Algorithm for designing low-noise frequency synthesizers for remote sensing systems

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Abstract. Frequency synthesizer is an important component of radar tracking system for remote sensing. Synthesizers generate wideband radio frequency signals with high frequency resolution. Parameters of radar depend on the synthesizers phase noise. This paper presents algorithm for structural design of signal generators based on various synthesis methods: direct, indirect and hybrid ones. Specialized software based on presented algorithm was developed in this work. Software allows calculating frequency ratios in the structure of synthesizers, selecting optimal parameters which can provide low phase noise level. Also software allows performing mathematical modelling and analysis of phase noise power spectral density (PSD) of frequency synthesizers. Presented algorithm and software can be useful for developers of remote sensing radio systems.

1. Introduction

Space-based passive remote sensing systems are characterized by relative simplicity of design and high resolution when taking images of the earth’s surface. However, a significant disadvantage of such systems is the dependence on meteorological conditions and time of day. This disadvantage is not present in remote sensing systems that support the radar method of obtaining information about the earth's surface [1-3]. Satellite radars allow to take pictures regardless of the weather and light conditions, while providing a spatial resolution of less than a meter.

The quality characteristics of images obtained by satellite radars directly depend on both external factors (for example, the instability of the carrier trajectory, the influence of the attraction of space objects, etc.) and on a number of technical parameters of the radar: from the antenna pattern to the selected range of operating frequencies. It is known that the best resolution is provided by remote sensing radar systems operating in the S-band (3.1–3.3 GHz), C-band (5.25–5.57 GHz), and X-band (8.025–8.625 GHz). In addition, the quality of the received images is directly affected by the characteristics of the frequency synthesizer (the level of its own phase noise and side components of the spectrum), and the speed of frequency tuning has an indirect influence.

The purpose of this work is developing algorithms for building frequency synthesizers for remote sensing systems, reviewing methods for analyzing phase noise of frequency synthesizers, and developing software for design and analysis of phase noise of frequency synthesizers.

2. Algorithm for synthesizers structural design and analysis of noise characteristics

Currently, direct and indirect methods of frequency synthesis are known [4, 5]. The direct method is divided into direct analog and direct digital synthesis methods. The frequency of output signal of
direct analog synthesizers is obtained from the frequency of reference signal by addition, multiplication, mixing or division. The development of digital engineering has led to the active dissemination of direct digital synthesizers (DDS) [6]. The advantages of DDS are high frequency resolution, the possibility of various types of modulation. The advantages of DDS include high frequency resolution, the possibility of various types of modulation. The indirect synthesizers are implemented on the basis of the phase-locked frequency (PLL) system [7]. Synthesizers based on each of these synthesis methods have both advantages and disadvantages. The hybrid synthesis method [8, 9], which is a combination of composite elements of synthesizers of the above-mentioned methods, allows reducing the impact of disadvantages. The most popular are hybrid frequency synthesizers based on direct digital and indirect synthesis methods. Such synthesizers have a small number of undesirable discrete components of the output signal spectrum and they generate a wide range of output frequencies and a small frequency tuning step.

Figure 1 (a) – (f) shows the structural diagrams of the main types of frequency synthesizers based on direct digital and indirect synthesis methods. The following notation is introduced in figure 1: REF – reference frequency generator, MUL – frequency multiplier, DIV – frequency divider, PD – phase detector, VCO – voltage-controlled oscillator, MIX – frequency mixer.

**Figure 1.** Block diagrams of frequency synthesizers
Developer can meet problems when he designs the signal generator. First, he needs to choose which synthesis method will be used to build the generator. The main criteria for this choice are the requirements for the frequency tuning time, the level of spectrum components, supported types of modulation, and so on. After selecting the method, the developer needs to calculate the frequency ratios the synthesizer. Moreover, for some synthesizers (for example, hybrid ones), the required output frequencies can be obtained with different frequency ratios. The total number of variants of frequency ratios can be equal to thousands, and the developer must choose the most optimal variant. The authors of this article suggest using the phase noise as an optimality criterion. The phase noise level of the output signal of the frequency synthesizers is estimated by power spectral density (PSD) \( L \) of the phase noise in a single sideband depending on a offset frequency \( F \) from the carrier frequency.

Mathematical models of phase noise PSD are used for analysis of phase noise level of frequency synthesizers. These models are presented as power polynomials [10–14]. These models allow to calculate the PSD of phase noise for any value of the output and reference frequency. The mathematical model of phase noise PSD of the DDS is [13]:

\[
L_{DDS}(F) = (K_{DDS})^2 \left( \frac{10^{L_1^2}}{F^2} + \frac{10^{L_2^3}}{F} + 1 \right) + 10^{L_4^4} + L_q,
\]

where \( K_{DDS} = f_{DDS}/f_{CLK} \) – the DDS transfer coefficient; \( f_{DDS} \) – frequency of the DDS output signal; \( f_{CLK} \) – frequency of the DDS clock signal; the coefficients \( k_1, k_2, k_3, k_4 \) determine the level of DDS 1/F² noise, 1/F noise, the natural noise component of the input circuits of the DAC and the quantization noise of the DAC; \( L_q = 2^{-2N_{DAC} - 0.59} \left( \frac{f_{DDS}}{f_{CLK}^2} \right) \) – PSD of phase noise, the natural noise of the load resistance, respectively; \( L_q = 2^{-2N_{DAC} - 0.59} \left( \frac{f_{DDS}}{f_{CLK}^2} \right) \) – PSD of phase quantization noise of the DAC; \( F \) – the offset frequency; the \( N_{DAC} \) – the number of DAC bits.

