



Research article

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Application of resonance functions in estimating the parameters of interwell zones

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Abstract. It is shown that the use of force resonance leads to the effect of “shaking” the formation, followed by breaking up the film oil and involving it in the further filtration process. For the first time in oilfield geophysics, the concept of passive noise-metering method is justified for monitoring oil and gas deposit development by measuring the quality factor of the contours in the point areas of formation development channels in interwell zones. It is established that determining the depth of modulation for the reactive substitution parameter of the linear FDC chain is crucial not only for determining the parametric excitation in FDC attenuation systems, but also without attenuation in the metrological support for the analysis of petrophysical properties of rock samples from the wells. It is shown that based on the method of complex amplitudes (for formation pressure current, differential flow rates, impedance), different families of resonance curves can be plotted: displacement amplitudes (for differential flow rates on the piezocapacity of the studied formation section), velocities (amplitudes of formation pressure current) and accelerations (amplitudes of differential flow rates on the linear piezoinductivity of the FDC section). The use of predicted permeability and porosity properties of the reservoir with its continuous regulation leads to increased accuracy of isolation in each subsequent sub-cycle of new segment formation in the FDC trajectories, which contributes to a more complete development of productive hydrocarbon deposits and increases the reliability of prediction for development indicators.

Keywords: productive formation parameters; formation development channel; wave resonance; interwell zone; permeability and porosity properties

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Introduction. One of the most efficient formation stimulation methods is waterflooding of productive horizons [1-3]. However, the efficiency of this method is not high enough and in some cases it can be negative [4, 5], which reflects a wide variety of deposits by geological structure [6, 8]. In this regard, investigations have been conducted, which refer to the field of fluid mechanics of oil recovery with increased indices of productive formation recovery by contours of its operating objects volume, developed with artificial waterflooding [9-11]. At the same time, the oil recovery factor (ORF) of a formation is largely determined by reliability and accuracy of predicting its parameters [12-14]. The Fetkovich palette method [15] and its variants: Blassingeme, Agarwal – Gardner, NPI and others are the most acceptable for predicting [16-18]. They are based on geological and geophysical data on the results of investigations of flow rate and pressure in injection (IW) and production (PW) wells [19-21]. However, their inherent low metrological capabilities of current formation parameters prediction should be taken into account. All these methods by their measurement capabilities refer to the class of indicator methods, as their reduced errors exceed permissible values ($\delta > 10\%$) both in steady-state and non-steady-state hydrocarbon recovery modes [22-24].

For this case, the problem of predicting formation permeability and porosity properties (PPP) under steady-state conditions is determinable. At the same time, the ORF for profitably operating



fields is 0.35 [25-27]. In general, the essence of investigating the predictable parameters is to determine the parameters of wave resonances. Their most demonstrative results were obtained in electrical, acoustic and other types of systems with concentrated parameters of control objects. However, the technological processes of, for example, adjacent petrochemical industries, are difficult to implement.

For the first time, Russian scientists (A.G. Butkovsky, E. Ya. Rapoport and others) substantiated directions for research of systems with distributed parameters. However, their modelling results refer only to available measurements of parameters of zonal sections (segments) of control objects. Conditions for modelling of formation operation with spatially distributed coordinates on the basis of electromechanical and hydraulic analogies are significantly violated in non-stationary mode of oil extraction [28-30].

The problems aggravate when modelling the formation performance based on more advanced hyperbolic equations instead of the previously used parabolic equations [31-33]. This is particularly noticeable in the implementation of meta-technology of hard-to-recover hydrocarbons production (HRH), when the operation object is subjected to extreme regulation [4, 16, 34]. Thus, adequate results are obtained in dimensionless formation values when modelling and solving Cauchy problem due to implementation of HRH meta-technology. In this case, stability and quality conditions of fluid mechanics of oil recovery can be obtained in computational form based on the mathematical apparatus of wave resonance [35-37].

Based on mentioned conditions, the aim of the work is to increase reliability and accuracy of predicting the parameters of remote interwell formation zones with extreme regulation of the wave resonance function in the process of increasing the oil recovery factor.

