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EXPERIMENTAL STUDIES ON THE DYNAMICS OF A VIBRATING MULTI-FREQUENCY SIEVE FOR DRILLING MUD CLEANING

Abstract. Experimental studies of the dynamics of a vibrating multi-frequency sieve for cleaning drilling muds were carried out. To determine the oscillation parameters of the experimental sieve sample, the accelerations of the sieve impactor oscillations were measured. Analysis of the oscillograms of the accelerations of the impactor oscillations showed at interacting with the limiters, peak accelerations are periodically excited in the impactor, which significantly exceed the accelerations at non-impact moments of movement, and both positive and negative accelerations are also excited at the nearest moments of time. The results of the spectral analysis of the sieve impactor accelerations showed that the spectra are continuous, since all frequencies are present on the spectrogram in the given frequency range, and there is no regularity in the change in the amplitude values of the excited frequencies. The sieve impactor performs non-periodic or chaotic oscillations, while the amplitudes of the accelerations of the oscillations at a significant number of frequencies that are excited exceed the amplitude at the frequency of external excitation. In addition to peak impact accelerations, non-periodic and uneven, alternating accelerations are excited in the impactor of the experimental sieve sample between impacts, which indicates the emergence of additional sources of vibration excitation in the sieve. As a result, there is a constant resonance of all structural elements of the sieve construction, which amplifies the vibrations and leads to the fact that the amplitudes of vibration accelerations at a significant number of excited frequencies exceed the amplitude at the frequency of external excitation. In a vibrating multi-frequency sieve, the energy of impact interaction depends on the ratio of masses between the impactor and the sieve frame, the force excited by the vibrator motor, the values of dynamic gaps in the elastic limiting limiters and the parameters of the bonds themselves and the elastic system, and the frequency spectrum also depends on the damping of vibrations in the sieve structural elements. The mathematical model of the sieve, due to the assumptions made, describes only the main oscillations caused by the influence of the vibration exciter and impact interactions with the elastic limiters of the impactor movements. The assessment of the adequacy of the mathematical model showed the coincidence of the oscillation frequencies of the impactor according to the model and the experimental sample of the sieve and the relative error in the difference of impact accelerations, which does not exceed 10%.

Keywords: vibrating multi-frequency sieve, drilling mud cleaning, experimental studies, dynamics, mathematical model, spectral analysis.

1. Introduction

Improving the technique and technology of cleaning drilling muds from drilled rock, increasing the speed of well drilling, and improving the quality of drilling mud is an important scientific and applied problem that is of great importance for the oil and gas industry [1–8].

The authors propose the use of drilling mud cleaning technology on a vibrating multi-frequency sieve. The realization of multi-frequency oscillations and a multiple increase in the acceleration of sieve oscillations, compared to typical vibrating sieves for cleaning drilling muds, will ensure increased productivity and efficiency of drilling mud cleaning on vibrating multi-frequency sieves compared to traditional vibrating sieves with single-frequency excitation [9, 10]. This will allow increasing the permissible drilling speed, which is limited by the degree of cleaning of drilling muds from rock particles, and will contribute to increasing the technical and economic indicators of the drilling process.

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The main directions of increasing the efficiency of vibration technologies for processing mineral raw materials are the selection and optimization of dynamic parameters of the load of vibration equipment and technological raw materials on the working body, related both to energy-force interactions and to the mechanical and structural characteristics of the raw materials. For polydisperse systems, which are the majority of technological materials in the processing of mineral raw materials, the optimal modes of vibration influence lie in the area of resonant multi-frequency excitation and require deep and independent regulation of the vibration excitation parameters taking into account changes in the values and characteristics of the technological load [11–23]. A dynamic scheme and mathematical model of a vibrating multi-frequency sieve for cleaning drilling muds [24] and a method for analyzing forced oscillations of a vibrating multi-frequency sieve for cleaning drilling muds by the method of computational experiment [25] have been developed, identification of parameters and research of a mathematical model of a vibrating multi-frequency sieve for cleaning drilling muds have been carried out [26]. For further study of the process and establishment of regularities of changes in power, energy and regime parameters of a vibrating multi-frequency sieve and substantiation of its rational parameters, it is necessary to conduct experimental research and assess the adequacy of the mathematical model of a vibrating multi-frequency sieve for cleaning drilling muds.

