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TÍTULO: Algoritmos de aproximación para el análisis de las características dinámicas de los generadores de señales de sondeo para los sistemas de monitoreo geotécnico.

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RESUMEN. El documento considera los problemas de desarrollo y diseño del subsistema para la formación y gestión de señales de sondeo para monitoreo geotécnico, que se basa en el método de sondeo de ondas de radio de la cimentación subterránea de los edificios. Esta técnica permite identificar y prevenir rápidamente procesos irreversibles (destrucción, deformación) en la base del suelo, que surgen bajo la influencia de cargas estáticas, sísmicas y dinámicas. Se desarrolla el algoritmo de análisis de la estabilidad de los sintetizadores computacionales digitales con compensación automática de las distorsiones de fase, que se utilizan como generadores de señales de sondeo para los sistemas de monitoreo geotécnicos.

PALABRAS CLAVES: monitoreo geotécnico, generadores de señales de sondeo, sintetizadores de frecuencia, compensación automática, distorsiones de fase.

TITLE: Approximation algorithms for analyzing the dynamic characteristics of the Probing Signal Generators for the Geotechnical Monitoring Systems.

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ABSTRACT: The paper considers the issues of development and design of the subsystem for the formation and management of probing signals for geotechnical monitoring, which is based on the method of radio wave sounding of the underground foundation of the buildings. This technique allowing quickly identify and prevent irreversible processes (destruction, deformation) in soil foundation, which arise under the influence of static, seismic and dynamic loads. The algorithm of analyzing the stability of digital computational synthesizers with automatic compensation of the phase distortions, used as probing signal generators for the geotechnical monitoring systems, is developed.

KEY WORDS: geotechnical monitoring, probing signal generators, frequency synthesizers, automatic compensation, phase distortions.

INTRODUCTION.

The requirements for the organization of geotechnical monitoring are expanding every year. Higher requirements are imposed on the organization of geotechnical monitoring at high-hazard technical facilities (nuclear reactors, fuel and energy complexes, etc.) (Sharapov, Kuzichkin, 2014; Sharapov, Kuzichkin, 2013). Geotechnical monitoring is a complex of works based on the observations of the behavior of the design of engineering structures (buildings) and the geological zone of their location. The purpose of geotechnical monitoring is the identification and prevention of irreversible processes of deformation and destruction of the construction of the buildings in soil foundation which arise under the influence of static, seismic and dynamic loads (Savin, 2000).

One of the most promising methods of geotechnical monitoring is the use of radio wave sounding of underground foundation of the buildings. Detailsation of the data in depth can be carried out by changing the frequency of the probing signals. This technique is based on the phenomenon of skin effect, which consists in the fact that currents are concentrated in the rather narrow upper ground layer when scanning the surface with high-frequency signals, and when scanning with low-frequency signals, currents penetrate more into the depth of the surface (Salawu, 1997). As a result, the role of sounding is reduced to an assessment of the characteristics of the vertical electric section in the limited area of an inhomogeneous geological environment. These studies make it possible to identify of the current state of the monitoring object and its trend of change with a view to further forecasting.

An important task in the practical implementation of the technique under investigation is the design of a probing signal forming device capable of ensuring the coherence of a discrete set of generated frequencies in a given frequency spectrum range, their high accuracy, stability and speed in reorganization. At the same time, it is necessary to take into account that the range of output frequencies of the signal former and their resolution is determined by the size of the construction of the buildings and the required depth of the conducting study.

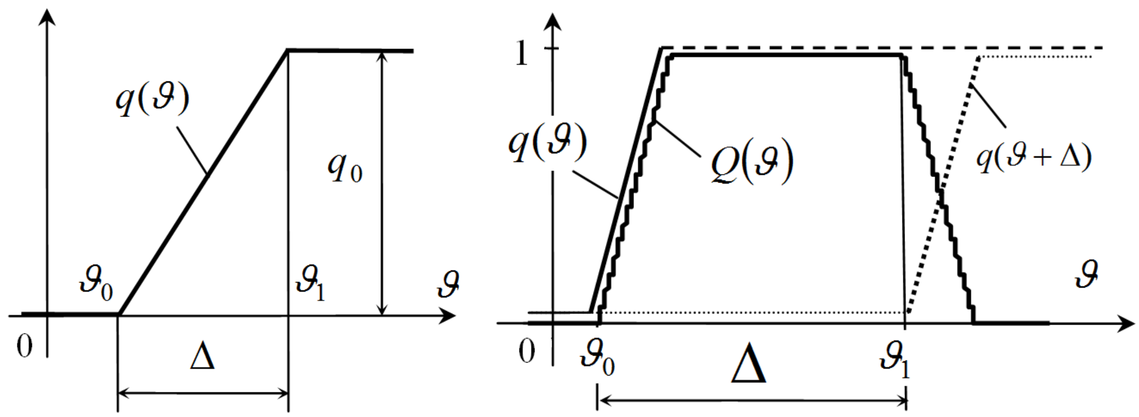
An effective solution to the formation of probing signals for tasks of geotechnical monitoring can be the use of digital computational synthesizers (DCS) (Vankka, 2000; Kroupa, 2003; Goldberg, 1999; Belov, 2005.). Synthesizers will automatically compensate for phase distortions associated with the presence in the spectrum of the synthesized signal of a set of discrete parasitic spectral components.

