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Application of the Autocompensation Principle to Improve the Noise Characteristics of Signal Generators in Wireless Communication Systems

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ABSTRACT

Flying ad-hoc networks (FANET) based on unmanned aerial vehicles (UAVs) and ground control systems is a convenient tool to collect data on the state of resources of agricultural facilities. Increasing the effectiveness of such network causes a need for new design of its radio transmitting equipment. Signal generators of radio transmitters of flying sensor networks and their spectral characteristics have been considered. In order to improve their spectral characteristics, the autocompensation principle has been applied. Block diagram and equivalent functional model of a carrier oscillator with automatic noise compensation have been shown. Transfer functions of the scheme for phase deviations of its various blocks have been obtained. Simulation had shown that the maximum degree of noise autocompensation reaches 13 dB, which confirms the effectiveness of the proposed approach.

Keywords: unmanned aerial vehicle, flying ad-hoc network, FANET, signal generators, hybrid frequency synthesizers, automatic compensation.

INTRODUCTION

One of the promising options for collecting data on the state of resources of the agro-industrial complex (AIC) in difficult conditions is the organization of flying ad-hoc networks (FANET) [1, 2], based on the use of groups of unmanned aerial vehicles (UAVs). These networks have an extensive wireless architecture, which allows to establish communication between remote network nodes in the absence of a developed infrastructure on the ground.

A variety of FANET networks are "flying sensor networks", or FUSN (Flying Ubiquitous Sensor Network), which represent two interacting segments: flying (airborn) and ground-based. The first segment is UAVs of various types and satellites (solving the problem of expanding a small range with the help of space telecommunications systems [3]), and the second segment is sensor-based sensor nodes installed in the territories of agricultural development (collecting information about the state of resources and managing remote objects, working in autonomous mode) and ground control complexes.

Possible options for organizing communication between the flying and ground segments in such networks can be divided into low-speed (used to transmit telemetry information and receive commands that control movement) and high-speed (designed to transmit useful information collected by the UAV from sensor nodes during flight). In this regard, at least two communication systems are placed on board the UAV: the equipment for transmitting command and telemetry information and the payload information transmission system.

In the process of performing flight tasks, the relative position of the flying and ground segments is constantly changing. As a result, the conditions for the propagation path and the energy reserve of communication channels, estimated by the value of the bit error probability with a different signal–to-noise ratio (SNR), also change. The continuous tightening of requirements to the technical characteristics and parameters of modern wireless communication systems (especially to increase the speed of information exchange and reliability of communication) [4, 5] force developers to look for new approaches to the design of their radio transmitting equipment. In particular, it is known that the spectral purity of signals synthesized using special multichannel signal generators of radio transmitters of such telecommunication systems significantly affects the SNR. If the spectral purity of the synthesized signal of the system's radio transmitter is insufficient, then its useful component may be masked when receiving it and it will not be possible to isolate the desired information.

SIGNAL GENERATORS OF RADIO TRANSMITTERS OF FLYING SENSOR NETWORKS AND THEIR SPECTRAL CHARACTERISTICS

Until recently, devices based on one of three methods of frequency synthesis were used as signal generators of radio transmitters of flying sensor networks: direct analog, indirect based on phase-locked loop (PLL) and based on direct digital synthesizers (DDS) [6, 7]. Each of these synthesis methods has both advantages and characteristic disadvantages that limit their use.

The hybrid method of frequency synthesis allows to significantly reduce the influence of the disadvantages of each of these methods of signal formation separately. It consists in the fact that a synthesizer built according to one of the synthesis methods is complicated by the introduction of structural elements of a frequency synthesizer built according to another synthesis method into its scheme. Thus, some of the disadvantages inherent in some synthesizers are compensated by the advantages of others.

Theoretical and experimental studies of modern authors have shown that hybrid frequency synthesizers combining direct digital and indirect synthesis are the most promising. They provide a wide range of synthesized frequencies (up to tens of gigahertz), a small tuning step (hertz – fractions of hertz), have the ability to program control and generate oscillations with complex modulation laws (in particular ultra-wideband). However, these synthesizers currently have insufficient spectral purity of the synthesized signals.

The spectral characteristics of the real output signal of a hybrid synthesizer contain components of parasitic amplitude and phase modulation, which in the frequency domain include two components:

– discrete, represented as separate harmonics, subharmonics and/or non–harmonic combinational components near the fundamental frequency of the synthesizer output signal;

- noise, having the form of a continuous part of the spectrum caused by short-term random phase fluctuations in the time domain and estimated by the level of spectral power density (SPD) of phase noise in a single sideband.

