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RESEARCH ON THE POSSIBILITY OF REDUCING THE ERROR IN MEASURING THE PHASE SHIFT OF RADIO SIGNALS

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Abstract. *The possibility of reducing the error in measuring the phase shift of radio signals by the orthogonal method using analogue quadrature demodulators in solving scientific and technical problems in energy, non-destructive testing, research on determining the composition of substances, in radar, radio navigation and radio direction finding is considered. The results of a mathematical analysis of the error in determining the phase shift of radio signals are provided, taking into account the main deviations of the technical characteristics of analogue quadrature demodulators from the ideal mathematical model, which made it possible to evaluate the effectiveness of the proposed improvements. To reduce the error in measuring the phase shift of radio signals by the orthogonal method using analogue quadrature demodulators, it is recommended to use the method of determining the phase shift in the control object at different phase shifts of the query signal applied to the control object. To achieve maximum accuracy, a sufficient number and maximum step of phase shifts of the query signal have been determined.*

Keywords: phase shift, orthogonal method, quadrature demodulator, non-destructive testing

BADANIE MOŻLIWOŚCI ZMNIEJSZENIA BŁĘDU POMIARU PRZESUNIĘCIA FAZOWEGO SYGNAŁÓW RADIOWYCH

Streszczenie. *Rozważono kwestię możliwości zmniejszenia błędu pomiaru przesunięcia fazowego sygnałów radiowych metodą ortogonalną z wykorzystaniem analogowych demodulatorów kwadraturowych przy rozwiązywaniu zadań naukowych i technicznych w energetyce, kontroli nieniszczącej, badaniach nad określeniem składu substancji, w radiolokacji, radionawigacji i radiopełngacji. Przedstawiono wyniki analizy matematycznej błędu określania przesunięcia fazowego sygnałów radiowych z uwzględnieniem głównych odchyleń charakterystyk technicznych analogowych demodulatorów kwadraturowych od idealnego modelu matematycznego, co umożliwiło ocenę skuteczności proponowanych ulepszeń. W celu zmniejszenia błędu przy pomiarze przesunięcia fazowego sygnałów radiowych metodą ortogonalną z wykorzystaniem analogowych demodulatorów kwadraturowych zaleca się stosowanie metody określania przesunięcia fazowego w obiekcie kontroli przy różnych przesunięciach fazowych sygnału zapytania, który jest podawany do obiektu kontroli. W celu osiągnięcia maksymalnej dokładności określono wystarczającą liczbę i maksymalny krok przesunięć fazowych sygnału zapytania.*

Słowa kluczowe: przesunięcie fazowe, metoda ortogonalna, demodulator kwadraturowy, kontrola nieniszcząca

Introduction

Comprehensive research of materials properties and control of their composition calls for development appropriate devices and the development appropriate research techniques. In order to solve scientific and technical problems in energy, non-destructive control, in researches for composition of substances, in radar, radio navigation and radio radio-direction finding, it is necessary to create high-precision measuring systems for precision measurements of radio signals phase shift [1].

Modern technologies and rapid development for elemental equipment base allow the creation of such high-precision systems. One of the best methods for measuring radio signals phase shift is an orthogonal method that uses digital or analog multipliers.

With the development of efficient radio-based systems based on phase modulation, there was need for high-precision highly integrated and radio frequency (RF-transceivers) that significantly expanded the possibilities for accurately measuring the phase shift of radio signals over wide range frequencies, both continuous and pulse signals.

This, in turn, allowed the introduction of such technologies as MIMO (systems for communication with transmitting and receiving antennas) and Beamforming (technology of directional beam formation), which significantly improves the efficiency of such devices. Modern RF-transceivers use quadrature modulation/demodulation signals. Various mathematical models and simulators in such software tools, such as MATLAB, are used for optimization and debugging of characteristics in systems. They allow to optimize system parameters and introduce corresponding corrections to characteristics of system elements to reduce the overall measurement error.

The purpose of this work is to research the possibility of reducing error of measurement of phase shift of radio signals in non-destructive control systems, devices for determining the composition and properties of substances in radar and radionavigation systems, radio direction finding devices using modern high-performance quadrature demodulators, highly integrated RF- transceivers, hardware and software tools for optimizing their characteristics.

1. Main research material

Among the methods for measuring the radio signals phase shift, one of the best is the orthogonal method, which uses digital or analog multipliers [1].