Methodology. Achievement of the generalized aim for the most complete formation development is ensured by numerical modelling and solution of two types of problems. The first one implies the use of a hyperbolic type hydromechanics model of oil displacement [34] in modelling the chain structure based on the parameters of hydroresistivity R_h of the flow tube, piezoinductivity in piezconductance ($L_h \equiv F(\eta)$) and piezocapacity ($C_h \equiv F(\sigma_{oil, res})$) in oil saturation of the formation section, with the addition of average results for petrophysics in metrological support of previous and intermediate stages of oil and gas deposits development (ODD).

The solution of the second problem is connected with determining the parameters of remote interwell zones by applying the principle of autonomy, which was first realized by using a new meta-technology of HRH production [38-40]. The essence of its implementation consists in combining oil displacement, investigation and isolating modes of areas in the formation development channel (FDC) with fulfillment of conditions: $P_{od, min} < P_{od, r} < P_{od, max} < P_{inv} < P_{is} < P_{hydr}$. These values are shown in Fig.1 as formation pressure maintenance: P_{inv} – investigation; maximum $P_{od, max}$, rated $P_{od, r}$ and minimum $P_{od, min}$ values during oil displacement; P_{hydr} – the value of hydraulic fracturing pressure.

In epures E_1 and E_2 (Fig.1), isolation pressure P_{is} is not used conditionally, since it is applied only in operations of isolation of worn-out FDC sections with a value less than hydraulic fracturing pressure. The investigation pressure P_{inv} is selected for the hard mode of formation operation, the elastic mode of which is used as the oil displacement mode.

The upper epure E_1 shows conditionally the operation of estimated delivery time τ_{inv}^t for portion of tracer markers under formation pressure P_{inv} to the estimated point i ($i = \overline{1, n}$) in controlled area of interwell zone. After that, a transition to oil displacement mode under pressure $P_{od, r}$ is made at calculated time τ_{odi}^t .

Epure E_2 shows the practical results of point i investigation in the FDC over time τ_{inv}^{pr} and delay τ_{del} during transient formation. At the completion of tracer markers delivery to a FDC given point from booster pumping equipment in surface conditions the formation pressure maintenance is reduced from P_{inv} to $P_{od, r}$.



Series of points 1, 2, 3 and 4 are formed at the tops of the transient processes under formation conditions (from the IW near-bottomhole zone side). This reflects the dynamics of the practical result for evolutionary development of the single i fluctuation F_i^{pr} at pressures with maximum five-point and minimum six-point values of amplitude. After formation of the transient process in the hard formation mode (between P_{inv} and $P_{op,max}$), the fluctuation F_i^{pr} is firstly produced with its further transition to the elastic mode, as depicted in the example of attenuation of the amplitudes to the minimum defined point 6.

Each fluctuation F_i^{pr} is characterized by different lengths (or slope) of forward (ascending branch) and back (descending branch) fronts of transient processes during current prediction of residual oil saturation $\sigma_{oil,res}$ and piezoconductance η linear values [15, 29, 41]. In terms of hydraulic shock theory, such localization of fronts of each fluctuation is characterized as amplitude of pulsations smoothing (“slumping”) in the disturbed interwell FDC area at continuous changes. All this causes determination of variable parameters of the FDC trajectories in the form of linear hydraulic resistance R_h , piezoinductivity L_h and piezocapacity C_h .

If the current parameters of steady-state investigation τ_{inv}^r and oil displacement τ_{odi}^r processes can be predicted in the solutions of hyperbolic equations according to the chain FDC scheme, then in non-steady-state transient processes of the formation additional parameters can be predicted according to the localized autonomous oscillator scheme.

From the point of view of electrohydraulic analogies, the method of complex amplitudes is the most appropriate for this research problem. The equation of motion for the oscillator can be expressed as:

$$L_h \frac{\partial P}{\partial t} + R_h P + \frac{1}{C_h} \int P \partial t = \tilde{q}_0 e^{j\omega t}, \tag{1}$$

where P – pressure in the tube of current lines at the developed formation; \tilde{q} – the difference in potential fluid flow rates between the injection and production wells; ω – frequency of the excitable oscillations.

When solving equation (1) by the method of complex amplitudes (for pressure in FDC current tube $P = P e^{j\omega t}$), we obtain $P = \tilde{q}_0 / Z$, $Z_h = R_h + j(\omega L_h - 1/\omega C_h)$, which is complex resistance of oscillator on line FDC section. For formation pressure modulus in formation current tube will be:

$$|P| = P_0 = \frac{\tilde{q}_0}{|Z|} = \frac{\tilde{q}_0}{\sqrt{R_h^2 + (\omega L_h - 1/\omega C_h)^2}}$$

To find the maximum formation pressure in the current tube of the formation, the condition $P_{0max} = \tilde{q}_0 / R$ must be met when $\omega L_h = 1/\omega C_h$ (at $\omega = \omega_0$).