Moreover, the quality of the spectral characteristics of hybrid frequency synthesizers is primarily determined by the level of discrete parasitic spectral components (PSC) of the output signal, most of which are concentrated near the carrier frequency within the bandwidth of the low-pass filter of the PLL synthesizer. The frequency range in which these components are present is chosen from a compromise between the degree of filtration and the speed of the PLL response. Synthesizer manufacturers, in particular Analog Devices, recommend choosing the specified band as a tenth of the maximum frequency of comparison of the phase detector of the PLL loop, which in modern integrated circuits reaches 125 MHz. As a result, the resulting noise band of the PLL loop, and, consequently, of the entire hybrid frequency synthesizer, can be a dozen megahertz.

As the main method of reducing the noise band of PLL systems at the moment is the use of several feedback loops, leading to the need to build two- or three-loop low-noise precision PLL synthesizers [8-10]. As a consequence, due to a significant reduction in the noise band, modern integrated circuits of precision hybrid frequency synthesizers using this technical solution have a phase noise level of minus 120 – minus 140 dB at a frequency of 1 GHz already when detuning from the carrier at 1 kHz. But at the same time, these devices are characterized by low performance, the need to select division coefficients for each PLL loop in order to maintain stability and have a price of several tens of thousands of dollars.

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AUTOMATIC COMPENSATION OF THE NOISE BAND OF THE CARRIER REFERENCE GENERATORS OF RADIO TRANSMITTERS OF FLYING SENSOR NETWORKS

A promising method to reduce the noise band of multichannel signal generators based on hybrid frequency synthesizers is the automatic phase compensation [11-13]. For an arbitrary signal, it is carried out by reducing undesirable deviations of its phase by an antiphase compensating change obtained from the original signal.

The automatic compensation principle to reduce the noise band of PLL systems was first proposed back in the 70s of the XX century in the works of V.V. Shakhgildyan [11]. It consists in processing the output signal of the phase detector of the PLL in the auto-compensation path with deviation control, so that its output signal goes to the phase shifter that controls the phase of the input signal and directly reduces the noise band of the device.

Combining the PLL synthesizer of an integer type and this principle of autocompensation, a block diagram of a carrier oscillator with automatic noise band compensation (ANBC) is shown in Figure 1. The following designations are adopted in the diagram: RG – reference frequency generator; PD – phase detector; LPF1,2 – low-pass filter of the PLL and compensation circuit, VCO – voltage–controlled generator, FD – frequency divider by an integer coefficient, Amp - amplifier, CPS - controlled phase shifter.

Based on this scheme, its equivalent functional model with all possible sources of phase deviations is obtained. The following designations are accepted for the model: *K* or *n* with an index in transmission coefficient of the corresponding block, $M_{1,2}(p)$ are the transmission coefficients of the LPF1,2, p is the Laplace operator, $\Delta\varepsilon$ is influence caused by phase deviations, $\Delta\varphi_{RG}$ and $\Delta\varphi_{out}$ are phase deviations at the outputs of the reference generator and the signal generator as a whole.

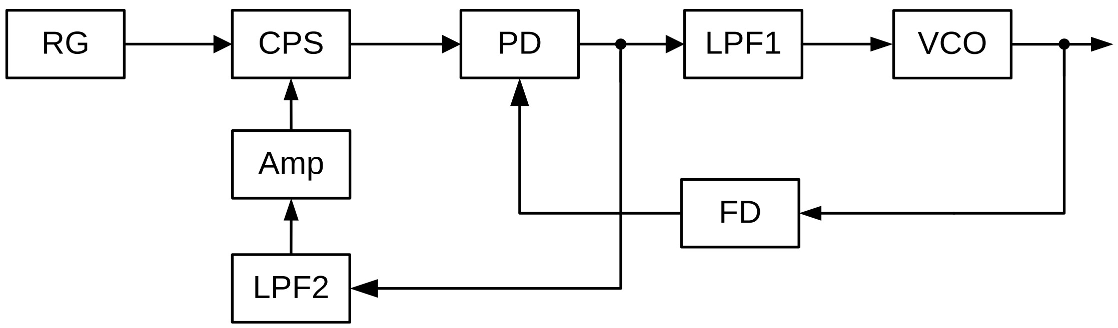

Figure 1. Block diagram of a carrier oscillator with noise band automatic compensation