In digital phase-shift measurement systems, the input analog measurement signal is subjected to analog-to-digital conversion and is digitally multiplied by the common-mode and quadrature component of the reference oscillator signal. Orthogonal digital signals from multiplier outputs are used by digital computing device to determine the phase shift input signals relative to phase reference digital signal. The digital multiplier phasemeter is implemented on both individual and specialized elements. Phase meters with digital multipliers have fairly high accuracy of phase shift measurement (>1%, that is, >3.6°) [2], but with increase in frequency of input signal it is necessary to significantly increase the ADC performance, digital multipliers and digital computers, which leads to significant the complexity of the device, the increase in power consumed and, consequently, a significant increase in value. Therefore, such phase meter is preferably used in cases where the frequency of measured signal is low, for example, in energy when measuring phase shifts in power networks or phase shifts low frequency ultrasonic signals. Also, such devices are used to measure phase noise of output signals of reference oscillators up to 30 MHz (Alan`s deviation) [9].

For implementation modern technologies it is necessary to increase the accuracy of the measurement of the phase shift of radio signals, the frequencies of which lie in RF and UHF (ultrahigh-frequency) ranges. Thus, by means of high-frequency sounding (1–6 GHz) of substance it is possible to carry out precise quantitative measurement volume fraction of substances without direct destructive influence on material during it`s analysis [5], or to establish the content of metals in food products [5]. Measurement of phase shift of high frequency signals in the range 400–3000 MHz is also used in contact and non-contact systems for measuring temperature and pressure using sensors on surface acoustic waves (SAW) [3, 4, 6–8].

In addition, it is often necessary to simultaneously measure phase signals simultaneously from several sources, for example, with the use technologies such as amplitude-phase detection

(detection), MIMO or Beamforming, as well as in microwave resonance therapy [11] and Diagnostics of Stress–Strain State of Shaped Profiles of Metal Structures [10].

Thus, Beamforming technology allows not only the measurement of substances volume fraction, but also to determine the location of this particle in the investigated object by scanning the object directed by beam of radiation.

Use of phasemeter with digital multipliers in these cases isn`t feasible due to lack of performance when processing high-frequency signals in real time. In such cases, a phase meter with analog multipliers is used. For today, the elements that perform analog signal multiplication have sufficient accuracy of signal multiplication. Such elements are quadrature demodulators that are widely used in communications. The principle of quadrature demodulator is considered in [5]. The quadrature demodulator forms a siphon *I* and quadrature (transmitted phase by 90°) *Q* signals by multiplying the input radio frequency signal by in-phase ($\cos(\omega_{RG}t)$) and quadrature component of the ($\sin(\omega_{RG}t)$) reference oscillator. Signals at the outputs of quadrature demodulator *I* and *Q* are vector values, and therefore change in amplitude and phase in the received signal can be determined by means of trigonometric identities.

If the input signals of the demodulator have the same frequency ($\omega_{IN} = \omega_{RG}$), that is, the pulse passing through the control object is formed from the output signal of reference oscillator, then the phase shift between input signal $U_{IN}(t) = A_{IN}\cos(\omega_{IN}t + \varphi_{IN})$ and signal of the reference oscillator $U_{IN}(t) = A_{IN}\cos(\omega_{IN}t)$ can be defined as:

$$\phi_{IN} = arctg(\frac{U_Q}{U_I}) = arctg(\frac{\sin\phi_{IN}}{\cos\phi_{IN}}) \qquad (1)$$

where: A_{RG}, ω_{RG} – amplitude and signal frequency of the reference oscillator; A_{IN}, ω_{IN}, φ_{IN} – amplitude, frequency and phase of the input signal of the demodulator relative to the signal phase of the reference oscillator.

In order to determine the phase shift between input signal and reference generator signal, the output analog signals *I* and *Q* must be converted to digital and find function $arctg(U_Q/U_I)$. Since the *arctg* function has -π/2 to +π/2 limit, in real calculations it`s more expedient to take the function *atan2*, which has limit from -π to +π.

The real quadrature demodulator has number of deviations from the ideal model and therefore the reason for input signal phase measurement error using a quadrature demodulator is:

- phase unbalance between outputs I and Q;
- amplitude misbalance between outputs I and Q;
- constant component shift at outputs of multipliers I and Q;
- penetration of the reference oscillator signal and it`s harmonic components on the outputs I and Q;
- the presence of harmonic components of the input signal;
- change of the phase shift of the input signal, depending on the level of input signal and the gain of input amplifier;
- reference oscillator phase noise;
- noises that arise in the measured environment and noise of input amplifier.

The influence of these factors on the phase measurement error is considered in [4] and [5]. Depending on the phase shift of the reference oscillator of the quadrature demodulator relative to the phase of the input signal, the first five factors affect the value of the constant component of the phase measurement error. Reference oscillator phase noise and noises that arise in the measured environment and noise of input amplifier affect the dynamic component of the measurement error, which can be reduced by statistical processing of the measurement results. In this paper, an analysis of the total influence of the first five factors on the phase measurement error is carried out and ways to reduce it are proposed.

Therefore, before choosing demodulator type for particular implementation of phase shift meter, it`s necessary to determine the requirements for frequency range of the RF input, the accuracy of signal amplification and phase measurement, that is, to determine the requirements for demodulator accuracy.

