bricks on the top of the system (Fig. 1). In each new system, similar investigations were carried out. For the data unification, the dimensionless acceleration was introduced:

$$\bar{a} = \frac{a}{a_0},$$

where a_0 is the maximal hammer acceleration during an impact, a is the recorded acceleration.

The propagation velocity and attenuation magnitude of the primary wave in the wave packet were studied as the basic parameters determining the behaviour of a signal in a block system. The velocity was evaluated by two methods. In the first one, it is determined by the time difference between the impact instant and the time of the first arrival of the primary wave. The velocity V_M calculated by this method characterizes the velocity of a pendulum wave.

In the second case, this time interval was measured starting with the impact instant till the moment of the first arrival of the wave packet, and the velocity V_l was determined. The distance l from the impact point and the number of blocks n were changed in the experiments. In Fig. 3 the experimental dependence $V_M(n)$ is shown. The measurements are made by the first method. After passing two interfaces between the bricks, velocity of the wave becomes stable and does not depend on the distance. In the presence of the rubber interlayers between the blocks, $V_M = 164$ m/s, and in the case of their absence, $V_M = 316$ m/s.

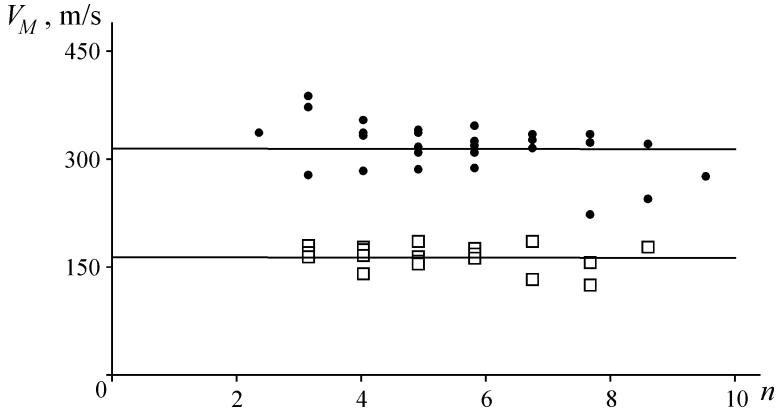

Fig. 3. Velocity V_M of pendulum wave propagation in the experimental system with (low line and squares) and without (upper line and circles) rubber interlayers depending on the number n of passed bricks

The velocity V_l to a great extent depends on the number of passed bricks. This relationship is described by the power dependence (Fig. 4); the propagation velocity varies from 3100 m/s, specific to a solid medium, to $400-600$ m/s after passing eight bricks and 700 mm of distance. This should be taken into account when locating acoustic emission sources in block media.

The rubber interlayers between the bricks, within the experimental data scattering, affect weakly the velocity V_l with an increase in distance from the place of an impact to a sensor. Nevertheless, the graph of interpolating function for the system with the rubber interlayers is lower as compared to the one corresponding to systems without the interlayers (Fig. 4). The interpolating functions have the form:

$$V_l = k_1 n^{\alpha} + k_2,$$

where k_1, α, and k_2 are the interpolation parameters. For the systems with the rubber interlayers, $k_1 = 200$ m/s, $\alpha = -0.84$, and $k_2 = 100$ m/s; without the interlayers, $k_1 = 2820$ m/s, $\alpha = -1.07$, and $k_2 = 400$ m/s.

An analysis of the wave acceleration magnitude makes it possible to evaluate its attenuation depending on the distance passed. In Fig. 5 the summarized data are presented for the maximal acceleration in a low-frequency signal versus on the brick number. The diagram shows that the signal attenuation rate substantially lowers on passing through a certain number of interfaces. It is especially obvious when bricks are separated with the rubber interlayers. If, at direct contacts, within experimental data scattering, a low-frequency signal practically stops attenuating after passing 5 or 6 interfaces, then, at presence of the rubber layers, the number of such interfaces reduces to two. In each case, these experimental relationships are described by the relation:

$$\overline{a} = k_3 n^{\beta} + k_4,$$

where k_3, β, and k_4 are the approximation parameters. When the rubber interlayers are present, $k_3 = 3.42 \cdot 10^{-4}$, $\beta = -3.09$, and $k_4 = 1.5 \cdot 10^{-4}$; otherwise, $k_3 = 2.76 \cdot 10^{-2}$, $\beta = -2.83$, and $k_4 = 3 \cdot 10^{-4}$.

