Noise Characteristics of the Sounding Signal Generator for Geodynamic Monitoring Systems of the Geological Environment Based on Geoelectric Control Methods

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Abstract
The work is devoted to the study of the noise characteristics of the probing signals generator for geodynamic monitoring systems of the geological environment based on geoelectric control methods implemented on the basis of a digital digital synthesizer (DDS). It is shown that the main sources of phase noise of the DDS are the clock signal generator, taking into account its transmission coefficient, as well as synthesizer links, and the phase noise of the DDS itself consists of two components: quantization noise and the device's own noise. To reduce their level, as well as generally improve the spectral characteristics of the genetator, it is proposed to use the principle of automatic compensation of phase distortions, its scheme with deviation control is obtained. Based on this scheme, as well as expressions of transfer functions, a mathematical model of the noise characteristics is obtained. A highly stable HCMOS/TTL quartz oscillator was used as a reference generator for the simulation, and an AD9854 integrated synthesizer was used as a DDS. Using their models, graphs of the spectral density of the phase noise of the sounding signal generator are obtained. The noise contributions of the component links and the degree of automatic phase noise compensation for various values of the amplifier gain of the autocompensator are obtained.
Keywords – phase noise, signal formers, digital computational synthesizers, automatic compensation, noise characteristics.

Introduction

One of the most important parameters of any signal generation systems is phase noise [1-5], which has a significant impact on their output characteristics. The main measure of its level is the spectral power density (SPD) of the output signal near the carrier frequency, depending on the tuning F at different values of the output frequency.

Generating equipment, in particular, includes generators [6-10] of sounding signals, with the help of which artificial electric fields are created for geodynamic monitoring systems [11-13] of the geological environment based on geoelectric control methods [14-18]. From a practical point of view (based on the features and requirements imposed on the radiating paths of geodynamic monitoring systems based on geoelectric control methods), modern signal generators for such systems are most effectively implemented on the basis of a direct digital method of frequency synthesis carried out using digital computational synthesizers (DDS) [19-23]. The main advantages of the direct digital synthesis method over direct analog and indirect methods [6-10, 19-23] are:

– digital control of the amplitude, frequency and phase of the output signal;
– extremely high frequency and phase resolution;
– extremely fast transition to another frequency (or phase) without phase discontinuity, glitches and other anomalies associated with transients;
– the digital interface makes it easy to implement control using a micro controller, a programmable logic integrated circuit (FPGA) or a computer.

The main sources of phase noise of the DDS is the clock signal generator, taking into account its transmission coefficient and synthesizer links (phase code, frequency and amplitude drives, read-only memory (ROM), direct-to analog converter (DAC)). In general, the phase noise of the DDS consists of two components: quantization noise and the device's own noise. The reason for the formation of quantization noise is the finite bit depth of the ROM and DAC data, which is manifested by the deviation of the device output signal samples from ideal theoretical values. The intrinsic noise of the DDS is associated with the random behavior and fluctuations of electrons and holes in the semiconductor components of the synthesizer.

The main method of reducing the phase noise level of the DDS at present is filtering its output signal of the DDS, which mainly serves to increase the maximum discrete parasitic spectral components, and therefore the method is insufficiently effective.

Application of the method of automatic phase distortion compensation to improve the spectral characteristics of signal generators based on digital computational synthesizers

It is known from literature sources that the most undesirable in the output spectrum of the DDS are spectral components that manifest themselves in the time domain in the form of phase interference of the synthesized signal. An effective method of their reduction is automatic compensation (ACPI) [24-26]. The idea of the method in relation to 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 different modulation indices, and since the clock frequency is constant, then by highlighting it in the spectrum of the output signal of the device, it is possible to carry out automatic compensation of phase distortions of the synthesizer output signal at a given frequency.