Table 1 shows the characteristics of some quadrature demodulators. From the analysis of the parameters it can be concluded that the phase imbalance between the outputs *I* and *Q* in most quadrature demodulators is no more than 1.5°, the imbalance between the outputs *I* and *Q* is no more than 0.2 dB, and the shift of constant component at the outputs of signal amplifiers *I* and *Q* multipliers is no more than 20 mV.

Methods for reducing the measurement error of phase shift by quadrature demodulators ADL5380 and U2794B are considered in [4] and [5]. The method proposed in [4] reduces the measurement error to <1°, but requires complicated calibration procedure using nodes of precise radio frequency signals phase shift.

Table 1. Characteristics of quadrature demodulators [6]

Type	Manufacturer	Input frequency range, MHz	Phase error, degrees	Amplitude error i/q max, dB
LT5506	Linear Technology	40–500	0.6	0.2
LT5516		800–1500	1.0	0.2
LT5517		40–900	0.7	0.3
LT5546		40–500	0.6	0.2
LTC5584		30–1400	0.2–0.7	0.01–0.02
LTC5585		400–4000	0.4–1.8	0.04–0.05
RF2713	RFMD	0.1–265	1.0	0.1
CMX994/A/E	CML Microcircuits	100–1000	0.5/1.0	0.03/0.1
CMX970		20–300	0.1	0.1
MAX2021	Maxim Integrated's	650–1200	1.1	0.06
HFA3783	Intersil (Renesas)	70–600	±2	±1
U2791B	ATMEL	100–1000	±1.5	±0.2
U2794B		70–1000	±1.5	±0.2
AD9361/ AD9364 RF Transceiver	Analog Devices	70–6000	0.2	0.2
ADRF6850		100–1000	0.5	0.1
ADL5380		400–6000	0.2	0.07
ADL5387		30–2000	0.4	0.05
AD8339/AD8333		0–50	1.0/0.1	0.05
AD8347		800–2500	1.0	0.3
AD8348		50–1000	0.5	0.25
LMS6002D	Lime Microsystems	300–3800	1.0 (800 MHz)	0.4
LMS7002M		0.1–3800	0.8 (850 MHz)	0.2

In [4], the calculation for error of phase shift determination between two different output signals from the control object is given, which makes it impossible to determine the constant component of fault of phase shift demodulator by calibration. Also, in [4] the value of the constant component of fault of phase shift demodulator isn`t investigated with maximum deviations the demodulator characteristics and it`s compensation is not provided.

To estimate the possibility of reducing the calculation measurement error of phase shift and to determine the methods for reducing the error, changes in the error of the phase shift measurement, depending on initial phase input signal of demodulator, are investigated with respect to reference oscillator phase.

For this purpose, the necessary coefficients are introduced into formula (1), which characterize the effect of destabilizing factors on phase shift measurement error.

Assume that the probing signal given to control object has an initial phase θ. It`s value depends on many variables, including the parameters of the nodes for signal formation, and may vary within the range from -π to +π. Then the total phase shift at the input of demodulator relative to the signal of reference oscillator:

$$\theta + \psi = arctg(\frac{U_Q}{U_I}) = arctg(\frac{\sin(\theta+\psi)}{\cos(\theta+\psi)}) \qquad (2)$$

where: θ – the initial phase of probe signal, which is fed to the control object; ψ – phase shift of signal in the control object;

U_I, U_Q – signals on outputs I and Q for the quadrature demodulator.

Introduce in formula (2) corresponding coefficients that characterize the effect of destabilizing factors for measurement error of phase shift, namely:
U_{Id} – the voltage of the displacement of constant component at the output of common-mode channel for quadrature demodulator; U_{Qd} – the voltage of the displacement of constant component at the output of common-mode channel for quadrature demodulator; U_m – signal amplitude at the output of quadrature demodulator ($U_m = 1$ V); $\Delta\varphi_{IQ}$– the value of phase imbalance between outputs I and Q, angular degrees; k – imbalance of amplitude between outputs I and Q.

Then get:

$$\theta+\psi = arctg\{\frac{[U_m(1+k)\sin(\theta+\psi+\Delta\phi_{IQ})+U_{Id}]}{[U_m\cos(\theta+\psi)+U_{Qd}]}\} \quad (3)$$

Replace the *arctg* function to *atan2* function, which has limit from -π to +π, then the measured value of the total phase shift at demodulator input relative to the signal of reference oscillator:

$$(\theta+\psi)_{MSD} = a\tan 2\{\frac{[U_m(1+k)\sin(\theta+\psi+\Delta\phi_{IQ})+U_{Id}]}{[U_m\cos(\theta+\psi)+U_{Qd}]}\} \quad (4)$$

Compare this value with the true one $(\theta+\psi)_{TR}$ and determine difference between phase shift of the measured and true values:

$$\delta(\theta+\psi) = (\theta+\psi)_{TR} - (\theta+\psi)_{MSD} \quad (5)$$

Also define the mean $\delta'(\theta+\psi)$ and the mean square $\sigma(\theta+\psi)$ error of phase shift (the difference between the measured and true values).