Therefore, conduction experimental researches and assessing the adequacy of the mathematical model of a vibrating multi-frequency sieve for cleaning drilling muds for further research of the process and establishing the regulatities of changes in the power, energy and operating parameters of a vibrating multi-frequency sieve and substantiating its rational parameters are an urgent scientific task that is of significant importance for the country's oil and gas production industry.

2. Methods

The results of the research show that the mathematical model of a vibrating multi-frequency sieve adequately responds to changes in the operating parameters of the sieve [24–26]. When adjusting the power of the drive motor, the characteristics of the sieve output change to the established vibro-impact oscillation modes. With insufficient power, the sieve “freezes” at startup at the frequency of oscillations on the supporting elastic bonds between the box and the fixed base. When a certain power is reached, the sieve overcomes its own frequency of oscillations on these elastic bonds and enters the established vibro-impact oscillation modes. At the same time, depending on the drive power, the duration of the start-up and exit of the sieve to the established oscillation modes changes.

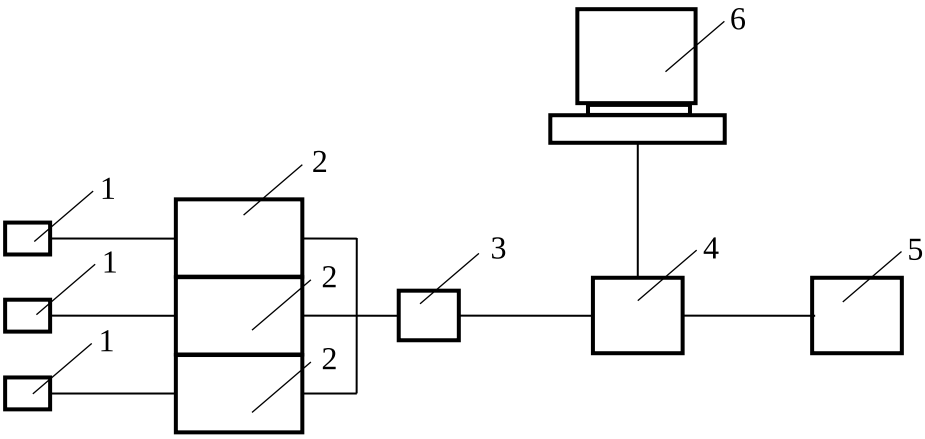
The adequacy of the mathematical model of a vibrating multi-frequency sieve can also be checked by comparing the oscillation parameters of the physical and mathematical models of the sieve. For this purpose, measurements of the oscillation parameters of the experimental sieve sample shown in Fig. 1 were carried out, the technical characteristics of which are given in Table 1. The results of the studies were compared with the calculated ones obtained using the mathematical model at the same operating parameters of the sieve. It should be noted that, unlike the mathematical model of the sieve where the movements of the impactor are limited by elastic limiters, which are modeled by point interactions with the upper and lower limiters, in the experimental sieve sample the movements of the impactor are limited by four upper and lower limiters. Each of these limiters has an independent system for adjusting the gaps between the impactor and the limiter and is characterized by the area of possible contact during interaction and elasticity.

a)

b)

a) general view; b) sensor installation locations on the impactor (marked in red)
Figure 1 – Experimental sample of a sieve for cleaning drilling muds

To determine the vibration parameters of the experimental sieve sample, the vibration accelerations of the sieve impactor were measured. The locations of the sensors on the sieve impactor are shown in Fig. 1,b. At this stage, the dynamic characteristics of the sieve impactor were studied, the characteristics of the sieveing surface (material, cell diameter, etc.), which is freely located on the impactor, were not taken into account, as they do not significantly affect the dynamics of the sieve as a whole. The structural block diagram of the measuring complex, developed on the basis of the Robotron vibration measuring equipment, is shown in Fig. 2.



1 – acceleration sensors; 2 – integrating amplifier; 3 – channel switch; 4 – display unit; 5 – oscilloscope; 6 – laptop computer
Figure 2 – Structural block diagram of the measuring complex

The vibration measuring complex was used to measure, record and analyze the parameters of the impactor oscillations vibrations. The measurements were carried out using KD 31 acceleration sensors of the Robotron vibration measuring equipment and recording the output signal from the Robotron integrating amplifier to a laptop computer. The technical characteristics of the acceleration sensors used are given in Table 2.