To isolate phase distortions and generate compensating signals, two algorithms have been developed that implement distortion detection at different frequencies and are aimed at eliminating differences between the reference and information signal(s) of the autocompensator in amplitude and shape while preserving phase shifts. The structural implementation of one of the algorithms is presented in the form of a path for generating ACPI control signals and is shown in Fig. 1.

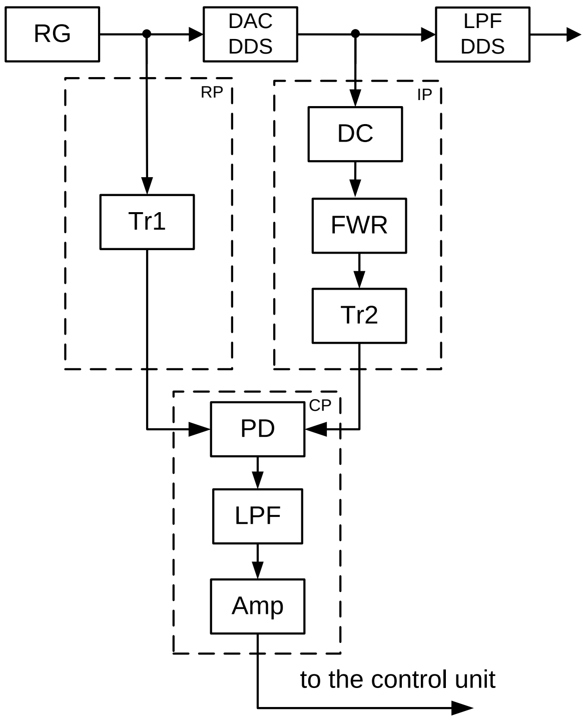


Fig. 1 - Block diagram of the ACPI control signal formation path

To form the reference signal of the phase detector PD from the output signal of the clock reference generator RG, the circuit uses the reference path RP, consisting of a T-trigger Tr1. To form an information signal from the output signal of the DAC, the circuit uses the information path IP, consisting of a differentiating circuit DC, an amplifier Amp1, a full-wave rectifier FWR and another T-trigger Tr2. Further processing of the reference and information signals is carried out in the control path CP, where phase detection of distortions in the PD and their low-frequency filtering in the LPF with subsequent amplification in the Amp2 takes place. As a result, a control compensating signal is formed, which is then used to reduce the phase distortion of the DDS in the control device of the control unit; in the low frequency region, it is easiest to use a controlled phase shifter (CPS).

The work considers a variant of a sounding signal generator for geodynamic monitoring systems of the geological environment based on geoelectric control methods based on a DDS with ACPI and deviation control - Fig. 2.

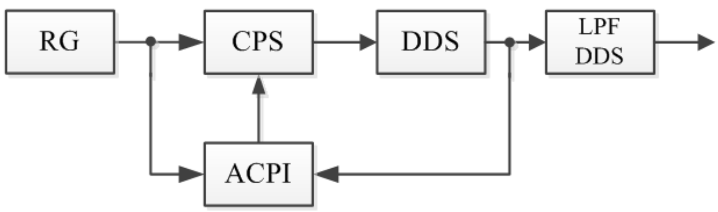


Figure 2 - A block diagram of a DDS with ACPI and deviation control

On the basis of combining the structural schemes of Fig. 1 and 2, an equivalent functional model of the shaper was obtained, supplemented by a power amplifier (Amp). The following designations are adopted: $\Delta\varepsilon_i$ – phase deviations of the signal shaper blocks, K_{ni} – transfer