Based on the conditions obtained, normalized resonance curves for formation pressure can be found in the form of a functional:

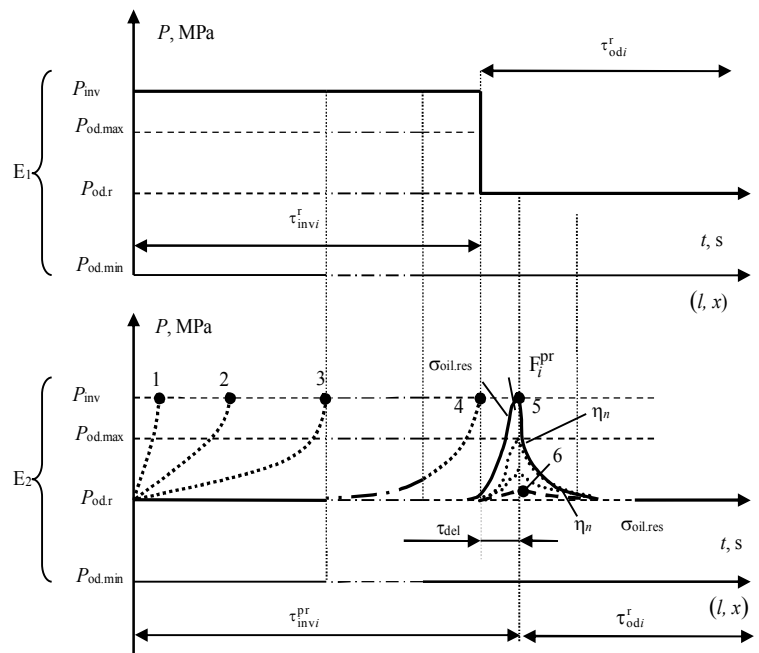


Fig. 1. Time diagrams of transient processes in FDC



$$F_{P_0}(\nu) = \frac{P_0}{P_{0max}} = \frac{R}{\sqrt{R_h^2 + (\omega L - 1/\omega C_h)^2}} = \frac{1}{\sqrt{1 + \gamma^2 \theta_0^2 (1 - 1/\gamma^2)^2}}, \quad (2)$$

where P_{0max} – maximum formation pressure; $\theta_0 = \omega_0 L/R$ – quality factor of the resonant circuit; $\gamma = \omega/\omega_0$ – coefficient of resonant frequencies in the ratio of the forced circular frequency ω to the natural ω_0 frequency of the resonant circuit (oscillator) of the investigated area in the remote FDC zone.

Figure 2 shows series of normalized resonance curves for the formation pressure in the linear current tube of the FDC when their quality factors $\theta_0 = 1; 2; 10$ are depicted.

Resonance of the flow rate drops as tension on the piezocapacity $\theta_0 \tilde{q}_0$ is obtained at a lower natural frequency ω_0 with respect to the circular frequency ω . This is achieved under (2) at $\gamma^2 = 1 - 1/2\theta_0^2$. In contrast, the flow rate drops as tension on the piezocapacity $\theta_0 \tilde{q}_0$ are obtained at a higher natural frequency ω_0 with respect to the circular frequency ω at $\gamma^2 = 1 + 1/2\theta_0^2$.

Presented resonance curves correspond to the results of investigations on deteriorated areas in the remote zone of the formation. Therefore, they are obtained with unambiguous symmetry of resonances for an oscillator with the following parameters: $L_h = \text{const}$; $C_h = \text{const}$; $R_h = \text{const}$; and only the values of the frequencies of excited oscillations are variable ($\omega = \text{var}$).

It is of practical interest to determine resonance dependencies when one of the energy-consuming linear parameters of piezocapacity or piezoinductivity in the investigated FDC segment changes: $L_h = \text{var}$ (or $C_h = \text{var}$) at $P = \text{const}$. For example, determining the parameters at the critical point of the investigated FDC area by calculating the values of piezoconductance. In this case, normalized

resonance curves in the form of current functional for formation pressure when changing natural frequency of the circuit can be found in analogy (2):

$$F_{P_0}(\omega_0) = \frac{P_0(\omega_0)}{P_{0max}} = \frac{1}{\sqrt{1 + \theta_0^2 (1/\gamma^2 - 1)^2}}, \quad (3)$$

where $\theta_0 = \omega L_h/R_h$ – quality factor of a resonant circuit at a constant forced oscillation frequency ω .