Table 1 – Technical characteristics of the experimental sieve sample

Parameter, units of measurement	Symbols	Value
Box weight, kg	m_1	568
Impactor weight, kg	m_2	120
Stiffness of two-way elastic bonds between the box and the fixed base, N/m	c_{p01}	12 0000
Viscosity of elastic bonds with stiffness c_{p01}, kg/s	b_{p01}	10 00
Stiffness of two-way elastic bonds between the box and the impactor, N/m	c_{p02}	1787500
Viscosity of elastic bonds with stiffness c_{p02}, kg/s	b_{p02}	1500
Stiffness of the upper one-way elastic bond between the box and the impactor, kN/m	c_{r01}	34000
Viscosity coefficient of one-way elastic bonds with stiffness c_{r01}, kg/s	b_{r01}	2000
The gap of the upper one-way elastic bond between the box and the impactor, m	δ_{01}	0.003
Stiffness of the lower one-way elastic bond between the box and the impactor, kN/m	c_{r02}	34000
Viscosity coefficient of one-way elastic bonds with stiffness c_{r02}, kg/s	b_{r02}	2000
The gap of the lower one-way elastic bonds between the box and the impactor, m	δ_{02}	0.003
Vibration exciter type IB-43-25	-	-
Synchronous angular speed of rotation of the electric motor, rad/s	ω_c	157
Nominal angular speed of rotation of the electric motor, rad/s	ω_n	156
Excitation force at synchronous frequency, kN	F_m	9.4; 13.5; 19.5; 24.2
Static moment of debalance, kg×m	L	0.38; 0.55; 0.8; 1.0
Mass of debalances, kg	m_d	5.85; 7.4; 8.0; 8.3
Eccentricity of debalances, m	r	0.065; 0.075; 0.1; 0.12
Moment of inertia of debalances, kg×m^2	I	0.025; 0.042; 0.08; 0.12
Rated power of the electric motor, kW	N_n	1.1
Number of pole pairs of an electric motor	p	2
Power supply frequency, Hz	f_c	50
Overload capacity of the electric motor	ζ	2.4

The vibration measuring complex allows measuring the dynamic parameters of vibrations of the sieve structural elements, processing the received signal by selecting the required range and time constant, visualizing the signal and processing it on a computer using standard programs. Standard sound programs Sound Forge and Wavel Lab were used to record, visualize and analyze signals on a computer.

Acceleration sensors were rigidly fixed on sieve impactor. Before recording the vibrations, the sensors were mechanically calibrated on a standard vibrating table of the Robotron equipment at various values of the supply voltage and, consequently, the acceleration values. The acceleration values were recorded using a Robotron pointer indicator and by recording them on a computer. After installing the sensors on the sieve on the Robotron equipment their electrical calibration was carried out.

Table 2 – Technical characteristics of acceleration sensors

Parameter	Units of measurement	KD31 (No. 1)	KD31 (No. 2)	KD31 (No. 3)
Transmission ratio (125 Hz)	mV/ms^2	0.97	1.0	1.1
Resonant frequency	kHz	40	40	40
Operating frequency range	Hz	3.5–12000	3.5–12000	3.5–12000
Calibration error	%	3	3	3
Transverse directivity coefficient	%	5.2	5.1	5.0
Temperature dependence of the transmission coefficient	%	0.07	0.07	0.07
Mass	g	18	18	18

The obtained calibration dependence of the accelerations of the vibrations of the sensors on the vibrating table of the Robotron equipment according to the acceleration oscillogram on the computer and on the pointer indicator device has a linear form with minor differences in the acceleration values obtained on the pointer indicator device of the Robotron equipment. This indicates the correspondence of the acceleration measurement scales obtained using the programs Sound Forge and Wavel Lab on a computer and on a indicator device.

3. Theoretical and experimental parts

Fig. 3 shows the oscillogram of the acceleration of the vibration of the impactor at the basic parameters of the sieve (Table 1) and the force of the vibrator of 13.5 kN. For comparison, calculations of the vibration parameters were carried out on the mathematical model of the sieve at the same operating parameters. Fig. 4 shows the dependence of the change in the acceleration of the vibration of the sieve impactor for 17 excitation periods (from 969 to 984 periods) from 1000 calculated ones at the number of steps per period NH=2000 and starting the system with operating parameters, as when recording the accelerations of the sieve impactor in Fig. 3. From Fig. 5 it is seen that for 968 excitation periods from the moment of system start-up, the sieve has reached the established modes of vibro-impact oscillations.