functions of phase deviations of the signal shaper blocks, K – transmission coefficient of the corresponding block for phase deviation, $M_A(p)$ is the transfer function of the ACPI filter.
On the basis of this equivalent functional model, the transfer functions of the shaper for the main effects are determined:
– for the power amplifier $\Delta\varepsilon_{Amp}$
$H_{Amp} = K_{Amp}$;
– for a controlled phase shifter $\Delta\varepsilon_{CPS}$
$H_{CPS} = K_{Amp}K_{DDS}K_{Amp}$;
– or the reference generator $\Delta\varepsilon_{RG}$
$H_{RG} = K_{RG}K_{Amp}K_{DDS}K_{Amp}$;
– for the auto-compensator amplifier $\Delta\varepsilon_{Amp}$
$H_{Amp\_ACPI} = -K_{Amp}K_{Amp}K_{DDS}K_{Amp}$;
– for the phase detector of the autocompensator $\Delta\varepsilon_{PD}$
$H_{PD}(p) = -K_{PD}M_A(p)n_A K_{Amp}K_{DDS}K_{Amp}$;
– for the trigger of the information path $\Delta\varepsilon_{Tr2}$

$$H_{Tr2}(p) = H_{PD}(p);$$

– for the trigger of the reference path $\Delta\varepsilon_{Tr1}$
$H_{Tr1}(p) = -H_{Tr2}(p)$;
– for a full-wave rectifier $\Delta\varepsilon_{FWR}$:
$H_{FWR}(p) = \frac{1}{2K_{DDS}} H_{PD}(p)$;
– for the DDS phase deviation $\Delta\varepsilon$:

$$H_{DDS}(p) = \frac{K_{Amp}}{1 + K_{CPS}K_{PD}M_A(p)n_y\frac{1}{2}}$$

Mathematical model of the noise characteristics of the sounding signal generator
Since all the noises generated or added by each component of the probing signal generator circuit for geodynamic monitoring systems of the geological environment based on geoelectric control methods are small compared to the power of the useful signal, they can be added to the corresponding input or output effects [27-30]

$$S_{SF} = \sum_{i=1}^{I} S_i|H_i|^2,$$

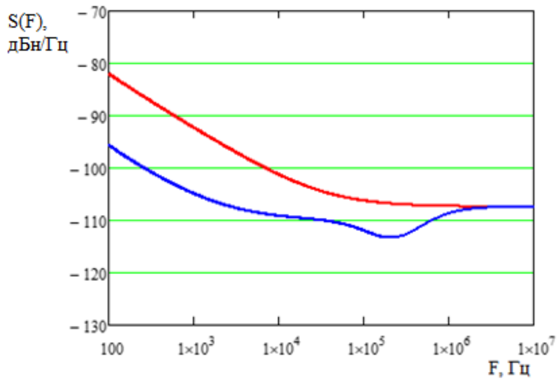
where I is the number of blocks of the probing signal generator, i is the number of the current block of the probing signal generator, S_i is the SPD of the phase noise of the block, H_i is the transfer function of the block.
For a theoretical description of the level of intrinsic phase noise of individual units of signal generators, an approximation of the SPD of their phase noise by power functions is used in accordance with the universal model. Typical ratios for the SPD of various blocks are given in [1-5].
Based on the generator transfer functions, a mathematical model of its noise characteristics is obtained as

$$S_{out}(F) = S_{RG}(F)|H_{RG}(F)|^2 + S_{CPS}(F)\,|H_{CPS}(F)|^2 + S_{Amp\_ACPI}(F)\,\left|H_{Amp\_ACPI}(F)\right|^2 + S_{PD}(F)\,|H_{PD}(F)|^2 + +2S_{Tr}(F)\,[|H_{Tr1}(F)|^2] + S_{FWR}(F)\,|H_{FWR}(F)|^2 + +S_{DDS}(F)\,|H_{DDS}(F)|^2 + S_{Amp}(F)\,\left|H_{Amp}(F)\right|^2 \quad (1).$$

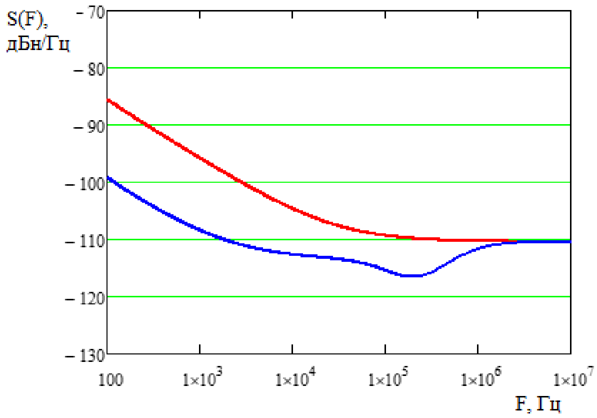
Modeling of the noise characteristics of the sounding signal generator

We will use a highly stable HCMOS/TTL quartz oscillator as a reference generator for modeling, and an AD9854 integral synthesizer as a DDS.