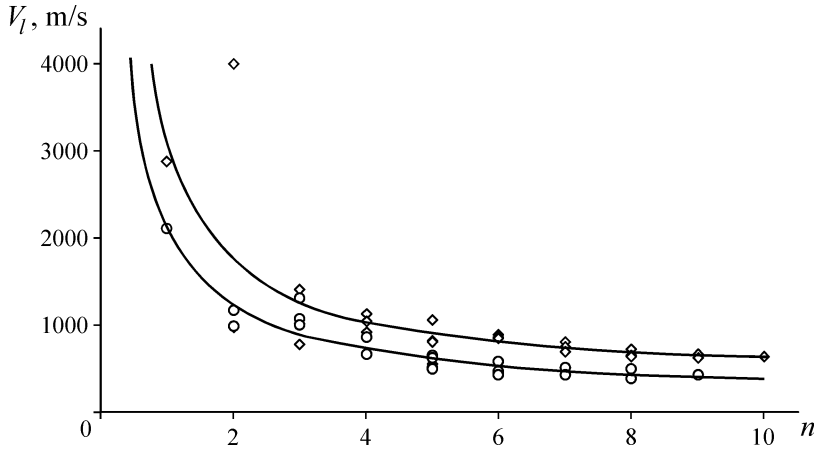

Fig. 4. Velocity V_l of wave propagation in systems with (low curve and circles) and without (upper curve and rhombuses) rubber interlayers

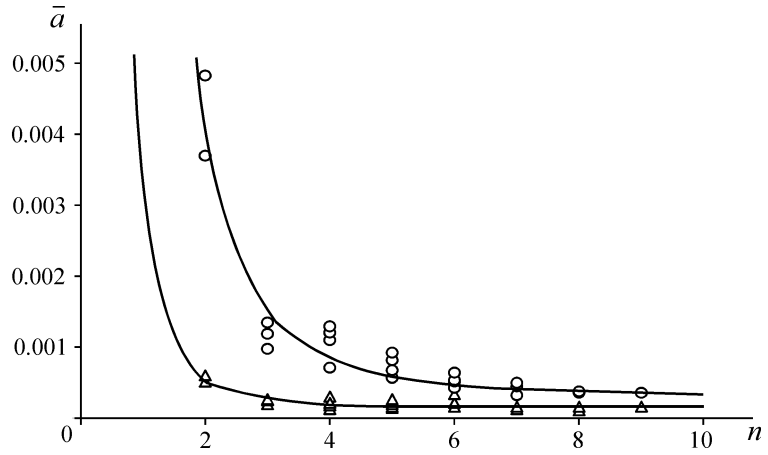

Fig. 5. Attenuation of magnitude of the primary wave of wave packet depending on brick number n in system with (low curve and triangles) and without (upper curve and circles) rubber interlayers

The obtained experimental data on propagation velocity and attenuation of low-frequency waves generated by an impact in a block system are used to determine the properties of contacts between bricks. For this purpose, the calculations were carried out on the basis of one-dimensional model of a chain of masses connected by viscoelastic springs [7]. The spring deformation is described using parallel and series connection of elastic elements and dash-pots (Fig. 6). The spring rigidities K_1, K_2 and viscosity coefficients λ_1, λ_2 were found based on the calculated and experimental values of the propagation velocity and attenuation of a low-frequency wave. Thus, it is obtained for the rubber interlayers: $K_1 = 5.3 \cdot 10^6$ N/m and $K_2 = 10^7$ N/m, $\lambda_1 = 10^4$ N·s/m^2 and $\lambda_2 = 2 \cdot 10^3$ N·s/m^2. For contacts without the interlayers: $K_1 = 15 \cdot 10^6$ N/m and $K_2 = 59 \cdot 10^6$ N/m, $\lambda_1 = 75 \cdot 10^3$ N·s/m^2 and $\lambda_2 = 4 \cdot 10^3$ N·s/m^2.