Analysis of the oscillograms in Fig. 3 and Fig. 4 shows that during interaction with the limiters in the impactor, peak accelerations are periodically excited, which significantly exceed the acceleration at non-impact moments of movement. Impact interactions on the oscillogram (Fig. 3) are periodically repeated at intervals of time

t=0.04006 s, equal to the period of rotation of the motor-vibrator with a circular frequency of 156.76 rad/s, which coincides with the established frequency of oscillations of the impactor on the oscillogram (Fig. 4). From the oscillogram in Fig. 3 it is seen that in the impactor are excited both positive (when interacting with the lower limiters) and negative (when interacting with the upper limiters) closely spaced peak acceleration bursts. On the calculated oscillogram (Fig. 4) during the excitation period there is one interaction with the upper and lower limiters. Such a difference in the characteristics of the oscillations is due to the fact that the mathematical model models a point interaction with one upper and lower limiters. In addition, the mathematical model with equal gaps between the impactor and the limiters is an absolutely symmetrical system, which is difficult to implement in the spatial physical model of the sieve. Symmetry of the parameters of the experimental sample of the sieve is absolutely impossible, since it is necessary to ensure not only the symmetry of the gaps in all elastic limiters, but also the symmetry of the elastic bonds, centers of mass, centers of inertia, centers of rigidity, etc. Therefore, base on the oscillogram in Fig. 3, the impactor, in addition to being plane-parallel, also performs rotational oscillations. As a result, in the impactor in the nearest moments of time is excited by both positive (when interacting with the lower limiters) and negative (when interacting with the upper limiters) accelerations.

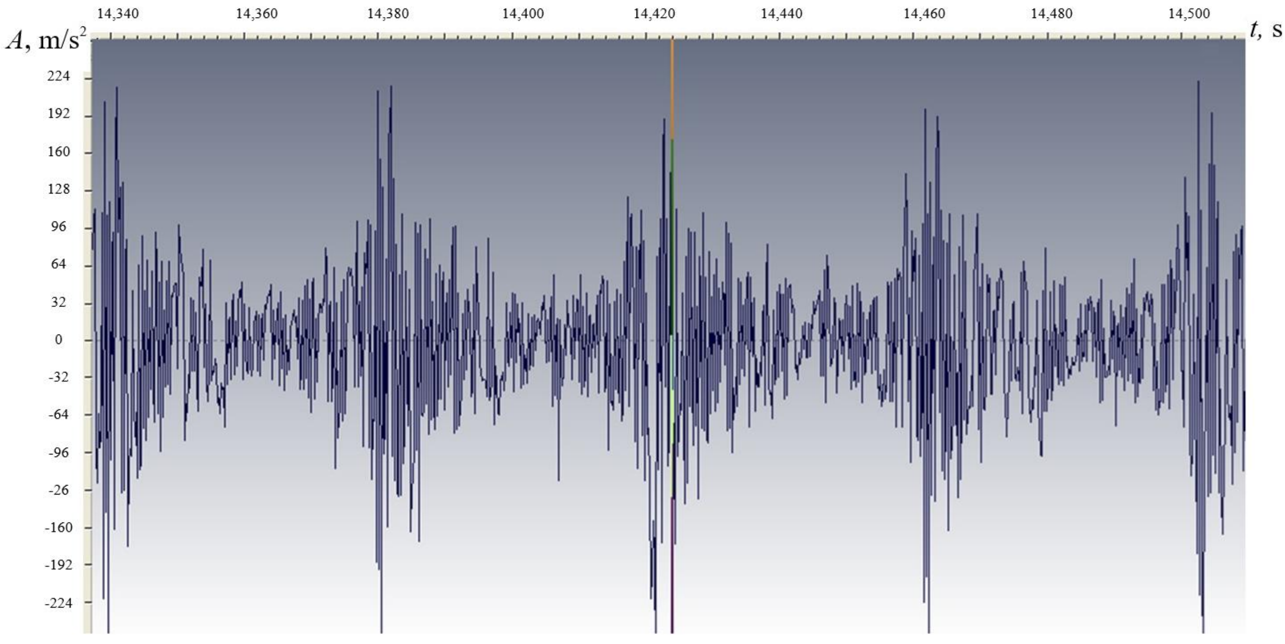


Figure 3 – Time dependence of the change in the acceleration of vibrations of the impactor of the experimental sieve sample at a force equal to 13.5 kN

On the oscillogram (Fig. 3), the sieve impactor oscillates with maximum accelerations that do not exceed 190 m/s^2, but on Fig. 4 – with peak accelerations equal to 171.6 m/s^2. In this case, the relative error of the acceleration values does not exceed 10%.