Figure 3 shows the graphs of the SPD of the phase noise of the sounding signal generator at output frequencies 900, 600, 300, 90 kHz, and K_{DDS} = 0.3, 0.2, 0.1, 0.03, respectively, obtained using (1), and in Figure 4 shows the noise contributions of the components links. In Figure 4, the dependencies with auto–compensation are indicated in blue, and without it in red; in Figure 5, the noise contributions of the reference generator are indicated in blue, the ACPI is green, and the DDS is red.



a)



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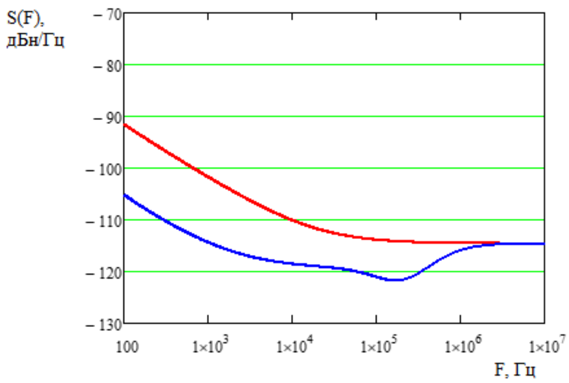

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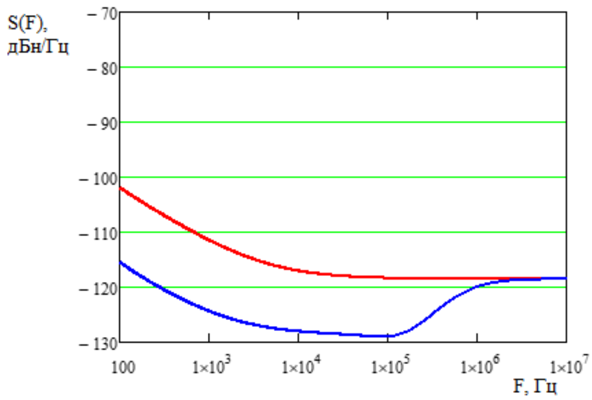
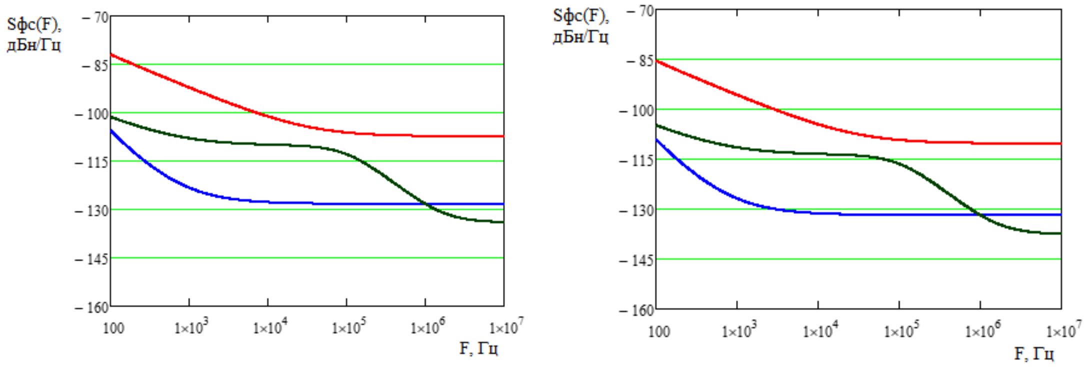
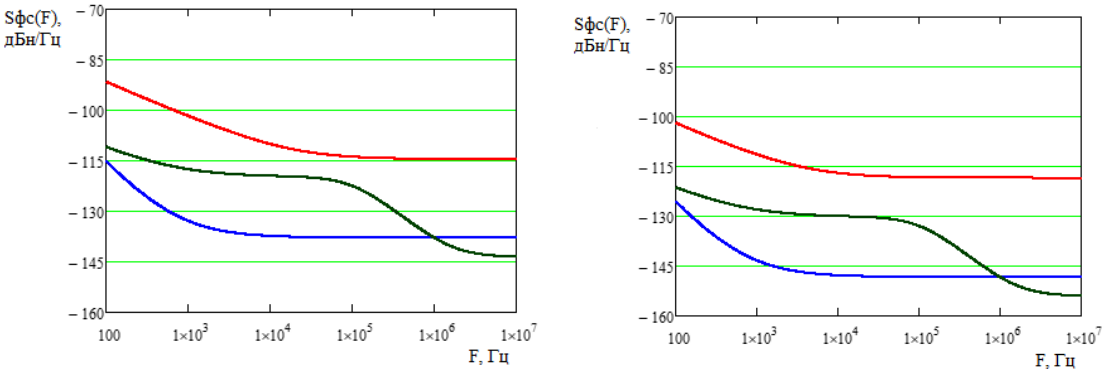