Figure 3 shows the family of resonance curves at changing of natural frequency of autonomous FDC oscillators for quality factors $\theta_0 = 1; 3; 10$. Thus, changing of one of reactive resistances (L_h) leads to changing of natural frequency of oscillator ω_0 .

This problem is considered in terms of the sensitivity threshold for optimal oil recovery. The solution to this problem is to a large extent reduced to the study of parametric resonance of remote areas in the interwell zones. At the same time, theory of oscillations considers the modulation depth of piezocapacity C_h or piezoinductivity L_h as the basic calculation values for this case.

By analogy with electrical oscillation systems, the depth of modulation for the piezocapacity as a function of residual oil saturation can be defined as:

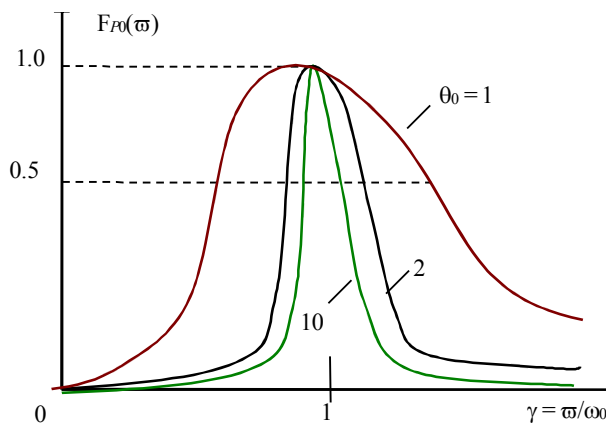


Fig.2. Interpretation of normalized resonance curves for different quality factors of autonomous FDC oscillators

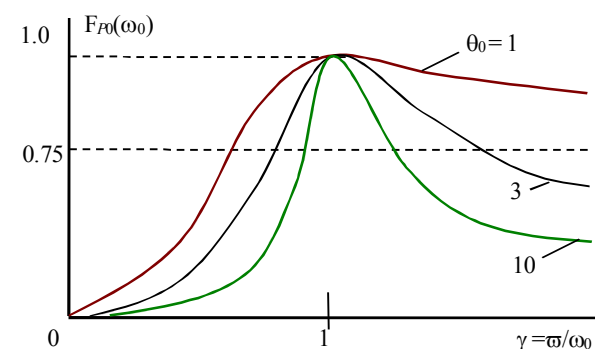


Fig.3. Family of resonance curves at changing of natural frequency of autonomous FDC oscillators for quality factors 1; 3; 10



$$\tilde{m}_C = \frac{C_{h,\max} - C_{h,\min}}{C_{h,\min} + C_{h,\min}} = \frac{\Delta C_h}{C_{0h}}, \quad (4)$$

and the depth of modulation for the piezoinductivity as a function of the piezoconductance of the controlled remote area of the formation can be expressed as:

$$\tilde{m}_L = \frac{L_{h,\max} - L_{h,\min}}{L_{h,\max} + L_{h,\min}} = \frac{\Delta L_h}{L_{0h}}, \quad (5)$$

where the increment of piezocapacity ΔC_h (or piezoinductivity ΔL_h) is many times less than its nominal value $\Delta C_h \ll C_{0h}$ (or $\Delta L_h \ll L_{0h}$).

If the energy input exceeds the losses, then there is an increase in the system oscillation:

$$\tilde{m} > \tilde{m}_{\text{thr}} = \frac{1}{2} \pi R \sqrt{\frac{C_0}{L}} = \frac{1}{2} d, \quad (6)$$

where d – logarithmic decrement of oscillation attenuation in the circuit.

In general, the description of parametric resonance for all systems is done using a differential equation in variable states, a particular form of which is the Mathieu equation:

$$\ddot{y} + \omega_0^2(1 + m \cos(\varpi t))y = 0, \quad (7)$$

where \ddot{y} – changes (in the second derivative) of the system state to characterize it in the phase plane; ω_0^2 – squared values of the resonance frequency of the system; m – the depth of modulation for the resulting parametric resonance. In this case, the solution of the Mathieu equation (7) is reduced to determining not only the modulation depth m , but also the value regions of the frequency ratio $2\omega_0/\varpi$.