Fig. 6 shows the spectral composition of the sieve impactor accelerations, performed using the program Wavel Lab according to the measurement results shown in

Fig. 3. The spectra are continuous, since all frequencies are present in the spectrogram in the given frequency range. There is no regularity in the change in the amplitude values of the excited frequencies. Such a spectrum is inherent in non- periodic oscillations. Therefore, in general, the sieve impactor performs non-periodic or chaotic oscillations. At the same time, it can be seen from Fig. 6 that the amplitudes of the oscillation accelerations at a significant number of excited frequencies exceed the amplitude at the external excitation frequency, i.e. 24.96 Hz.

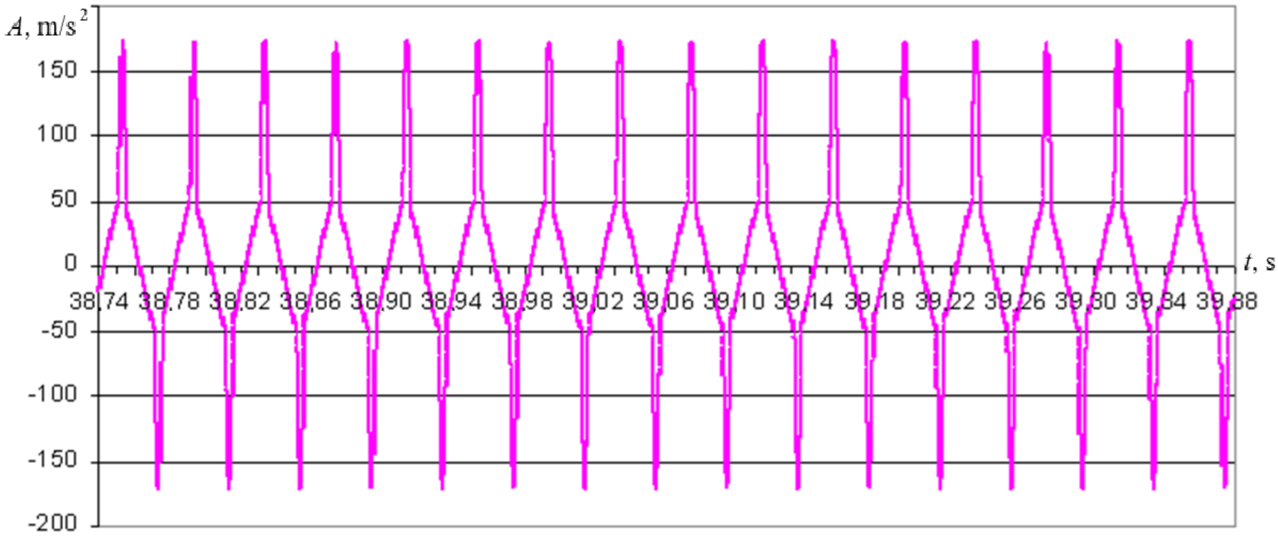


Figure 4 – Time dependence of the acceleration of the sieve impactor oscillations from 969 to 984 excitation periods system (from 38.74 to 39.88 s) with 1000 calculated