The separate complexity is the analysis of the characteristics of the DCS (and synthesized signals by it), which is caused by the introduction into its circuit the devices of the auto compensation circuit with different types of regulation (deviation, disturbance or combined), since the devices in this case are described by nonlinear differential equations of high order (Ridiko, 2001; Koester, 2007; Surzhik, 2015.). In this case, it is necessary using approximation methods to obtain analytical or numerical solutions, which use for designing and analyzing the subsystem for the formation and control of probing signals in geotechnical monitoring.

The method for approximating of the nonlinear characteristics of the probing signals former by the continuous piecewise functions.

The conducted research has shown the effectiveness of approximation (various effects, nonlinear and frequency characteristics of radio devices, characteristics of probing signal generators) by continuous piecewise functions (CPF), which have high accuracy and simple analytical recording form (Vasilyev, 2013; Kurilov, 2014).

At this moment, the authors of this paper have developed several types of CPF, the main of which are switching and incorporating CPF (Figure 1).



a) б)

Figure 1 - Switching (a) and inclusive (b) CPF.

As can be seen in Fig. 1, the switching CPF serves as the basis for obtaining other CPFs and consists of three linear sections (Murphy, 2005). The accuracy of the approximation depends on the approximation step and on the order of the approximating functions, which makes it possible to represent the nonlinear characteristics of the formers of the probing signals with the required accuracy.

The general formula of the approximating function based on the application of switching CPFs for the generalized variable ϑ has the form:

$$q_{\Sigma}(\vartheta)=\sum_{i=0}^{N-1} q_i(\vartheta)=\sum_{i=0}^{N-1}\frac{q_{0_i}}{2\Delta_i}\left(\left|\vartheta-\vartheta_i\right|-\left|\vartheta-\vartheta_i+\Delta_i\right|+\Delta_i\right), \quad (1)$$

where ϑ_i is the value of the argument in the current approximation node, N is the number of approximation nodes, q_{0_i} is the approximation coefficient of the i-th function, $\Delta_i=\vartheta_{i+1}-\vartheta_i$ is the approximation step.

Another considered form of CPF (inclusive) is an elementary approximating function with a flat vertex, consisting of four linear modules and taking the value "1" in the interval $(\vartheta_0;\vartheta_1)$ and "0" outside it. This is a simple way to approximate a specific characteristic on a separate interval, where its value is "1" and ignore its change outside this interval.

The general formula of the inclusive CPF has the form:

$$Q_i(\vartheta) = K_\sigma \sum_{\lambda=0}^{1} \sum_{\gamma=0}^{1} (-1)^{\lambda+\gamma} \left| \vartheta - \vartheta_i - \gamma \Delta_i - \frac{\lambda}{2K_\sigma} \right|, \quad (2)$$

where K_σ is the steepness of the CPF; λ, γ are the coefficients equal to "0"or "1".

In order to approximate the nonlinear characteristic of the probing signals former (Figure 2), it is required to multiply the inclusive CPFs by linear functions corresponding to these sections:

$$Q_\Sigma(\vartheta) = \sum_{i=0}^{N-1} f_i(\vartheta) = \sum_{i=0}^{N-1} (K_i \vartheta + L_i) Q_i(\vartheta), \quad (3)$$

where N is the order of the approximating function, $K_i = \dfrac{f(\vartheta_{i+1}) - f(\vartheta_i)}{\Delta_i}$ is the steepness of the i-th approximating line, $L_i = f(\vartheta_i) - K_i \vartheta_i$ is the value of the i-th straight line at $\vartheta = 0$.