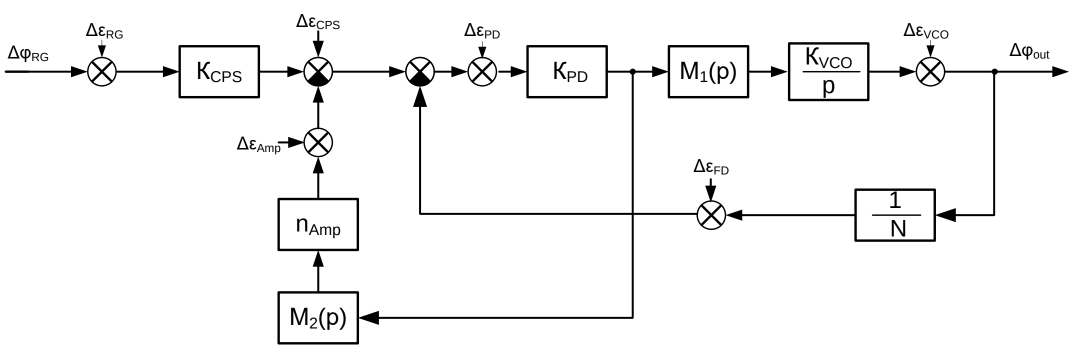

Figure 2. Equivalent functional model of a carrier oscillator with noise band automatic compensation

A positive feature of the backward loop used in the automatic compensation system is that an accurate selection of the characteristics of the constituent links is not required. In addition, it allows to filter internal phase deviations caused by the influence of destabilizing factors.

This model allows us to obtain mathematical relations that fully describe the behavior of a linearized carrier oscillator with an automatic transmission in the presence of phase deviations of its structural blocks. Taking the deviations of the parameters of the output signals and impacts small, expressions of the "phase-phase" transfer functions are obtained for this shaper with arbitrary characteristics of the constituent units, allowing quantitative and qualitative investigation of its properties:

For phase deviations of VCO

$$H_{VCO}(p) = \frac{1}{1 + \frac{K_{PD}K_{VCO}M_1(p)}{pN\left(1 + n_{Amp}K_{PD}M_2(p)\right)}};$$

For phase deviations of PD

$$H_{PD}(p) = \frac{K_{PD}K_{VCO}M_1(p)}{p\left(1 + n_{Amp}K_{PD}M_2(p)\right)}H_{VCO}(p);$$

For phase deviations of FD

$$H_{FD}(p) = -H_{PD}(p);$$

For phase deviations of CPS

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

For phase deviations of Amp

$$H_{Amp}(p) = -H_{PD}(p);$$

For phase deviations of RG

$$H_{RG}(p) = K_{CPS}H_{PD}(p).$$

The obtained expressions of transfer functions for various phase deviations allow us to analyze various operating modes, quantitatively and qualitatively investigate the properties of the devise with arbitrary characteristics of the constituent units.

NOISE CHARACTERISTICS OF A CARRIER OSCILLATOR WITH NOISE BAND AUTOCOMPENSATION

To evaluate the effectiveness of autocompensation circuit, it is necessary to evaluate the noise characteristics [14,15] of the entire carrier oscillator in its presence and absence.

Figure 3a shows the SPDM of the phase noise of the carrier oscillator (blue indicates the dependence with the APNC on, red - with APNC off). Figure 3b shows the noise contributions of the components of the device (red indicates the noise contributions of the RG, blue - PLL and green - APNC) for the output frequency of 250 MHz at the amplifier gain equal to 1. As a PLL, an ADF5355 synthesizer chip was used, clocked by a 125 MHz SMD07050C4 reference quartz oscillator.

