Using Method Frequency Scanning Based on Direct Digital Synthesizers for Geotechnical Monitoring of Buildings

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Abstract. The possibility of using the principle of frequency scanning as an alternative to the spectral-time analysis method for isolating the own frequencies of structures to provide their geotechnical monitoring with the help of an accelerometric phase-metric method is considered in the article. As the devices realizing this method, direct digital synthesizers, are considered, their determining advantages are indicated and the main drawback associated with the presence of a lot of parasitic spectral components in the spectrum of the synthesized signal is indicated. To reduce them, it is suggested to use the method of automatic compensation of phase distortions, its structural realization and frequency synthesizer circuits based on it with various types of regulation are shown. It is shown that the degree of auto-compensation in practice can reach 15 dB and is determined by the amplitude-frequency response of the devices by the phase distortions of the synthesizer, as well as by the conditions for full compensation, which are depending on the type of control used.

Keywords: Geotechnical monitoring · Accelerometric phase-metric method · Own frequencies of constructions · Frequency scanning · Direct digital synthesizers · Automatic compensation of phase distortions

1 Introduction

Geotechnical monitoring is one of the integral components of ensuring the safety of projected buildings and structures of a high level of responsibility and should be carried out both during their construction and during the subsequent exploitation [1]. It includes observations of the subsidence of the buildings, stresses in the foundation and bearing structures of the underground part, deviations, fluctuations of buildings with simultaneous observations of external impacts on the object, including measurements of wind loads, vibration and seismic influences, air temperature, atmospheric pressure, atmospheric precipitations [2].

An informative method for monitoring the state of structures is to control the own frequencies of their designs [3]. One of the variants of its implementation is the use of the accelerometric phase-metric method [4, 5], which makes it possible to excrete the

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values of the dominant own frequencies of the monitored objects. This method is based on the collection of dynamic data by converting signals from accelerometers placed between control points of structures which having their own technogenic rhythm, in the phase of the sinusoidal oscillation.

For the preliminary processing of accelerometric signals, the method of spectral-temporal analysis is currently widely used [6]. It allows to excrete the main frequency components of the signal on the distributed measuring network of primary accelerometric transducers with minimal phase distortions and consists in synchronous passing of the output signal of the accelerometer through a system of narrowband filters and obtaining the distribution of the amplitude values of the envelopes and their phases at the filters outputs at the corresponding frequencies.

However, in the organization of geotechnical monitoring of structures of high level of responsibility, the method of spectral-temporal analysis becomes unrealizable for a number of reasons [6]. In particular, it has a low speed, does not allow real-time geotechnical monitoring, and also for overlapping even a very narrow frequency range is requires the use of scores of bandpass filters. For example, in order to allotment the own frequencies of a structures in the interval from 1.6 to 4.2 Hz with an accuracy of less than 3%, 30 filters are required.

2 Using the Method of Frequency Scanning Based on Direct Digital Synthesizers

An effective alternative to the method of spectral-temporal analysis can be the use of the principle of scanning by frequency and isolating the own frequencies of structures in a given range of the frequency spectrum. The main requirements for devices, which implementing this method, are to ensure the coherence of scanning signals and their high stability.

One of the attractive options for implementing the proposed method from a practical point of view is the use of direct digital synthesizers (DDS) [7–13]. In the Fig. 1 is shows the block diagram of the device proposed for use, on which the following designations are accepted: CG - clock generator, PA - phase accumulator, ROM - read-only memory, DAC - digital-to-analog converter, LPF - low-pass filter.

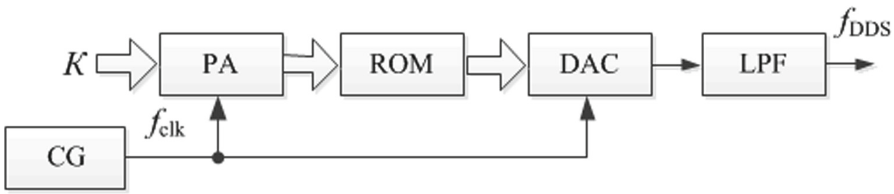

Fig. 1. Block diagram of the DDS.