Russian scientists A.A.Andronov and M.A.Leontovich calculated these ranges of values for systems without attenuation (necessary for determining the petrophysical properties of the rock sample) and with attenuation (providing for determination of FDC linear PPP) based on the following equations:

$$\ddot{x} + \omega_0^2(1 + m \cos(\varpi t))x = 0; \quad (8)$$

$$\ddot{y} + 2\delta\dot{y} + \omega_0^2(1 + m \cos(\varpi t))y = 0. \quad (9)$$

The results of the calculations can be explained in the form of graphs (Fig.4), which show that the tops of the parametric instability regions rise in the presence of losses in the system. In the case

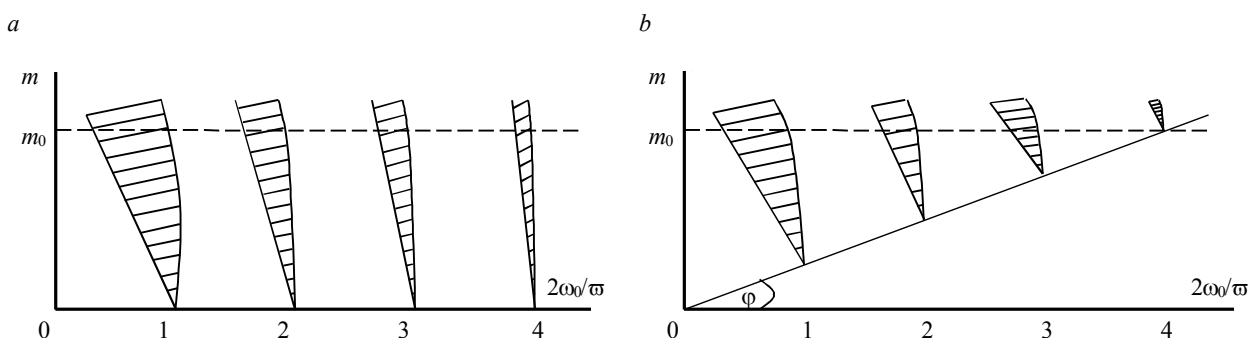


Fig.4. Areas of parametric excitation of autonomous FDC oscillators for the system without attenuation (a) and with attenuation (b)



of a conservative system, there is a non-attenuated complex process outside these regions, and in the case of a dissipative system there is a attenuated oscillation process. At the boundary of these regions a balance of energy is observed.

In the same regions the width of the instability region is smaller for dissipative than for conservative oscillatory system. As the number of the instability region increases, due to a rarer energy input into the system ($\varpi = 2\omega/n$ at $n = 1, 2, 3 \dots$) to obtain the same width of the excitation region one must increase the modulation depth of the reactive parameter m .

Thus, the obtained values of parametric excitation without attenuation (Fig.4, a) can serve as a basis for petrophysical determination of wave properties for rock samples parameters at metrological support of investigations, and with attenuation for determining parameters of the studied FDC segments. Combined use of force and parametric resonance methods provides reliable prediction of parameters for separate regions of interwell distant zones.

Discussion of the results. In the late stages of ODD, formation ORF values are conditioned by a small increase [42, 43]. Therefore, for oscillators at different points I in FDC between IW and PW, linear parameters $R_h \approx \text{const}$ and $C_h \approx \text{const}$. The depleted regions of the interwell zones are characterized by variable values of piezoconductance, i.e. the linear piezoinductivity $L_h \approx \text{var}$.

Figure 5 shows E_1 and E_2 epures of the results for interwell investigations in spatial formation geometry (E_1) and the determination of piezoconductance values (E_2).

The basis of instrumentation for the considered investigations is a complex well equipment installed in the intervals of IW and PW perforation. It consists of well pressure, temperature, flow rate and watercut transducers together with passive noise-metering and gamma equipment for tracer markers control.

As a result of the FDC parameters investigation using quality factor diagrams (see Fig.2, 3), the deteriorated areas of the interwell zones are determined based on the force resonance techniques with identification of areas A, B and C.