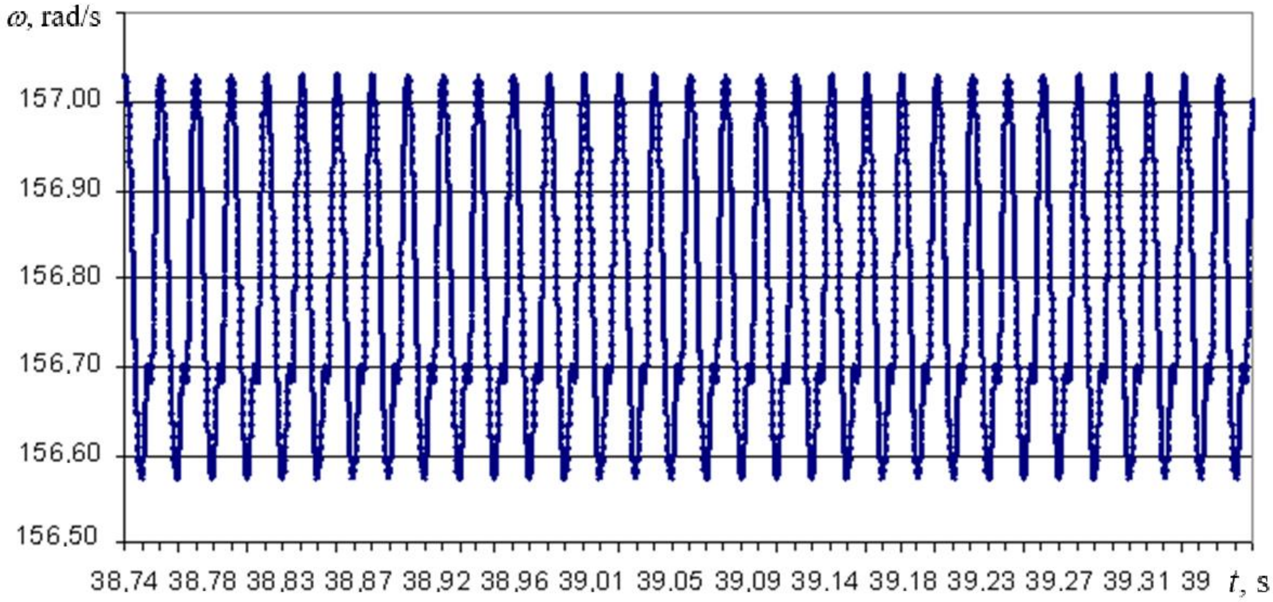


Figure 5 – Time dependence of angular speed of rotation of the electric motor from 969 to 984 system excitation period (from 38.74 to 39.35 s) with 1000 calculated

Analysis of the oscillogram in Fig. 3 shows that in addition to peak impact accelerations, in the impactor of the experimental sample of the sieve between impacts, non-periodic and uneven, alternating accelerations are observed, which indicate the emergence of additional sources of excitation of vibrations in the sieve. These accelerations vary from maximum in the intervals of movement close to the impact to minimum in the intervals of movement between impacts and reach values comparable to the impact accelerations. It can be assumed that as a result of superimposing these accelerations on periodic impacts caused by impacts on the limiter, the values of the ones from period to period of interaction with the same limiters vary in size.