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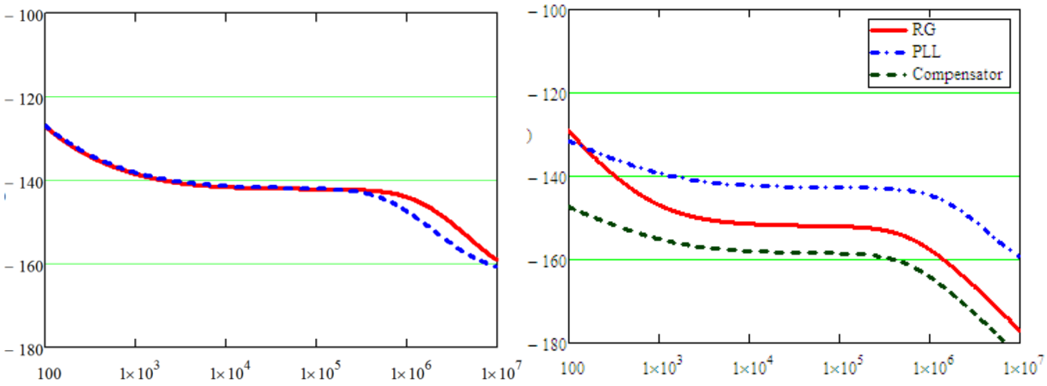
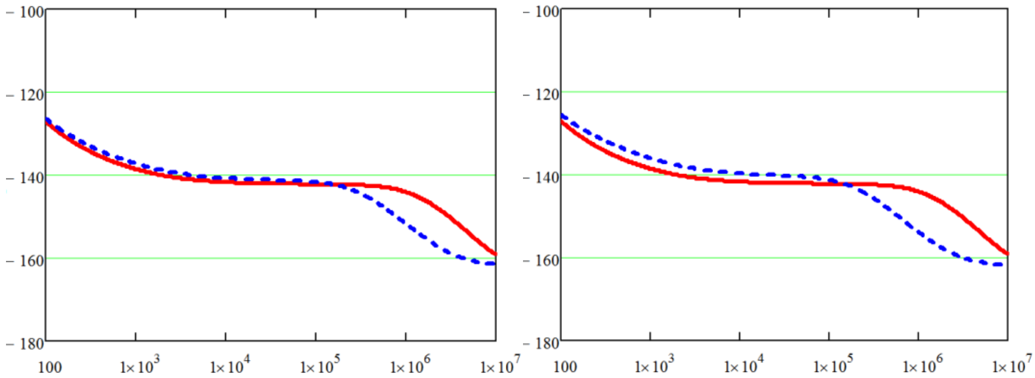


a) b)

Figure 3. SPD of phase noise of a carrier oscillator based on a PLL synthesizer with noise band compensation (a) and noise contributions of the constituent units (b) at carrier frequency of 250 MHz

The degree of noise band compensation is determined by the accuracy of the autocompensator blocks paramenters, which further necessitates the study of parametric sensitivity. Thus, Figure 4 shows the SPD of phase noise of a 250 MHz carrier oscillator based on a PLL synthesizer with compensation and the amplifier gain of n_y=3 (a) and n_y=5 (b)



a) b)

Figure 4. SPD of phase noise of a 250 MHz carrier oscillator based on a PLL synthesizer with compensation and the amplifier gain of n_y=3 (a) and n_y=5 (b)

The influence of the amplifier gain on the degree of noise compensation is also considered in Figure 5.

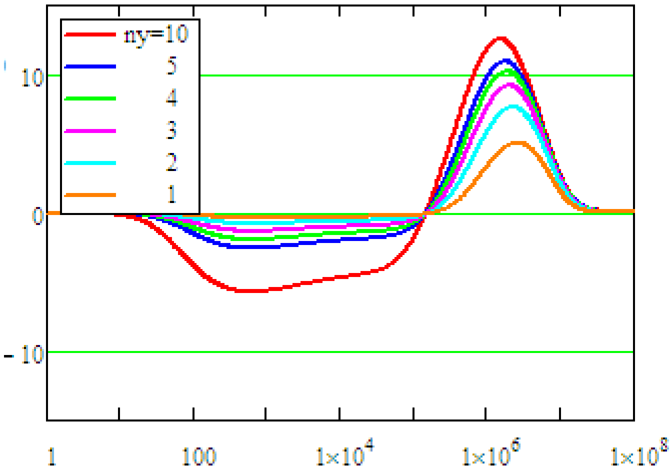


Figure 5. Dependences of the degree of noise compensation on frequency offset at a carrier frequency of 250 MHz for various ampifier gain

CONCLUSION

Based on the simulation results, it was found that the phase noise level of the oscillator based on a PLL synthesizer with automatic compensation at 1 kHz offset from the carrier in the range from 250 to 1000 MHz is about minus 125 - minus 138 dB. At the same time, the higher the frequency, the greater the level of phase noise.

An increase of the amplifier gain narrows the noise band of the scheme (due to a decrease in the phase noise of the RG and PLL at large offsets) and a section with negative compensation appears due to an increased PLL noise. The main contribution to phase noise at small offset is made by RG noise, and at larger offset the PLL noise prevails. At the same time, the noise of the autocompensator 1 is insignificant, minus 145 - minus 150 dB at the tuning of 1 kHz from the carrier oscillation.

The higher the output frequency, the lower the level of auto-compensation. At the same time, the maximum degree of autocompensation of the noise band of the device reaches 13 dB, which allows us to conclude about the effectiveness of the proposed autocompensation principle.

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