The theoretical acceleration — time diagrams matching with the oscillograms in Fig. 2, are shown in Fig. 7. The vertical lines in the diagrams correspond to the incident and reflected pendulum waves propagating with a velocity of 164 m/s. For the first two blocks, the model provides the low-frequency wave form, which is not seen in the experimental oscillogram because of natural oscillations of the bricks. For the third and the following bricks, this wave is clearly observed. The apparent difference in shapes of the curves can be explained by the irregularity of contacts in the brick system separated by the rubber interlayers, in particular. The description of the propagating waves whose frequency is close to eigenfrequencies of blocks in one-dimensional model [6, 7], is difficult, as at a longitudinal, point impact the free oscillations, which correspond to different modes of natural oscillations: longitudinal, transverse and bending, arise in the first bricks of the system. This explains the oscillation with a period equaling 300 μs (Fig. 2) instead of 55 μs typical to resonance oscillation of longitudinal wave.

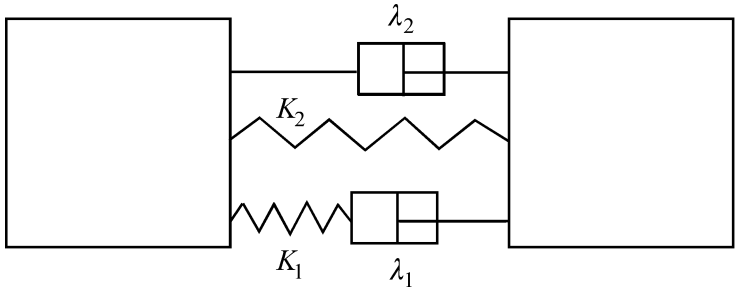

Fig. 6. Viscoelastic model of interlayers between blocks

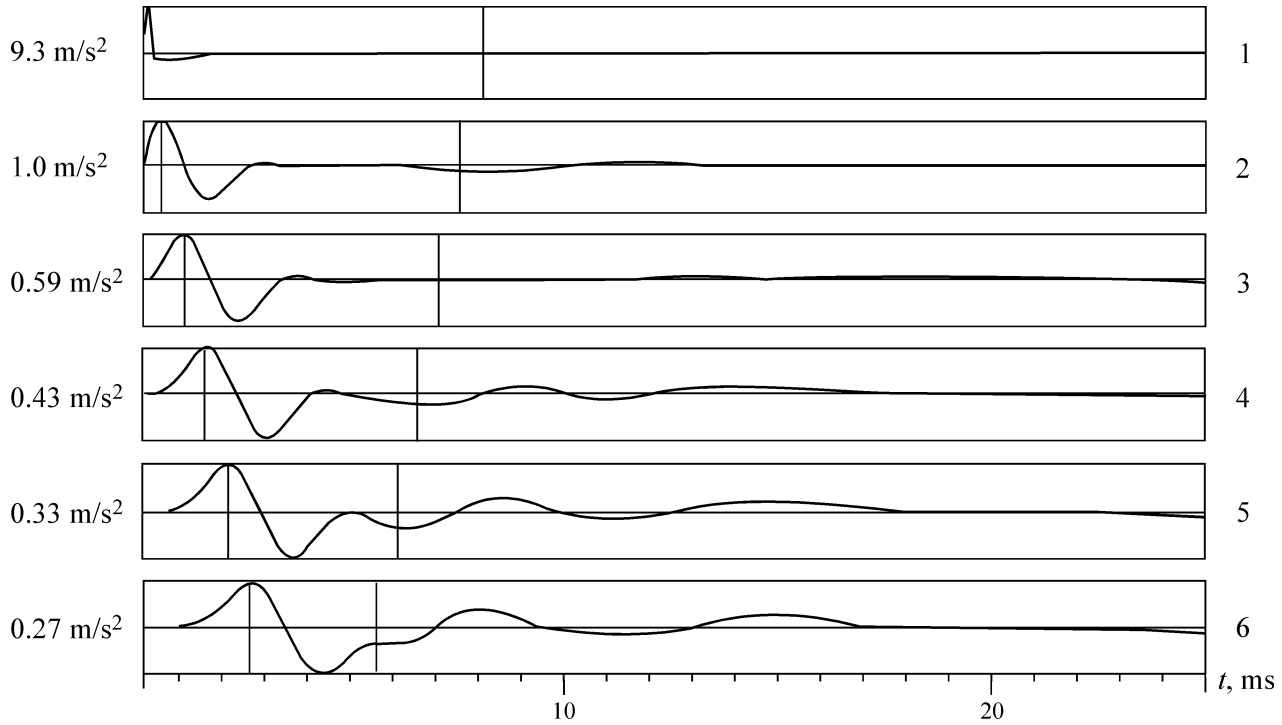

Fig. 7. Theoretical accelerations on wave propagation along brick system with rubber interlayers at impact duration of 0.21 ms

Figures 8 and 9 demonstrate the recorded and calculated accelerations of a wave generated by the hammer impact 1.85 ms in duration through a rubber interlayer. At this impact, natural oscillations of the bricks are weakly excited, and a satisfactory good compliance of oscillations of the first two bricks can be seen in the experimental and theoretical diagrams.

For the brick system without the interlayers, the experimental oscillogram and calculated diagrams of the low-frequency wave propagation are shown in Figs. 10 and 11.

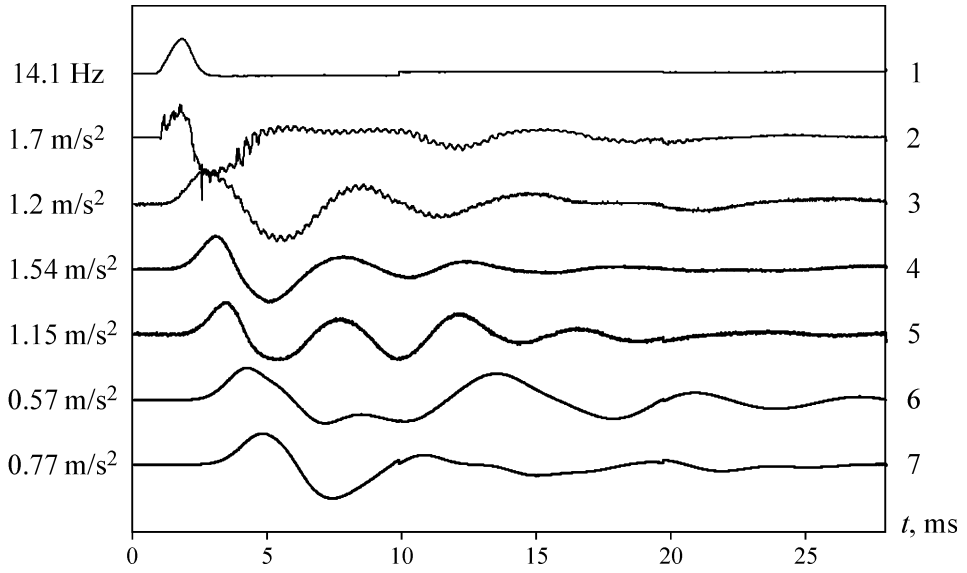

Fig. 8. Recorded accelerations in brick system with rubber interlayers at impact duration of 1.8 ms