To do this, in the calculation formula (4), introduce successively the following values $U_{Id} = \pm 0.02$ V, $U_{Qd} = \pm 0.02$ V, $\Delta\varphi_{IQ} = \pm 1.5°$, $k = \pm 0.0233$ (0.2 dB). These technical data correspond to technical data of demodulator U2794B taken in calculations to compare the calculations obtained with the calculations given in [4]. The calculations of the error of phase shift $\delta(\theta+\psi)$ determination characteristics from the phase shift value of the signal in control object -ψ, graphically represented in Fig. 1, 2, 3, and also in table 2. The value of the initial phase of probing signal θ, which is applied to the control object in series with the step $\Delta\theta = \pi/4$ (45°).

Table 2. Results of calculations

Polarity of maximum values U_{Id}, U_{Qd}, $\Delta\varphi_{IQ}$, k,	Mean value of phase shift bias $\delta'(\theta+\psi)$, degree	Maximum error of phase shift determination $\delta(\theta+\psi)_{max}$, degree	Medium-quadratic phase biasing error $\sigma(\theta+\psi)$, degree
U_{Id} = +0.02 V, U_{Qd} = +0.02 V, $\Delta\varphi_{IQ}$ = + 1.5°, k = +0.0233	0.750	3.345	1.392
U_{Id} = -0.02 V, U_{Qd} = +0.02 V, $\Delta\varphi_{IQ}$ = + 1.5°, k = -0.0233	0.715	3.356	1.423
U_{Id} = -0.02 V, U_{Qd} = -0.02 V, $\Delta\varphi_{IQ}$ = + 1.5°, k = -0.0233	0.714	2.732	1.438
U_{Id} = -0.02 V, U_{Qd} = -0.02 V, $\Delta\varphi_{IQ}$ = + 1.5°, k = +0.0233	0.732	3.345	1.409
U_{Id} = +0.02 V, U_{Qd} = -0.02 V, $\Delta\varphi_{IQ}$ = + 1.5°, k = +0.0233	0.765	2.680	1.378
U_{Id} = +0.02 V, U_{Qd} = -0.02 V, $\Delta\varphi_{IQ}$ = + 1.5°, k = +0.0233	-0.767	1.805	1.379
U_{Id} = +0.02 V, U_{Qd} = +0.02 V, $\Delta\varphi_{IQ}$ = - 1.5°, k = +0.0233	-0.767	-2.68	1.379
U_{Id} = -0.02 V, U_{Qd} = +0.02 V, $\Delta\varphi_{IQ}$ = - 1.5°, k = -0.0233	-0.748	-2.732	1.419
U_{Id} = +0.02 V, U_{Qd} = +0.02 V, $\Delta\varphi_{IQ}$ = - 1.5°, k = -0.0233	-0.714	-3.356	1.423
U_{Id} = +0.02 V, U_{Qd} = -0.02 V, $\Delta\varphi_{IQ}$ = - 1.5°, k = -0.0233	-0.714	-2.732	1.438
U_{Id} = +0.02 V, U_{Qd} = -0.02 V, $\Delta\varphi_{IQ}$ = - 1.5°, k = +0.0233	-0.732	-3.345	1.409
U_{Id} = -0.02 V, U_{Qd} = -0.02 V, $\Delta\varphi_{IQ}$ = - 1.5°, k = +0.0233	-0.765	-2.68	1.378
U_{Id} = -0.02 V, U_{Qd} = +0.02 V, $\Delta\varphi_{IQ}$ = - 1.5°, k = +0.0233	-0.764	-3.345	1.391

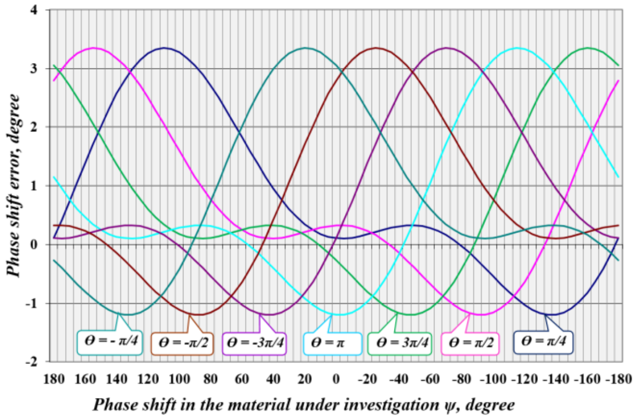

Fig. 1. Value of phase shift error δ(θ+ψ), depending on phase shift value of the signal in the control object -ψ, is ψ in range from -π to +π with the initial phase of probe signal θ taken in series with step Δθ = π/4 (45°) in range -π to π (U_{Id} = +0.02 V, U_{Qd} = +0.02 V, $\Delta\varphi_{IQ}$ = +1.5°, k = +0.0233)