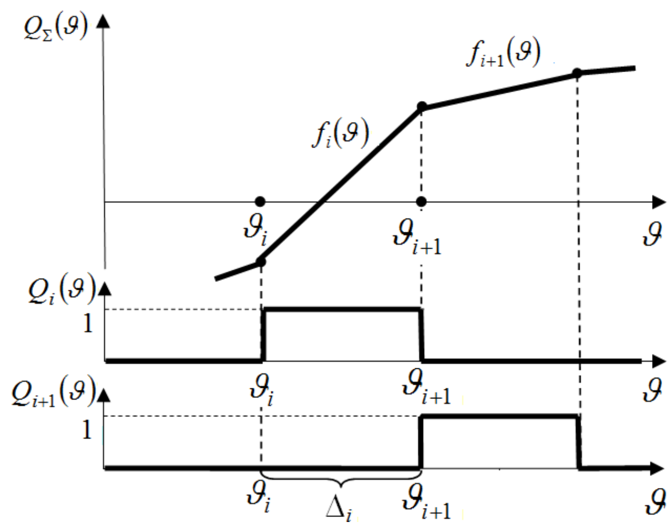


Figure 2 - Approximation of the nonlinear characteristic of the probing signals former using inclusive CPFs.

The considered CPFs can be used to approximate of the non-linear characteristics by applying analytical methods for analyzing of the dynamic regimes for the various of generating signals devices to the geotechnical monitoring systems, in particular, the former of the probing signals based on a CPFs with automatic compensation of phase distortions (Yampurin, 2003).

The algorithm of analyzing of the parametric stability of the probing signals former.

One of the most important quality indicators that determine of the efficiency of signal forming devices is its stability with changes in the parameters of functional links and qualitative dynamic changes in the monitoring object. In the general case, an arbitrary feedback device is stable if all the roots of the characteristic polynomial of its transfer function have a negative real part. When this condition is fulfilled and at least one imaginary root is present, the device is at the stability boundary.

The algorithm for analyzing the parametric stability of the devices for forming of the probing signals (DFSS) for geotechnical monitoring systems is developed. This algorithm based on the Nyquist frequency criterion. A block diagram of this algorithm is shown in figure 3.