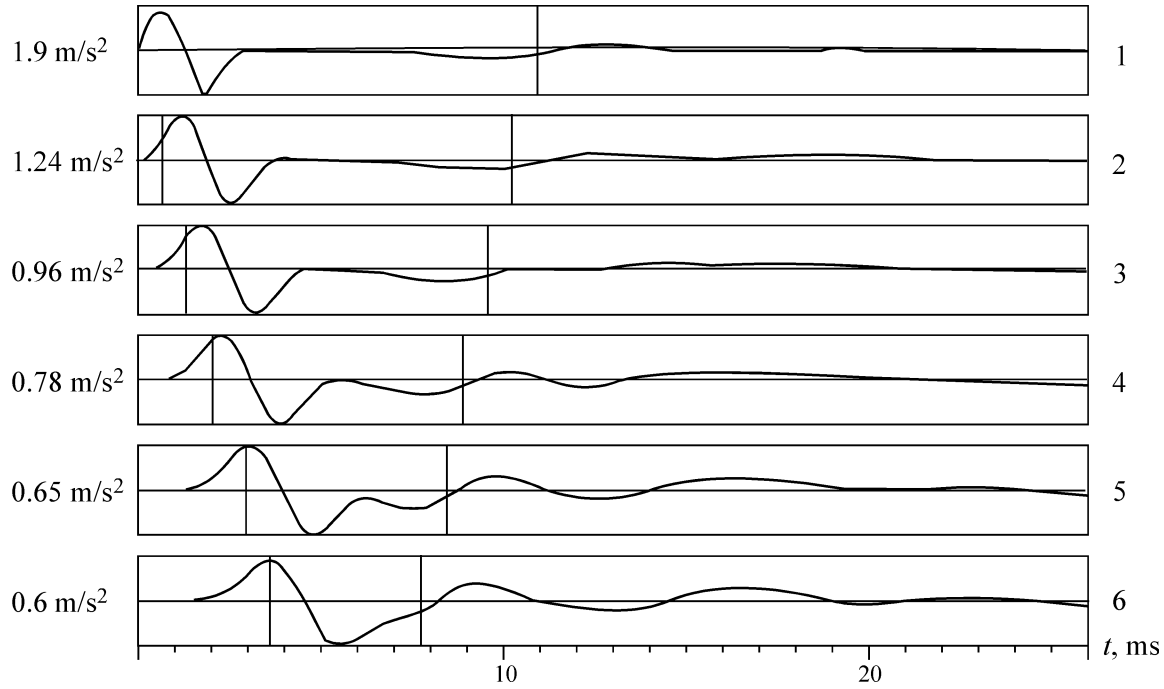

Fig. 9. Theoretical accelerations in block system with rubber interlayers at impact duration of 1.8 ms

As is shown in Fig. 10, in the brick system without additional interlayers, the impact generates high-frequency oscillations with a period of 300 ms in the first three bricks similarly to Fig. 2. The theoretical diagrams in Fig. 11 describe the low-frequency oscillations, as they are obtained in the one-dimensional model. The characters of the low-frequency wave distributions in Figs. 10 and 11 are well consistent, especially in the time range before the arrival of the reflected wave depicted by the second vertical line in Fig. 11.