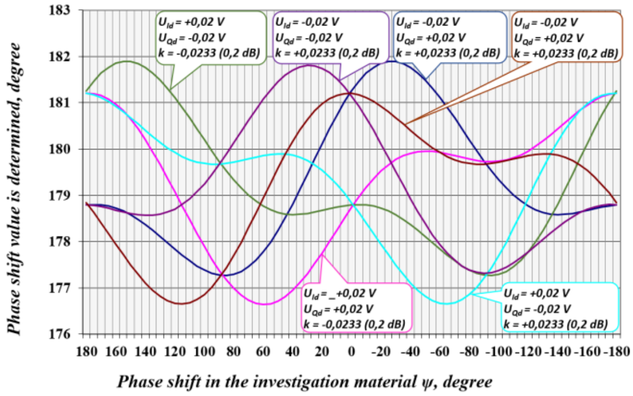

Fig. 2. Phase value of θ+ψ depends on phase shift to the signal in control object -ψ in the range from -π to +π with the initial phase of probe signal θ = π(180°) and different polarity of the maximum values U_{Id}, U_{Qd}, k and $\Delta\varphi_{IQ}$ = -1.5°

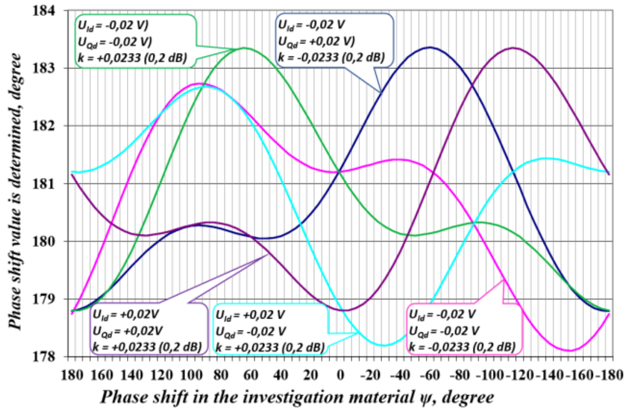

Fig. 3. Phase value of θ+ψ depends on phase shift to the signal in control object -ψ in the range from -π to +π with the initial phase of probe signal θ = π (180°) and different polarity of the maximum values U_{Id}, U_{Qd}, k and $\Delta\varphi_{IQ}$ = + 1.5°

The graphs show that when changing the phase shift of the signal $\theta+\psi$ the measurement error value is changed. Despite the fact that the calculations are taken $\Delta\varphi_{IQ} = \pm 1.5°$ the maximum error value is ± 3.345°. The reason for this is the difference in the characteristics of the real quadrature demodulator from its ideal mathematical model. At the same time, the average value of phase shift error is $\theta+\psi$ when changing the phase shift θ in the range from -π to +π is only ± 0.767°. It is obvious that in order to reduce the error of the measurement results, it is necessary to measure the phase shift of the signals when the phase θ changes in the range from -π to +π and in calculations take their average value taking into account the constant component of the error determined by calibration.

The graphs show that changing the phase shift of $\theta+\psi$ signal, the value of measurement error also changes. Despite fact that at calculations $\Delta\varphi_{IQ} = \pm 1.5°$ is taken, the maximum error value is $\pm 3.345°$. The reason for this is the difference in the characteristics of the real quadrature demodulator from it`s ideal mathematical model. At the same time, the average value of the phase shift error in phase shift θ in the range from -π to +π is only ±0.767°. It is obvious that in order to reduce the error of measurement results, it is necessary to measure the phase shift of signals when the phase θ changes in the range from -π to +π and, in the calculations, take their average value taking into account the constant component of the error determined by calibration.

2. Research results. Reduced error of measurement of radio signals phase shift

For research the possibility of reducing the error of determining radio signals phase shift in the control object by averaging the measured values of signal phase at the output of control object $\theta+\psi$ at different phase shifts θ in the range from -π to +π with the step of $\Delta\theta$ signal, which is fed to object of control.

The average value of signal phase $\theta+\psi$ is determined by the formula:

$$\delta'(\theta,\psi) = \frac{1}{(n+1)} \sum_{i=1}^{n} \left[(\theta(i)+\psi)_{TR} - (\theta(i)+\psi)_{MSD} \right] \qquad (6)$$

where: n – number of times for phase shift of signals when changing the phase of the request signal θ in the range from -π to +π with the step of $\Delta\theta$; $\theta(i)$ –current value of the phase of the request signal at the second step of the phase shift θ of the request signal in the range from -π to +π with the step of $\Delta\theta$; $(\theta(i)+\Psi)_{TR}$ – true value of phase of the signal at the input of demodulator at the second step of phase change θ of the request signal in the range from -π to +π with the step of $\Delta\theta$; $(\theta(i)+\Psi)_{MSD}$ – value of signal phase at the output of control object at second step of phase change of query signal θ in the range from -π to +π with the step of $\Delta\theta$, defined by the formula (4).