d)

Figure 3 – SPD of the phase noise of the sounding signal generator in dBc/Hz as a function of frequency offset F in Hz at 900 kHz and K_{DDS} =0.3 (a), 600 kHz and K_{DDS} =0.2 (b), 300 kHz and K_{DDS} =0.1 (c), 90 kHz and K_{DDS} =0.03 (d)



a) b)



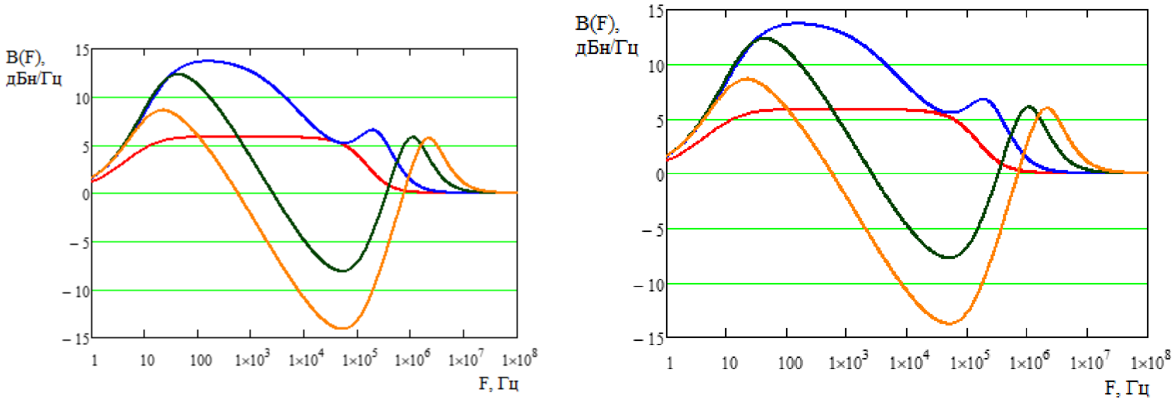
c) d)

Figure 4 – Noise contributions of the components in dBc/Hz as a function of frequency offset F in Hz at 900 kHz and K_{DDS} =0.3 (a), 600 kHz and K_{DDS} =0.2 (b), 300 kHz and K_{DDS} =0.1 (c), 90 kHz and K_{DDS} =0.03 (d)