The mathematical model of the phase noise PSD of PLL synthesizer has the form:

\[
L_{PHS}(F) = \left[ \frac{L_{REF}(F)}{N_1^2} + L_{DIV}(F) + L_{PD}(F) + L_{LoopFilter}(F) + L_{MIX}(F) \right] \|H_1(j2\pi F)\|^2 + \\
+ L_{VCO}(F) \|H_2(j2\pi F)\|^2,
\]

where \( L_{REF}(F) \), \( L_{DIV}(F) \), \( L_{PD}(F) \), \( L_{LoopFilter}(F) \), \( L_{VCO}(F) \) – mathematical models of PSD of phase noise of synthesizer blocks [10, 11]: reference frequency generator REF, frequency dividers DIV, phase discriminator PD, low-pass loop filter, voltage-controlled generator VCO.

Formulas for defining transfer functions for (2):

\[
H_1(j2\pi F) = \frac{H_2(j2\pi F) \cdot N_2}{1 + H_2(j2\pi F)} - \text{PLL external noise transfer function;}
\]

\[
H_2(j2\pi F) = \left(1 + H_1(j2\pi F)\right)^{-1} - \text{PLL internal noise transfer function;}
\]

\[
H_3(j2\pi F) = \frac{F_{LoopFilter}(j2\pi F) \cdot s_{PD} \cdot s_{VCO}}{j2\pi F \cdot N_2} - \text{PLL open loop transfer function;}
\]

\[
F_{LoopFilter}(j2\pi F) - \text{transfer characteristic of the PLL loop filter; } s_{PD} - \text{slope of discrimination curve PD; } s_{VCO} - \text{slope of regulation curve VCO; } j = \sqrt{-1} - \text{imaginary unit.}
\]

Mathematical models of PSD of phase noise of hybrid synthesizers are made up of the models presented above, depending on the position of the DDS in the PLL system [14].

Algorithm for structural design of synthesizers will consist of the following steps:

Step 1. Selecting the frequency synthesis method and setting the source data: the frequency of the input (reference) signal, the range of output frequencies.

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Step 2. The calculation of frequency ratios in the structure of the synthesizer. All possible parameters of the synthesizer (values of division, multiplication, and transfer coefficients of composite blocks) are calculated depending on the selected type to achieve the specified source data.

Step 3. Select the optimal synthesizer parameters in terms of phase noise level. At this step, each combination of parameter values calculated in the previous step is inserted into the mathematical model of phase noise PSD and the value of phase noise PSD is calculated for a fixed or more values of the offset frequency from the carrier. The parameters corresponding to the lowest value of the phase noise PSD are optimal.

Step 4. Calculation of the remaining parameters of the synthesizer (nominal values of loop LF elements, frequency tuning step, etc.).

Step 5. Modeling and analysis of noise characteristics of the synthesizer. Using the analysis, you can determine the composite blocks of the synthesizer that make the greatest contribution to the level of phase noise PSD at different values of the offset frequency from the carrier.

3. Software for analysing of phase noise

Specialized software was developed based on the presented algorithm. This software allows calculating frequency ratios in the structure of synthesizers, selecting optimal parameters, and performing mathematical modeling and analysis of noise characteristics of frequency synthesizers.

The interface of the software tool is shown in figure 2: 1 – pop-up menu for selection method of synthesis; 2 – the fields of the data input; 3 – pop-up menu for selecting of integrated circuits, which will be built on a synthesizer and a loop low-pass filter; 4 – the field of the characteristics of integrated circuits; 5 – the field of the block diagram of the synthesizer; 6 – the graph of the simulation results of PSD phase noise; 7 – the field of calculated parameters for chosen synthesizer.

![Figure 2](image_url)

**Figure 2.** Graphical user interface of the software with the results of phase noise modeling for \( f_{\text{OUT}} = 5200 \text{ MHz} \)

The software contains an updated database of modern integrated circuits. The database contains the main characteristics of chips: the ranges of supported frequencies, values of approximation...
coefficients of power polynomials that form mathematical models of phase noise PSD. Methods for calculating approximation coefficients based on experimental data from direct digital synthesizers and phase detectors of PLL chips were developed by the authors of this article.

Figure 2 shows the results of simulating phase noise PSD of various types of C-band signal generators with an output frequency $f_{\text{out}} = 5200$ MHz. The types of synthesizers that were modeled: curve 1 – a direct digital synthesizer; curve 2 – synthesizer based on a PLL system; curve 3 – hybrid frequency synthesizer with DDS as a reference generator; curve 4 – hybrid frequency synthesizer with DDS in the feedback circuit; curve 5 – hybrid frequency synthesizer with a DDS as offset frequency generator; curve 6 – hybrid frequency synthesizer used images of the output frequency of the DDS. The software tool calculated all the parameters of the synthesizers and conducted mathematical modeling of noise characteristics.

4. Conclusion
The algorithm for structural design of signal generators based on various synthesis methods presented in this paper allow to calculate the main frequency ratios in the structure of synthesizers, select those ratios that achieve the lowest level of phase noise PSD, conduct mathematical modeling and analysis of noise characteristics.

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