Signal phase shift indicators for changing phase of the request signal θ in the range from -π to +π with step $\Delta\theta$ (at $\Delta\theta = \pi/2$ n = 4, at $\Delta\theta = \pi/4$ n = 8, at $\Delta\theta = \pi/8$ n = 16) is depicted in Fig. 4.

Calculations of the mean value $\delta'(\theta+\psi)$, the mean square value $\sigma(\theta-\Psi)$ and the maximum value $\delta(\theta-\Psi)$ given with steps $\Delta\theta$ = 2π/3, π/2, π/3, π/4, π/6, π/8 in the range from -π to +π. Calculations of the maximum value of $\delta(\theta-\Psi)_{max}$ depending on step $\Delta\theta$ shown in Fig. 5. The analysis for obtained values suggests that the 4 offset phases of the query phase θ in the range from -π to +π with the step $\Delta\theta = \pi/2$ are sufficient to determine the phase shift of the radio signals in control object with an accuracy of no worse than $\pm 0.76^{o}$ without compensation of error constant component by calibration, despite the fact that $\Delta\varphi_{IQ} = \pm 1.5°$.

If by means of calibration to determine the constant component for error (in the case of calculations given in table 3: $\delta'(\theta+\psi) = 0.759°$) then the error of determining radio signals phase shift in the control object will be no worse than ±0.1°.

The block diagram for practical implementation of such a device using the proposed method for reducing the measurement error of radio signals phase shift in the control object is shown in Fig. 6.

The results of calculations for error n of bias times phase shift the mean value with step $\Delta\theta$ in the range from -π to +π for U_{Id} = +0.02 V, U_{Qd} = +0.02 V, $\Delta\varphi_{IQ}$ = + 1.5°, k = +0.0233 and ψ = 0, π/4, π/2, 3π/4, π are given in table 3.

The formation to request signal with a phase shift θ in the range from -π to +π with the step $\Delta\theta$, which is applied to the control object of the (CO), is carried out by a quadrature modulator. The voltage at it`s inputs I and Q is formed at the outputs of DAC by the control unit (CU), corresponding to the value of the phase shift θ. The pulse modulator M, in turn, creates, under the control of the CU, a probing impulse of corresponding form and duration. The measured signal from the control object is amplified by input amplifier and is converted into digital orthogonal signals I and Q using quadrature demodulator and ADC. The digital signal processing unit calculates the phase shift $\theta+\psi$, taking into account the current value of θ. The value of the phase shift in the control object ψ is determined by averaging the measurement results when the θ is changed in the range from -π to +π with the step $\Delta\theta$. To increase the accuracy of the measurement, a constant component of phase shift error measurement is taken into account, which is determined by calibrating the device, for which the request signal is fed through the multiplexer to the input of demodulator and the current value of it`s phase shift θ is measured. In the following, this value is taken into account when calculating the phase shift in control object ψ. If the dynamic range of the signal attenuation in control object is significant, then a corresponding calibration procedure is necessary to compensate for the phase shift error for different levels of input signal.

Modern transceivers have quadrature modulator and quadrature demodulator (quadrature modulator/demodulator) in it`s composition. The control functions of the CU, ADC, DAC, and DSP digital signal processing can be performed by the microcontroller, so practical implementation of such device can be very simple and cheap.