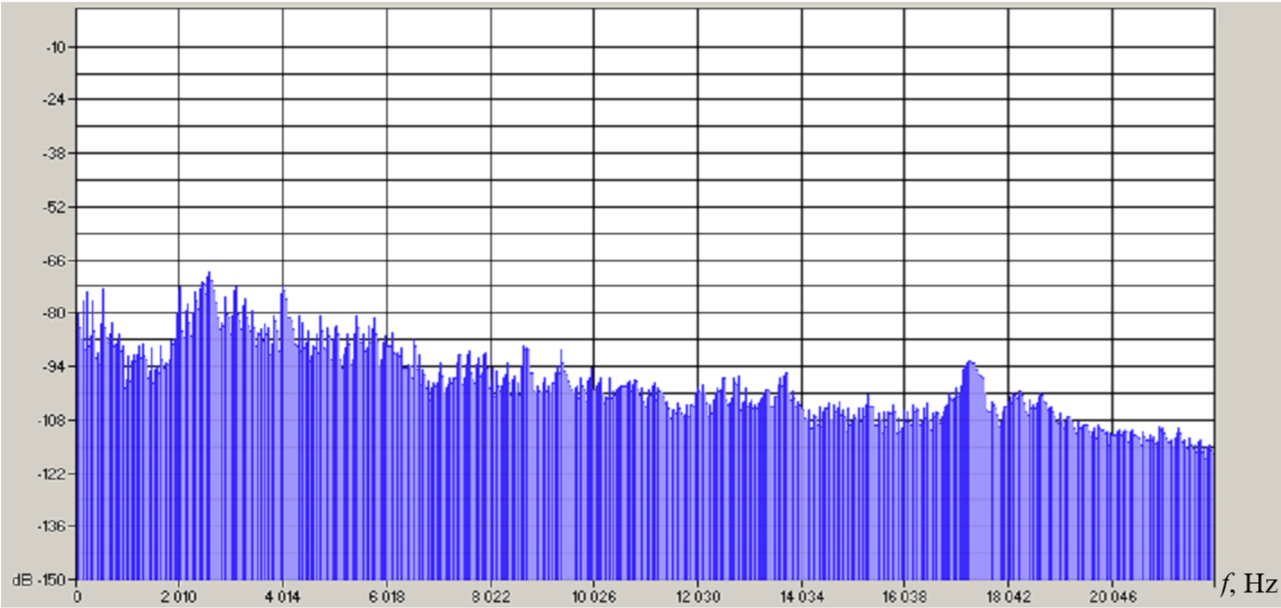


Figure 6 – Spectrograms of vibration accelerations of the sieve impactor

These additional vibrations are excited by impacts at the vibration frequencies of the sieve structural elements, in particular, in the sieve box. Such vibrations are excited when one or more frequencies from the excited frequency spectrum coincide with one or more natural frequencies of the sieve structural elements. As a result, there is a constant resonance of all structural elements of the sieve construction, which amplifies the vibrations and leads to the fact that the amplitudes of the vibration accelerations at a significant number of excited frequencies exceed the amplitude at frequencies and external excitation (24.96 Hz).

4. Results

The analysis shows that as a result of harmonic and impact loading in the working body of the sieve, complex vibration forms arise. They depend on the parameters of the impact and mechanical properties of the vibro-impact system of the sieve. It is known that in a solid medium, under impact loading, in addition to longitudinal waves, transverse waves spread, and due to the limited dimensions of the elements of mechanical structures, surface, bending and some other types of waves also spread. Each type of wave is characterized by its spreading speed, as well as other features, for example, the speed of bending waves depends on the frequency, dimensions and thickness of the element of the mechanical structure.

The mechanical structure of the sieve can be conditionally divided into component elements - plates, rods, interconnected to each other. In such a distributed system, the impact energy is redistributed and transformed in each bond. Part of the impact energy, spreading in the elements, is reflected in the bonds, part is converted into the energy of waves of a different type (longitudinal into bending or transverse, etc.), part of the energy passes into the next element of the structure, part is radiated into the environment or converted into heat. If the distributed system has resonant properties, then the impact load, spreading through the structures, causes intense oscillations of the elements that have sufficient quality factor at their natural frequencies. Since the mechanical parts of the vibrating sieve are systems with distributed parameters, they all have an infinite discrete sequence of natural frequencies.

Therefore, in the elements of the sieve structure, elastic oscillations at various natural frequencies of the distributed mechanical system are excited during impact loading, which leads to resonance of its various elements and the excitation of multi-frequency oscillations. Due to insignificant damping in various elements of the mechanical system, these oscillations at the stages of non-impact movements of the vibration system do not have time to fade out, thereby creating the so-called “noise” or oscillations with a continuous frequency spectrum. Therefore, the nature of the oscillations of the sieve structure elements has a complex appearance, revealing sharply expressed frequency properties and, due to nonlinearity, instability, both in space and time. In this case, nonlinear system parameters cause the appearance of total and difference frequencies and their harmonics and the emergence of low-frequency component oscillations. Nonlinearity also affects the change in the values of the natural frequencies of oscillations of the sieve structure elements depending on the intensity of the impact effect.

In a vibrating multi-frequency sieve, the energy of the impact interaction depends on the mass ratio between the impactor and the sieve body, the force excited by the vibrator motor, the values of the dynamic gaps in the elastic limiting bonds and the parameters of the bonds themselves and the elastic system. In addition, the frequency spectrum also depends on the damping of vibrations in the sieve structural elements.

5. Conclusions

1. Experimental studies of the dynamics of a vibrating multi-frequency sieve for cleaning drilling muds were carried out. To determine the vibration parameters of the experimental sieve sample, the accelerations of the sieve impactor oscillations were measured. Analysis of the oscillograms of the accelerations of the impactor oscillations showed that when interacting with the limiters, peak accelerations are periodically excited in the impactor, which significantly exceed the accelerations at non-impact moments of movement, and at the nearest moments of time, both positive (when interacting with the lower limiters) and negative (when interacting with the upper limiters) accelerations are excited.