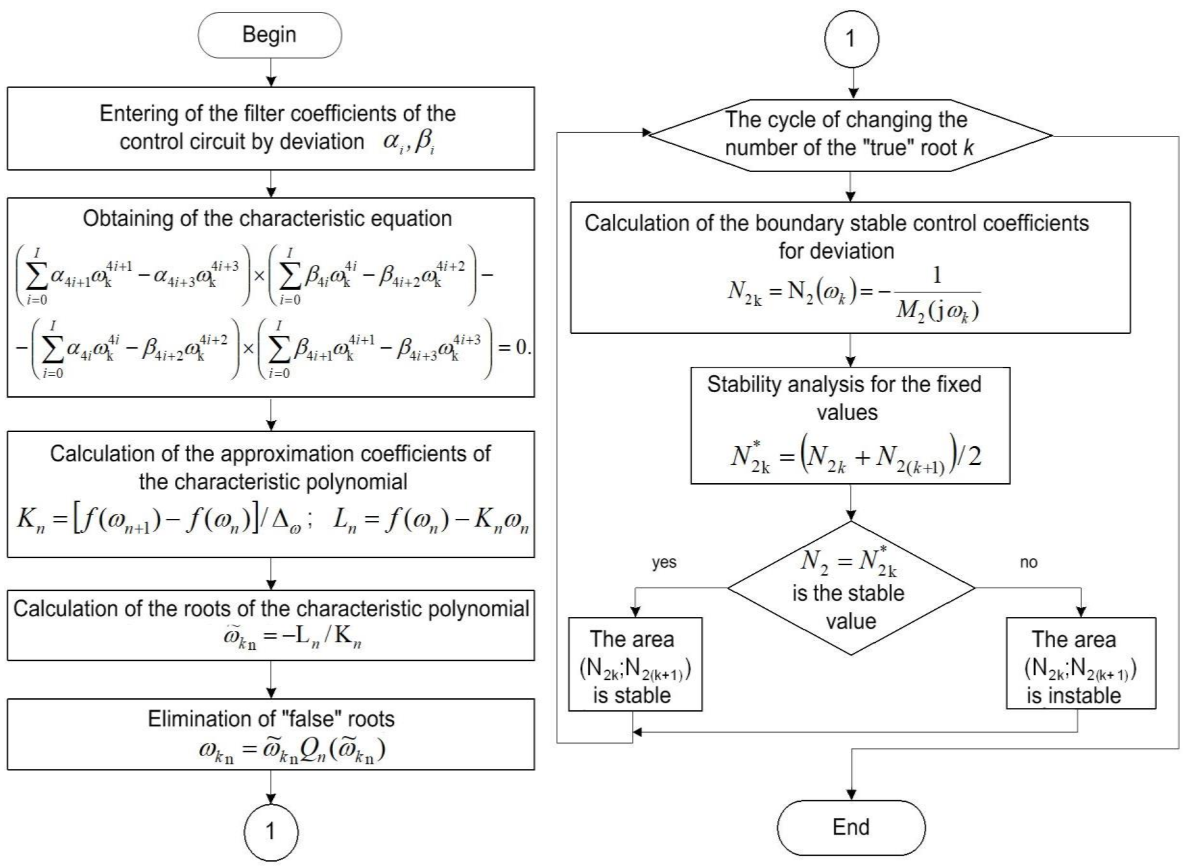


Figure 3 - The block-diagram of the algorithm for analyzing the stability of the former of probing signals based on the approximation with the use of CPF.

The algorithm is based on the analysis of the characteristic operator polynomials of the denominators of the transfer function of the former of the probing signals. Polynomials are defined by the presence of a control device with one or more feedback loops over the signal being recorded:

$$1 + N_2 M_2(p) = 0\,, \tag{4}$$

where N_2 is the frequency-independent transmission coefficient of the open control feedback loop, $M_2(p)$ is the frequency-dependent transmission coefficient of the open feedback loop, p is the Laplace operator.

The former by the Nyquist criterion is stable under the condition that the imaginary part of the transmission coefficient of the open control loop $M_2(p)$ is zero:

$$\mathrm{Im}[M_2(\mathrm{j}\omega)] = \mathrm{Im}[\sum_{i=0}^{I} \alpha_i (\mathrm{j}\omega_k)^i \Big/ \sum_{i=0}^{I} \beta_i (\mathrm{j}\omega_k)^i] = 0\,, \tag{5}$$

where I is the order of the transmission ratio of the control circuit, α_i, β_i are the transmission coefficient parameters, ω_k is the critical frequencies (the root values corresponding to the stability boundary), k the root number.

To find the roots of a given polynomial whose general solution is absent, it is necessary to designate its left-hand side as a function of frequency $f(\omega)$ and approximate it with the help of CPF (3), where the roots of the resultant polynomial are defined as the intersection points of the approximating lines with the abscissa axis.

According to formula (4), it is obvious that the boundary values of the frequency-independent coefficient of the former N_{2k} for each true root corresponding the values:

$$N_{2k} = N_2(\omega_k) = -\frac{1}{M_2(j\omega_k)}\,. \tag{6}$$

With the value of the frequency-independent coefficient N_2=0, the former of the probing signals will be stable for any type and order of the filter used. Thus, in order to find the resulting boundary of parametric stability, it is necessary to choose one negative and one positive from all the boundary coefficients (6), which are close to zero, i.e. define the area $N_2^L \leq N_2 \leq N_2^H$. The lower limit of this area N_2^L corresponds to the maximum of all negative values N_{2k}, the upper limit N_2^H to the minimum of all positive values N_{2k}.

In general, the area of stability in geotechnical control systems is multiply connected, that is, it consists of several section. In many practical examples (Vasilyev, 2013; Postnikov, 1981), the section of the multiply connected domain is small and can be point wise for the variation of the coefficients of the characteristic polynomial. The choice of the circuit parameters in one of these small stable sections is unacceptable, since it can lead to loss of stability when the parameters are changed. Thus, the stable functioning of the former is guaranteed only in a simply connected area (section) $N_2^L \leq N_2 \leq N_2^H$. The stability (instability) of a DFSS when a fixed $N_2 = N_{2k}^*$ determines the stability (instability) of a section $N_{2k} \leq N_{2k}^* \leq N_{2k+1}$ and can be easily verified by the Routh-Hurwitz criterion (Grecheneva, et al, 2017).

The algorithm for calculating and analyzing of the dynamic characteristics of the probing signal formers.

To assess the duration and character of transient processes when switching of the formers of probing signals from one frequency to another, one must study their dynamic properties by considering the reaction to typical deterministic impacts.

The algorithm is developed for calculating the dynamic characteristics of the formers of probing signals using approximation based on the CPF and the spectral method. Its block diagram is shown in Fig. 4.