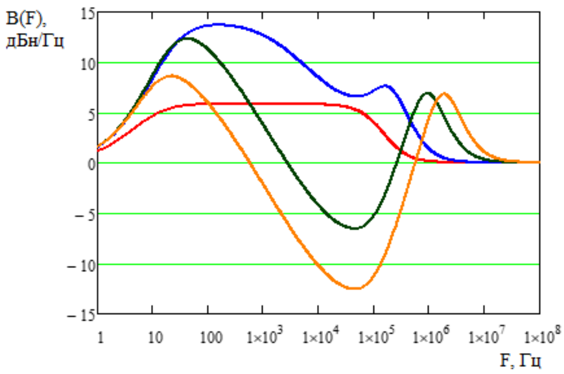
In particular, the degree of compensation of phase noise is determined by the accuracy of setting the parameters of the autocompensator. What makes it necessary to consider its parametric stability. So in Figure 6 graphs of phase noise suppression on the offset frequency are calculated as

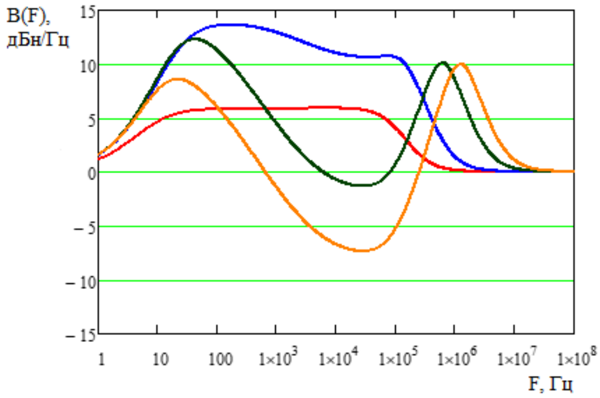
$$B(F) = 10\log\left(S^{*}_{out}(F)\right) - 10\log\left(S_{out}(F)\right),$$

where $S_{out}^{*}(F)$ is the SPD of phase noise with compensation circuit turned off. In the figures, the red color is indicated by dependencies at n_y = 2, blue – at n_{Amp} = 10, green – at n_{Amp} = 50 and orange – at n_{Amp} = 100.



a) b)





c) d)

Figure 5 – Degrees of phase noise compensation for various gains of ACPI amplifier in dBc/Hz as a function of frequency offset F in Hz at 900 kHz and K_{DDS} =0.3 (a), 600 kHz and K_{DDS} =0.2 (b), 300 kHz and K_{DDS} =0.1 (c), 300 kHz and K_{DDS} = 0.1 (c), 90 kHz and K_{DDS} =0.03 (d)

Conclusion

According to the simulation results, it was found that the level of phase noise of the sounding signal generator at 1 kHz offset from the carrier oscillation for the output frequency of 900 kHz is about minus 93 dB in the absence of ACPI and minus 105 dB if available, for the output frequency of 600 kHz – minus 97 dB in the absence of ACPI and minus 108 dB if available, for the output frequency of 300 kHz is minus 103 dB in the absence of ACPI and minus 115 dB if available, and for the output frequency of 90 kHz – about minus 110 dB in the absence of ACPI and minus 125 dB if available.

The obtained noise contributions of the generator units show that, regardless of the output frequency of the device and the DDS transmission coefficient, the main contribution to the phase noise of the shaper is made by the DDS, followed by ACPI and the reference generator. The lower the value of the KDDS, the lower its phase noise becomes.

From the curves in Fig. 6, it can be seen that the maximum possible reduction in phase noise is about 15 dB and is achieved at nAmp values close to 10. At the same time, with a nAmp of more than 50, an area with negative compensation appears, due to the significant contribution of ACPI to the phase noise, and the higher the output frequency of the shaper, the larger this area is.

The schemes, mathematical models and research results obtained in the work allow planning the parameters of the phase distortion autocompensator at the design stage of the entire sounding signal generator for geodynamic monitoring systems of the geological environment based on geoelectric control methods.

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