2. A spectral analysis of the sieve impactor accelerations was carried out. The results showed that the spectra are continuous, since all frequencies are present on the spectrogram in the given frequency range, and there is no regularity in the change in

the amplitude values of the excited frequencies. As a rule, the sieve impactor performs non-periodic or chaotic oscillations, while the amplitudes of the oscillation accelerations at a significant number of excited frequencies exceed the amplitude at the external excitation frequency.

3. In addition to peak impact accelerations, non-periodic and uneven, sign-changing accelerations are excited in the impactor of the experimental sieve sample between impacts, which indicates the emergence of additional sources of vibration excitation in the sieve. As a result, there is a constant resonance of all structural elements of the sieve construction, which amplifies the vibrations and leads to the fact that the amplitudes of vibration accelerations at a significant number of excited frequencies exceed the amplitude at the frequency of external excitation.

4. The adequacy of the mathematical model of a vibrating multi-frequency sieve was assessed by comparing the oscillation parameters of the physical and mathematical models of the sieve. The mathematical model of the sieve, due to the assumptions made, cannot reflect the oscillations of the sieve structural elements and therefore describes only the main oscillations caused by the influence of the vibration exciter and impact interactions with the elastic limiters of the impactor movements. However, given the coincidence of the oscillation frequencies of the impactor obtained by the model and the experimental sample of the sieve and the relative error in the difference of impact accelerations, which does not exceed 10 %, it can be concluded that the model adequately describes the main processes occurring in the sieve under the influence of forced oscillations.

Conflict of interest

Authors state no conflict of interest.

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ЕКСПЕРИМЕНТАЛЬНІ ДОСЛІДЖЕННЯ ДИНАМІКИ ВІБРАЦІЙНОГО ПОЛІЧАСТОТНОГО СИТА ДЛЯ ОЧИЩЕННЯ БУРОВИХ РОЗЧИНІВ

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Анотація. Проведено оцінку адекватності математичної моделі вібраційного полічастотного сита. Для визначення параметрів коливань експериментального зразка сита було проведено вимірювання прискорень коливань ударника сита. Аналіз осцилограм прискорень коливань ударника показав, що при взаємодії з обмежувачами в ударнику періодично збуджуються пікові прискорення, які суттєво перевищують прискорення у безударні моменти руху, також в найближчі моменти часу збуджуються як позитивні, так і негативні прискорення. Результати спектрального аналізу прискорень ударника сита показали, що спектри є суцільними, оскільки на спектрограмі в заданому частотному діапазоні присутні всі частоти, а у зміні амплітудних значень збуджуваних частот відсутня будь-яка закономірність. Ударник сита здійснює неперіодичні чи хаотичні коливання, при цьому амплітуди прискорень коливань на значній кількості частот, що збуджуються, перевищують амплітуду на частоті зовнішнього збудження. Крім пікових ударних прискорень, в ударнику експериментального зразка сита між ударами збуджуються неперіодичні та нерівномірні, знакозмінні прискорення, що свідчить про виникнення у ситі додаткових джерел збудження коливань. Внаслідок цього відбувається постійне резонування всіх структурних елементів конструкції сита, що посилює коливання, і призводить до того, що амплітуди прискорень коливань на значній кількості частот, що збуджуються, перевищують амплітуду на частоті зовнішнього збудження. У вібраційному полічастотному ситі енергія ударної взаємодії залежить від співвідношення мас, між ударником і корпусом сита, сили, що збуджується мотор-вібратором, величин динамічних зазорів в пружних обмежуючих зв'язках і параметрів самих зв'язків і пружної системи, а частотний спектр також залежить від демпфування коливань в елементах конструкції сита. Математична модель сита в силу прийнятих припущень описує тільки основні коливання, викликані впливом віброзбудника і ударними взаємодіями з пружними обмежувачами переміщень ударника. Оцінка адекватності математичної моделі показала збіг частот коливань ударника по моделі та експериментального зразка сита та відносну похибку в розбіжності ударних прискорень, яка не перевищує 10 %.

Ключові слова: вібраційне полічастотне сито, очищення бурових розчинів, експериментальні дослідження, динаміка, математична модель, спектральний аналіз.