The DDS is generates the output signal of the required shape and specified frequency f_{DDS}, which is determined by two parameters: the clock frequency f_{clk} and a binary frequency code K, controlled by an automated geotechnical monitoring system. The most important advantages of DDS over other variants of frequency scanning devices are: high accuracy of synthesized signals, extremely high resolution in frequency (up to thousandths of Hz); high speed, easy control, the ability to generate quadrature components of the output signal and low cost of integrated circuits [7, 11]. However, their significant disadvantage at the moment is the insufficient spectral purity of the synthesized signals, which is determined by the presence in the output signal spectrum of a noise component and a scores of discrete parasitic spectral components (PSC). When forming signals with the help of a DDS in the low-frequency region corresponding to ranges of the own frequencies of various structures, in the region of small detuning with respect to the carrier oscillation the discrete components of the output signal spectrum of the DDS due truncation of the phase code and the action of destabilizing factors are most undesirable.

Discrete PSCs caused by the truncation of the phase code are associated with discarding the low-order bits of the phase accumulator when transmitting them in the ROM, which leads to an error in the representation of phase and the appearance of the amplitude inaccuracies when the phase is converted to amplitude [13, 14]. The number of PSCs is determined by two sequences with frequencies:

$$\frac{\kappa}{2^r} \pm n\frac{\kappa}{2^b}, \tag{1}$$

where r - the bit capacity of the phase accumulator; n - an integer corresponding to the PSC number, $b = r - a$ - number of rounding bits; a - the bit capacity of the ROM.

For $b = 4$, the maximum PSCs level due to truncation of the phase code is independent of the phase accumulator bit capacity and is determined by the number of bits of the ROM [13, 14]:

$$A_{max} = 20\log(2^{-a}) = 6.02a, \text{ dB} \tag{2}$$

ROMs that are part of the modern DDS, to ensure the required speed are use the value of bit capacity in 14–16 bits. As a result, in the case of a 14-bit ROM the signal-to-noise ratio of the device will be minus 84.28 dB, in the case of a 15-bit ROM - minus 90.3 dB, and in the case of a 16-bit ROM - minus 96.32 dB.

PSCs, caused by the impact of destabilizing factors on the DDS, are related to the instability of its DAC, which is the only analog element of the device [14] and, therefore, is most susceptible to their influence. To the destabilizing factors, manifested by the PSCs in the field of small detunings relative to the carrier oscillation of the DDS, are include: instability of supply voltage, fluctuations of climatic factors (temperature, ambient humidity, atmospheric pressure, etc.), electromagnetic interferences generated by pulsed power supplies and high-voltage lines, as well as mechanical impacts in the form of shock and vibration, under which some radio electronic components can work as converters of mechanical energy into electricity.

PSCs, caused by the impact of destabilizing factors on the DDS, reach their maximum values on the certain time intervals and is characterized by an amplitude value. Their spectrum contains PSCs at certain detunings from the carrier frequency, which can be clearly correlated with certain factors for a given source of signal (for example, frequency of the power line, frequency of vibration).

At the moment, there are two main methods for reducing of PSCs in the spectrum of the output signal of the DDS, are arising from several sources: filtering and randomization. The problems of improving the spectral characteristics of the DDS with the help of filtering are consecrated in the works of F. Kroupa, J. Vankka, K. Halonen, Bar-Giora Goldberg, E. Murphy, C. Slattery, L.I. Ridiko, N.P. Yampurin, L.A. Belov, V.N. Kochemasov, A. Chenakin; with the help of randomization - in the works of Foster Dai Fa, Ni Weining, Yin Shi, C. Jaeger Richard, A.I. Polikarovskih. However, these methods at this moment have limited application and are not effective enough. When filtering is used, the cutoff frequency of the LPF (LPF DDS in Figs. 2, 3, 4 and 5) is adjusted to the maximum output frequency of the DDS, or limited to a value $0.25f_{\mathrm{clk}}$, so that the maximum PSC due to the nonlinearity of the DAC was above the sampling frequency and it can be filtered out. As a result, there is always an extremely high probability what discrete PSCs with high amplitudes were falling into the passband of the filter. Randomization of the output signal of DDS is realized by deliberately introducing a random sequence into the low bit of its DAC in the form of jitter of fronts within the clock interval. As a result, the spectrum of the PSCs expands and transforms from a discrete one into a close-to-noise one. However, such a modification of the spectrum, which reduces the level of the PSCs, is equivalent to a significant increase in the phase noises level of the synthesized signals of the device.

3 Application of the Automatic Compensation of Phase Distortions Method to Improve the Spectral Characteristics of Direct Digital Synthesizers

The researches of authors has shown that an effective method of reducing discrete PSCs in the spectrum of the synthesized signal of the DDS is using the method of automatic compensation of phase distortions (ACPD) [15–19]. It has been proved that the unwanted discrete and noise components present in the spectrum of the output signal of the DDS correspond to the parasitic phase modulation of the useful signal. The idea of the autocompensation method for the DDS is that, in the presence of parasitic phase modulation, all components of the spectrum are modulated according to the same law as the synthesized frequency, but with other modulation indices. Since the clock frequency is constant, selecting it in the spectrum of the output signal of the device, it is possible to automatically compensate for phase distortions of the synthesizer output signal at a given frequency.