When the formation is investigated in the later stages of deposit development, spatial and temporal coordinates are determined in parametric resonance to determine the isolation points of the FDC segments by determining their piezoconductance. As a result, regions of different piezoconductance are identified on the E_2 epure to determine further isolation operations of the segments in the functioning trajectories of the / FDC.

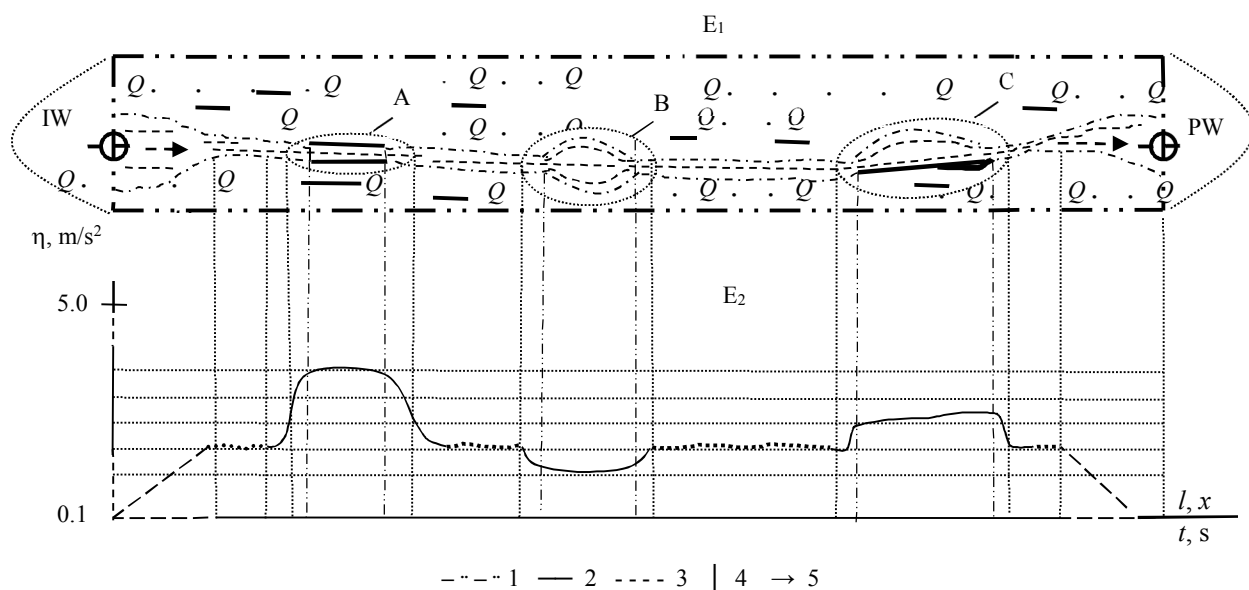


Fig.5. Epures of results for the investigations of interwell zones (Q – residual oil saturation)

1 – production object contour; 2 – carbonate inclusions; 3 – working agent (water) phase; 4 – sandstone rock; 5 – fluid flow direction



Conclusion. The use of force resonance leads to the effect of “shaking” the formation, followed by breaking up the film oil and involving it in the further filtration process. This necessitates control of quality factor in the point area of the remote FDC zone when excited, as well as additional implementation of parametric resonance conditions.

For the first time in oilfield geophysics, the concept of passive noise-metering method is justified for monitoring ODD by measuring the quality factor of the contours in the point areas of interwell zones. Application of measurements for slowly changing amplitude-frequency spectrum during the “slumping” of the resonance region in the study area is also justified for the first time.

Parametric excitation of oscillations in the controlled FDC region is possible only by changing one of the energy-intensive linear parameters of piezocapacity C_h as a function of oil saturation or piezoinductivity L_h as a function of piezoconductance with terrigenous, clay and carbonate rocks of productive formations.

Determining the depth of modulation for the reactive substitution parameter of the linear FDC chain is crucial not only for determining the parametric excitation in FDC attenuation systems, but also without attenuation in the metrological support for the analysis of petrophysical properties of rock samples.

Based on the method of complex amplitudes (for formation pressure current, differential flow rates, impedance), different families of resonance curves can be plotted: displacement amplitudes (for differential flow rates on the piezocapacity of the studied formation section), velocities (amplitudes of formation pressure current) and accelerations (amplitudes of differential flow rates on the linear piezoinductivity of the FDC section).

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