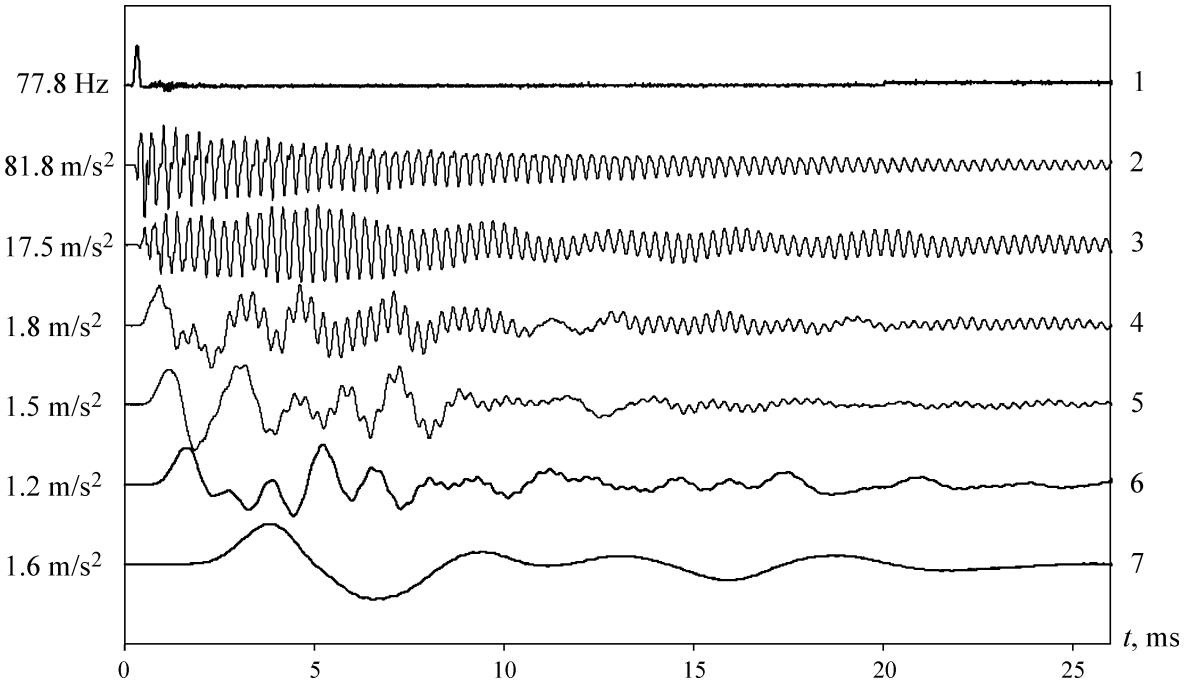

Fig. 10. Recorded accelerations in brick system without interlayers at impact duration of 0.21 ms

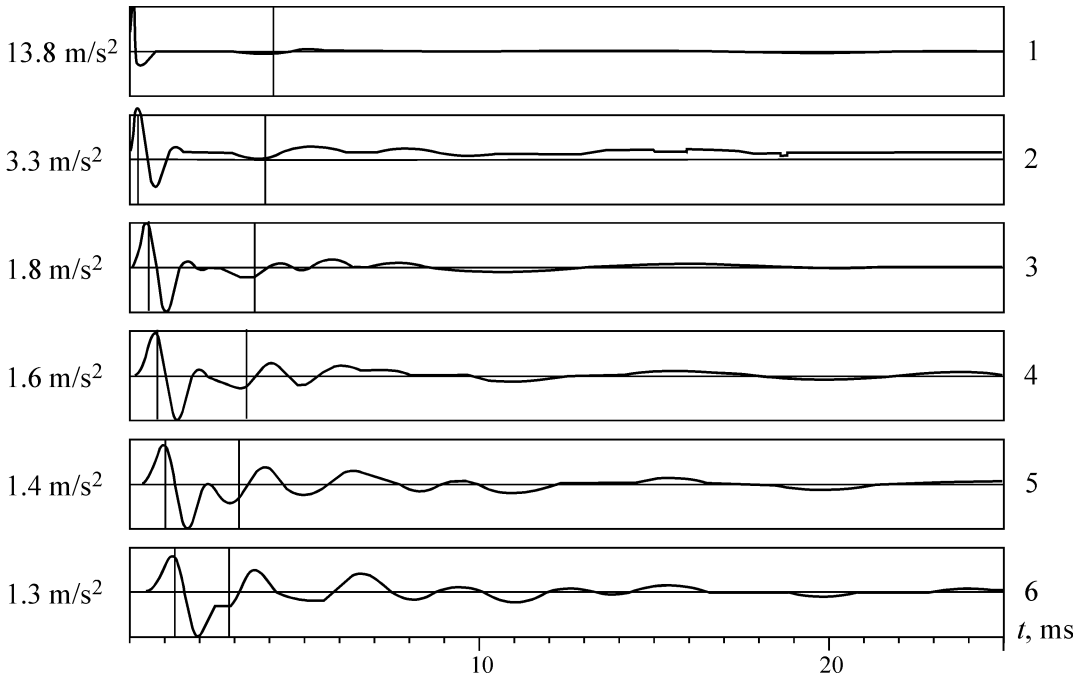

Fig. 11. Theoretical accelerations in block system without interlayers at impact duration of 0.21 ms

CONCLUSIONS

1. Based on the theoretical model [6, 7], the low-frequency pendulum wave propagation in the one-dimensional block system under the impact action is described. A good compliance of the theoretical and experimental data is obtained.

2. The high-frequency oscillations generated in a block model on propagation velocity and attenuation of waves were achieved by a suitable choice of interblock layer properties. They correspond to different frequency modes of natural block oscillations. The block model is required to be modified for the theoretical description of the high-frequency oscillations with taking into account the internal block structure.

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