To isolate phase distortions and form compensating signals, two algorithms are proposed to eliminate differences between the reference and information signal(s) of the ACPD in amplitude and shape while maintaining phase shifts. Both algorithms are implemented structurally by the tracts of formation of control signals of ACPD. The scheme of one of them is shown in Fig. 2. To form the reference signal of the phase detector PD from the output signal of the clock generator CG in the scheme is used the reference tract RT, consisting of the T-trigger Tr1; for the formation of an information

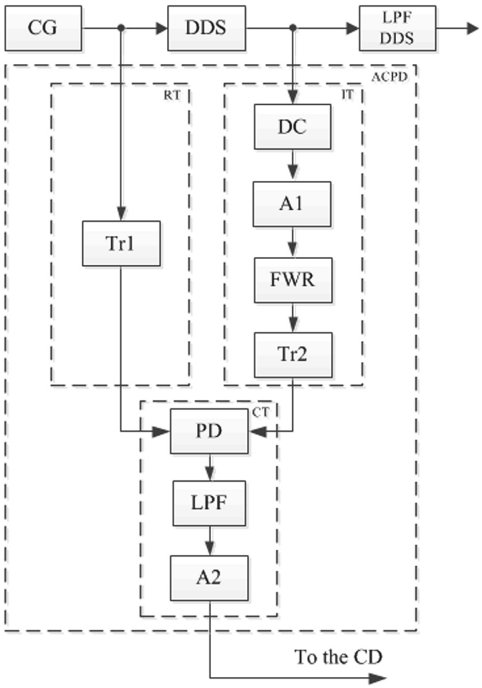

Fig. 2. Block diagram of the formation tract of control signal of ACPD.

signal from the output signal of a digital-to-digital converter DAC - an information tract IT, consisting of a differentiating circuit DC, an amplifier A1, a full-wave rectifier FWR, and a T-trigger Tr2. Further processing of the reference and information signals is carried out in the control tract CT, where phase distortions detection in the PD occurs and their low-frequency filtering in the LPF with subsequent amplification in A2. As a result, a control compensating signal is formed, which is then used to reduce the phase distortions of the DDS in the control device CD.

The transmission coefficient of the phase deviations of the DAC of the DDS to the control output of the CD is determined by the transfer functions by the phase of the links of the tract of the formation of the control signal of the ACPD. Assuming that the transmission coefficient of the information tract by the phase is defined as 0.5, the transmission factor of the amplifier A2 as n_{A}, denoting the transmission coefficient of the low-pass filter of the control tract in operator form as $M(p)$, and replacing the quasilinear characteristic of detector PD with the corresponding slope K_{PD}, the resulting expression of this transfer function is obtained:

$$H_{\Delta\varepsilon_{DDS}\Delta u} = \frac{\Delta u}{\Delta\varepsilon_{DDS}} = \frac{1}{2} n_A K_{PD} M(p), \tag{3}$$

where $\Delta\varepsilon_{dds}$ – the phase deviations of the output signal of the DAC of the DDS, Δu – the control compensating signal of the ACPD, p – the Laplace operator.

As the control device of ACPD in the low frequency range it is easiest to use a controlled phase shifter (CPS), the reduction of phase distortions in which is based on the antiphase modulation of the input or output signal of the DDS in accordance with the control signal ACPD. Depending on the location of the CPS relative to the DDS and in which points of the scheme the information about of phase distortions is allocated, developed several types of DDS with ACPD depending on the type of regulation: with the regulation by the perturbation, regulation by the deviation and combined regulation with an adder (Add) - Figs. 3, 4 and 5.

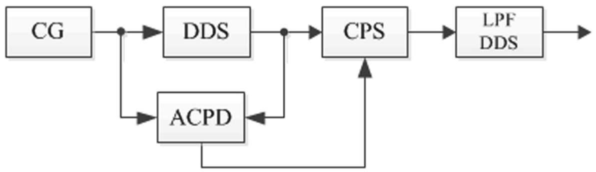

Fig. 3. Block diagrams of the DDS with ACPD and regulation by perturbation.