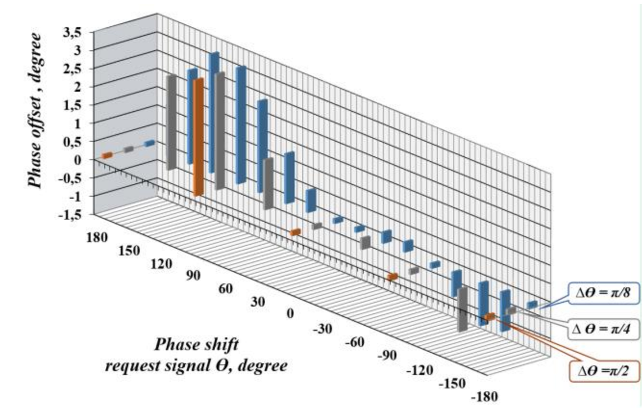

Fig. 4. Phase offset signals when changing phase of the request signal θ

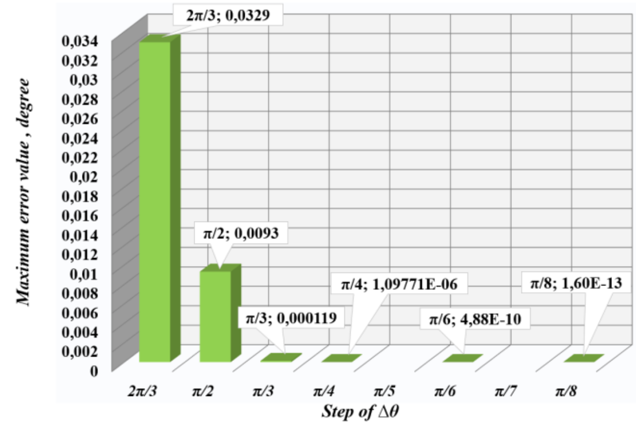

Fig. 5. Maximum error value $\delta(\theta+\psi)_{max}$ when the measured values are averaged from -π to +π depending on the step $\Delta\theta$

Table 3. Results of the error n calculations of phase shift bias average values $\delta'(\theta+\psi)$

Step $\Delta\theta$, n – number of phase shift indicators	Mean value of phase shift bias $\delta'(\theta+\psi)$, degree	Maximum error of phase shift determination $\delta(\theta+\psi)_{max}$, degree	Medium-quadratic phase biasing error $\sigma(\theta+\psi)$, degree
$\Delta\theta = 2\pi/3, n = 3$	0.75864	0.0329	0.0211
$\Delta\theta = \pi/2, n = 4,$	0.75864	0.0093	0.00667
$\Delta\theta = \pi/3, n = 6$	0.75864	0.000119	8.4E-05
$\Delta\theta = \pi/4, n = 8$	0.75864	2.3E-06	9.6E-07
$\Delta\theta = \pi/6, n = 12$	0.75864	4.88E-10	3.52E-10
$\Delta\theta = \pi/8, n = 16$	0.75864	2.4E-13	2.0E-13

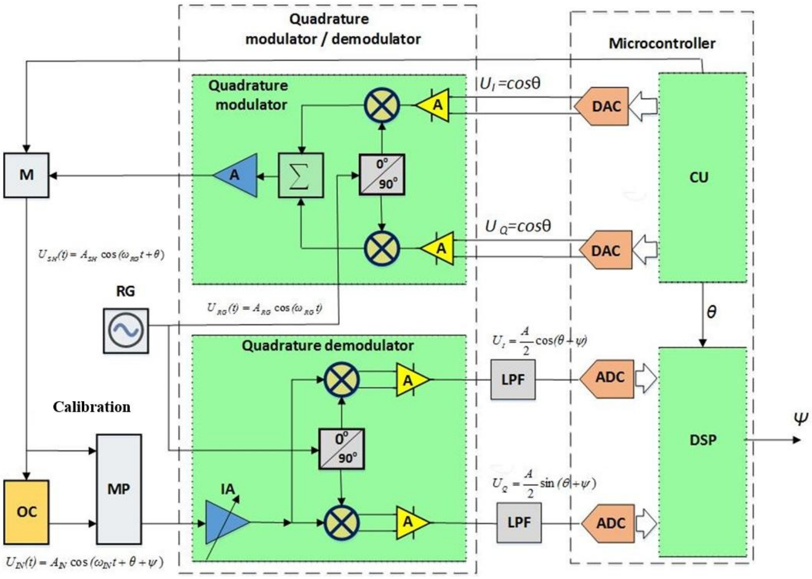

Fig. 6. The block diagram of the device using the proposed method for reducing the error of measuring the radio signals phase shift in the control object, where: OK – object of control, M – pulse modulator, MP – multiplexer, IA – input amplifier, A – amplifier, RO - reference generator, LPF – low pass filter, ADC – analog-to-digital converter, DAC – digital-to-analog converter, CU – control unit, DSP – digital signal processing unit

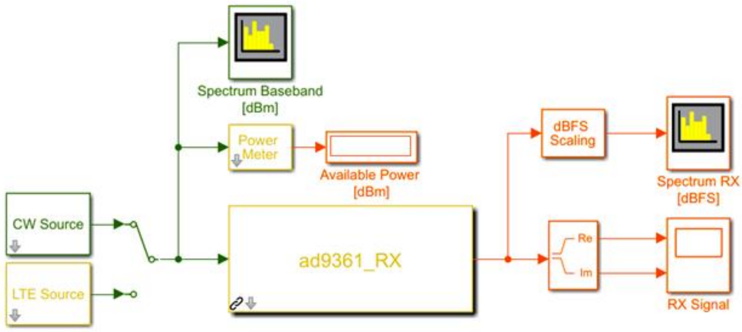

Fig. 7. Model in Matlab Simulink for AD9361 by Analog Devices receiver for research and optimization of it`s characteristics