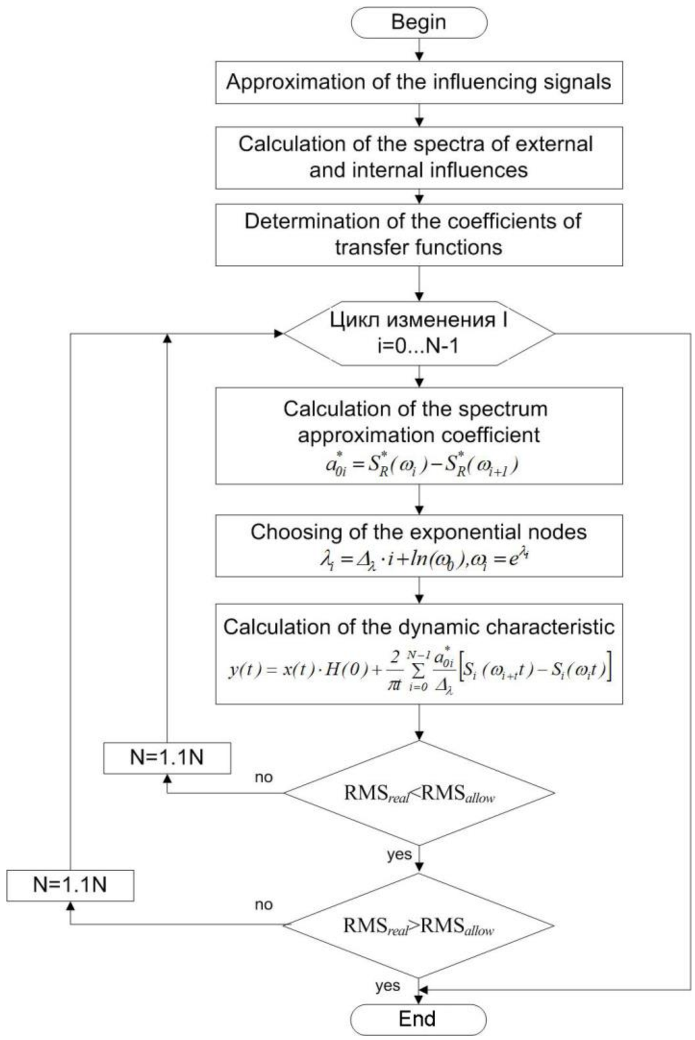


Figure 4 - The block diagram of the algorithm for calculating the dynamic characteristics of the formers of probing signals, based on the use of approximation based on the CPF and the spectral method.

The first stage of the shown algorithm is the approximation of the input signal acting on the researching former with the sum of the switching CPF (1). Next, the spectrum of the input signal $X(j\omega)$ is calculated using the Fourier transform and the determination of the transmission coefficients of the structural links of this device. Further, with the known spectrum of the action $S_{вых}(j\omega)$ and the transfer function of the former of probing signal $H(j\omega)$, an inverse Fourier transform is performed to calculate the output signal of the former. A spectral method is used and the real $S_R(\omega) = Re[S_{вых}(j\omega)]$ and imaginary $S_I(\omega) = Im[S_{вых}(j\omega)]$ parts of the spectral density of the output signal are approximated on the basis of switching CPFs. The generalized analytical formulas obtained in the case of approximation of the real spectrum $S_R(\omega)$ of the logarithmic frequency have the form:

$$y(t) = x(t) \cdot H(0) + \frac{2}{\pi t} \sum_{i=0}^{N-1} \frac{a_{0i}}{\Delta_\lambda} \left[Si(\omega_{i+1} t) - Si(\omega_i t) \right], \quad (8)$$

where $x(t)$ is the input signal of the device; $a_{0i} = S_R(\omega_i) - S_R(\omega_{i+1})$ is the coefficient of CPF approximating $S_R(\omega)$ in the current section $[\omega_i; \omega_{i+1}]$; Δ_λ is the step of the logarithmic frequency; $Si(x)$ is the integral sine.

The algorithm contains the control of the accuracy of the calculated dynamic characteristic of the sounding sensor driver on the basis of the comparison of the achieved (RMS_{real}) and the allowable (RMS_{allow}) error.

CONCLUSIONS.

The proposed technique and algorithms implemented on the basis of switching CPFs were applied during the deployment of the geotechnical monitoring system on the life support facilities in the karst areas of the Nizhny Novgorod region (Russia) as part of the implementation of the project of the Ministry of Education and Science of the Russian Federation No. 5.3606.2017 "Development of technology for early detection and forecasting of emergency situations in the natural-technical systems based on automated joint processing of heterogeneous geodynamic and geological data of the technical monitoring at local levels" (Kuzichkin, et al. 2017; Waldman, et al. 2018; Salman & Borkar, 2016). Practical results proved that the technique possesses a high degree of accuracy in describing the characteristics of the arbitrary devices, allow one to simulate and investigate the stability and dynamic characteristics of the formers of probing signals for the geotechnical monitoring systems. The characteristics of the systems realized on the basis of the DCS with automatic compensation of phase distortions were evaluated with different types of regulation and with different variants of construction and arbitrary orders of the filters used.

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