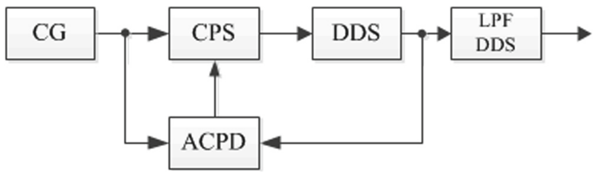

Fig. 4. Block diagrams of the DDS with ACPD and regulation by deviation.

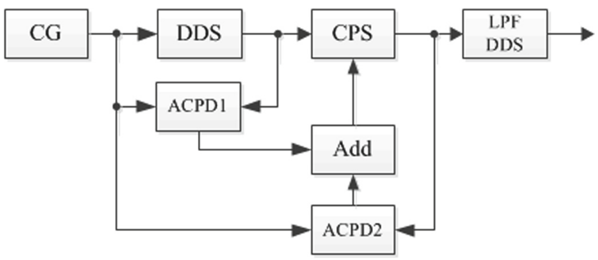

Fig. 5. Block diagrams of the DDS with ACPD and combined regulation.

The DDS with ACPD and the regulation by the perturbation are stable with any characteristics of the components of links, but full compensation of phase distortions in them is impossible. The use of ACPD with a regulation by the deviation allows eliminating this disadvantage: the closed loop of the feedback loop creates conditions for filtering the internal phase deviations of the autocompensator caused by the action of destabilizing factors. However, the use of feedback implies that the device has a static error of compensation. The use of the principle of combined regulation with the use of control circuits by the disturbance and deviation allows us to combine the advantages of both schemes and more flexibly to overcome the main disadvantages of the lasts. So the main suppression of phase distortions is provided in the tract with the regulation by the perturbation (in ACPD1), and the improvement in the quality of the device and the filtering of internal distortions of the all ACPD - in the tract with the regulation by the deviation (ACPD2).

4 Conclusions

It has been theoretically and experimentally established that the degree of automatic compensation of phase distortions, present in the output signal of the DDS, is determined by two factors: the amplitude-frequency response of the devices based by the phase distortions of the DDS and the conditions for full compensation, depending on the type of regulation used. Theoretically, when these conditions are achieved, the phase distortions of the output signal of the DDS are compensated, and the corresponding PSC and noise components are completely eliminated from the output spectrum of the device. However, in practice this is not achievable due to the previously mentioned limitations for each type of regulation. For example, for a DDS with ACPD and the regulation by the perturbation the parameters of the links of autocompensator (LPF and amplifier A2) will have values close to the conditions of full compensation, due to the absence of a feedback loop in the device. The more values of these parameters approach these conditions, the lower the transfer of phase distortions of the DDS to the output of the device. For example, if the gain of A2 deviates from one of the conditions of full compensation (n_{fc}) by 3% the PSCs are reduced by 15 dB, and if deviation is 20%, then by 7 dB - Fig. 6.

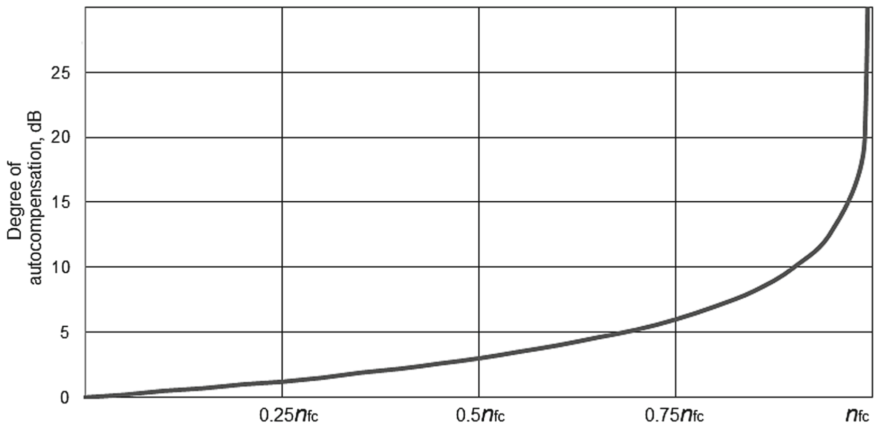

Fig. 6. Dependence of the degree of automatic compensation of the PSCs of spectrum of the output signal of the DDS from the change in the gain factor A2 of the ACPD relative to the conditions for full compensation.

The resulting graphical dependence has two characteristic regions: quasilinear for large detunings from the conditions of complete compensation (0–0.85 nfc) and sharply increasing in the remaining range. This allows us to recommend keeping the values of this coefficient in the band from 0.85 nfc to the maximum attainable in practice values of deviations of this coefficient from the conditions of full compensation in 2–3%.

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