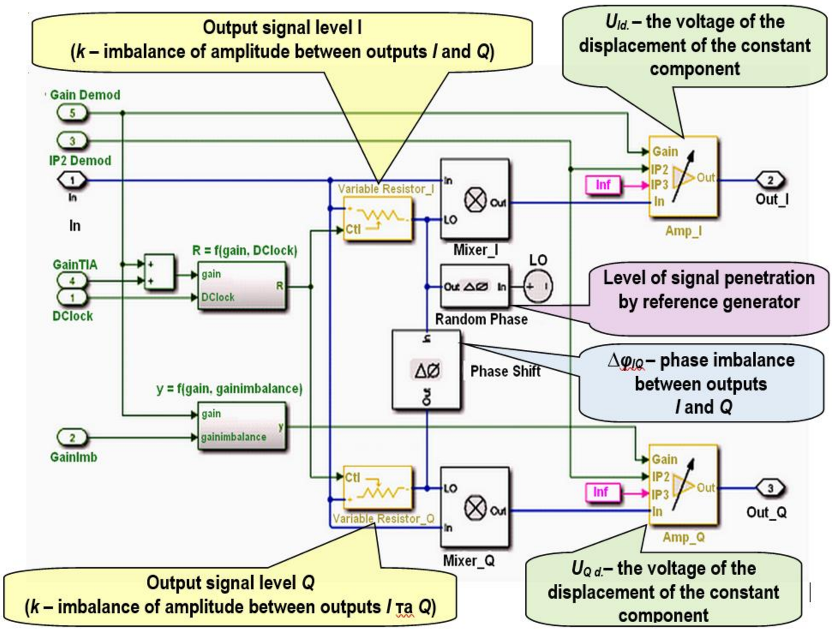

Fig. 8. Modules of receiver-transceiver AD9361of Analog Devices, which allow to simulate the influence of various factors on phase bias measurement errors

To accurately measure phase shift in wide range of frequencies, it`s effective to software defined radio (SDR) devices that consist of a quadrature modulator/demodulator with built-in frequency synthesizer and ADC. Program-configurable radio is a universal device whose functions are determined by software tools such as Matlab Simulink, MatWiever, GNU Radio. For example, the software program-configurable radio module USRP B210 USB Software Defined Radio (SDR) from Ettus Research [14], which can be used for preliminary research and small projects, as its functionality is limited by USB bandwidth. When prototyping devices, it is worth using more powerful high-performance, multi-channel SDRs, such as the USRP E310/E312, X310, and X410 to create high-performance, multi-channel devices.

The Communications Toolbox Support Pack for USRP™ Embedded Series Radio allows you to use MATLAB and Simulink to prototype devices, verify, and test practical wireless systems. Using this support pack with the USRP E310 or USRP E312 SDR hardware, you can work with real-world RF signals using one (1×1) or two (2×2) transmit and receive streams. Using HDL Coder or Embedded Coder, you can implement your own hardware device for your SDR models.

These devices, using the software Matlab Simulink, allow not only mathematical modeling of the device to measure phase shift, but also research on optimizing parameters directly on devices. The model AD9361 transceiver of Analog Devices [12, 13] used in the SDR in Matlab Simulink is shown in Fig. 7.

In receiver AD9361 (Fig. 8) have been introduced modules to simulate the phase shift between *I/Q* outputs, *I/Q* amplitude imbalance, and *I/Q* output oscillator signal penetration. This allows the device to be modeled as a whole, to determine the effect of each destabilizing factors, to introduce corrective corrections, to determine optimal parameters of filters and, thus, to reduce the total error of measurement.

3. Conclusions

1. In the case of solving scientific and technical problems in energy, non-destructive control, in materials control researches, in radar, radionavigation and radio-optical testing, it`s expedient to use analog quadrature demodulators to measure the phase shift of radio signals by orthogonal method. The scientific novelty of the proposed method for reducing phase shift measurement errors lies in compensating for the constant component of the input signal phase measurement error by stepwise changing the phase of the probing signal in the range from $-\pi$ to $+\pi$ with subsequent averaging of the measurement data.

2. For various phase shifts in the range from $-\pi$ to $+\pi$, the request signal, which is sent to the control object, to reduce the error of determining radio signals phase shift in control object must be determined by averaging the phase shift of these signals, taking into account the predetermined by previous calibrate of the request signal phase shift. The request signal phase shift in the range from $-\pi$ to $+\pi$ to obtain a minimum error of measurement of $\pm 0.1°$ must be no more than $\pi/2$.

3. For precise measurements of phase shift in wide range of frequencies, it`s effective to use software-configurable radio devices that, using Matlab Simulink software, can not only make mathematical modeling by device for phase shift measurement, but also conduct explorations on optimization of parameters directly using devices.

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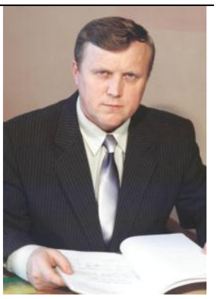

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