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METHOD OF DETERMINING THE PITCH ANGLE OF AN AIRCRAFT IN NAVIGATION SYSTEMS BY RADIO BEACON SIGNALS

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Abstract. The polarization-modulation method of determining the pitch angle of an aircraft based on the emitted horizontally polarized signals of a radio beacon is considered. The polarization modulator is implemented as a Faraday rotator of the polarization plane of the received radio beacon signals and is installed in the microwave path of the onboard receiving antenna. The pitch angle is determined based on the phase of the second harmonic of the rotation frequency of the polarization plane contained in the spectrum of the envelope of the receiver output signal. A model of the experimental setup implementing this method is described. Experimental results of measuring the pitch angle of an aircraft are presented and estimates of the measurement accuracy are obtained.

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1. INTRODUCTION

In existing radio beacon signal navigation systems (RBS), aircraft navigational elements such as roll and pitch are not measured [1, 2]. Traditionally, in practical navigation, expensive onboard autonomous gyroscopic orientation systems are used to measure them [3], in which measurement errors constantly accumulate over time [3, 4]. A promising direction for improving onboard navigation equipment is the development of integrated navigation systems that combine both radio engineering and non-radio engineering systems for determining the same navigational elements [4]. Papers [5, 6] propose radio engineering methods for measuring aircraft navigational elements. Polarization-amplitude [5] and polarization-modulation [6] methods for measuring the roll angle are considered, based on the use of horizontally polarized radio beacon signals; the possibility of measuring the aircraft pitch angle is not investigated. In paper [7], a polarization-amplitude method for determining the aircraft pitch angle using vector properties of radio beacon signals is proposed. The essence of the method is that a radio beacon from a point with known coordinates emits horizontally polarized signals, whose electric field vector lies in the horizontal plane. On board the aircraft, a receiving antenna performs lateral reception of radio beacon signals in relation to the direction of movement in a linear polarization basis (LPB). The aircraft pitch angle is determined by the ratio of amplitudes of in-phase linearly polarized orthogonal components of the received radio beacon signals from the outputs of the linear polarization separator (LPS) arms, oriented at an angle $\pi/4$ to the vertical and longitudinal structural axes of the aircraft. The proposed polarization method for determining aircraft pitch has one significant drawback – the onboard receiving microwave equipment is two-channel, which increases its dimensions and weight and limits the practical use of the method.

This article proposes a polarization-modulation single-channel microwave method for determining the aircraft pitch angle using emitted horizontally polarized radio beacon signals.

2. METHOD DESCRIPTION

The development of polarization methods for determining aircraft navigation elements involves the representation of transmitted and received vector signals in specific polarization bases and in several coordinate systems [5, 6]. The choice of the reference coordinate system (RCS) associated with the radio beacon, and the aircraft's own coordinate system (OCS) associated with its structural axes, as well as the choice of the polarization modulator type, is determined by the physical meaning of the problem being solved.

The essence of the considered method for determining the aircraft pitch angle is as follows.

Let's place the radio beacon at the origin of a Cartesian coordinate system (at the beginning of the fixed RCS), whose axes OX and OZ lie in the horizontal plane XOZ, and the axis OY is perpendicular to this plane (Fig. 1a). Let the radio beacon emit in the direction of the OZ axis a signal in the form of a plane monochromatic wave with horizontal polarization. We represent the emitted wave in the LPB, whose unit vectors coincide with the positive directions of the axes OX and OY, as a projection of the electric field vector $\mathbf{E}$ onto the plane XOY, perpendicular to the direction of wave propagation OZ. Then the graphical representation of the horizontally polarized wave is the vector $\mathbf{E}$, which coincides with the positive direction of the OX axis, located in the horizontal plane XOZ (Fig. 1a). We represent the horizontally polarized wave in LPB (omitting the time dependence) by the Jones vector in the form [8]

$$\mathbf{E} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}. \tag{1}$$

Fig. 1. Explanation of determining the aircraft pitch angle ξ.

Let's assume that the aircraft is moving in a direction perpendicular to the radiation direction *OZ*. On board the aircraft, a receiving antenna, whose directional pattern symmetry axis is perpendicular to the aircraft's direction of motion, performs lateral reception of radio beacon signals (1) in the LPB. Let's define the BCS (Body Coordinate System) associated with the aircraft body as a mobile Cartesian coordinate system $X_C O'Y_C$, formed by the longitudinal $O'X_C$ and vertical $O'Y_C$ structural axes of the aircraft. We place its origin at point O' , coinciding with the aircraft's center of mass. The axis $O'Z$ will be considered directed along the radiation direction OZ . The direction of axes $O'X_C$ and $O'Y_C$ in the plane *XOY* of the GCS (Global Coordinate System) is linked to the aircraft's pitch angle ξ. The axis $O'Y_C$ in the absence of pitch is assumed to be directed vertically upward and coinciding with the axis *OY*. The axis $O'X_C$ is longitudinal and coincides with the axis *OX* of the GCS. Obviously, when the aircraft has no pitch, the direction of the longitudinal axis $O'X_C$ and the electric field intensity vector of the radiation **E** coincide (see Fig. 1b).

In the case of aircraft pitch, the longitudinal axis $O'X_C$ will be rotated in one direction or another in the plane *XOY*. The angle between the vector **E** and the direction of the longitudinal axis $O'X_C$ will be equal to the pitch angle ξ, which determines the physical basis for its measurement. In this case, if the longitudinal axis $O'X_C$ is below the horizontal plane *XOZ* , then the pitch is negative (-ξ) (Fig. 1c), and if above, then the pitch is positive (+ξ) (Fig. 1d) [4].

Let's assume that a polarization modulator in the form of a Faraday rotator of the polarization plane (FRPP) for received beacon signals is installed in the microwave path of the receiving antenna of an onboard single-channel microwave radio receiver. To describe the interaction of horizontally polarized beacon signals with microwave elements of the onboard receiving antenna, we will use the formalism of Jones vectors and matrices [8]. Then the Jones vector at the output of the FRPP on board the aircraft with pitch angle ±ξ can be found using transformations of the form [9]

$$\mathbf{E}_{вых} = C \cdot [\Pi][R(\alpha)][R(\pm\xi)] \cdot \mathbf{E}, \qquad (2)$$

where **E** – Jones vector (1) of the emitted horizontally polarized wave [6],

$$[R(\pm\xi)] = \begin{bmatrix} \cos\xi & \pm\sin\xi \\ \mp\sin\xi & \cos\xi \end{bmatrix}$$

– rotation operator by pitch angle ±ξ; +ξ – positive pitch angle of the aircraft when the longitudinal axis $O'X_C$ of the aircraft is above the horizontal plane *XOZ* [4], -ξ – negative pitch angle of the aircraft when the longitudinal axis $O'X_C$ of the aircraft is below the horizontal plane *XOZ* [4],

$$\left[R(\alpha)\right]=\begin{bmatrix}\cos\alpha & \sin\alpha\\ -\sin\alpha & \cos\alpha\end{bmatrix}$$

– FRPP operator at an angle $\alpha=\Omega t$ (Ω – rotation frequency) [10],

$$\left[\Pi\right]=\begin{bmatrix}1 & 0\\ 0 & 0\end{bmatrix}$$

– polarizer operator [6] (transition from circular waveguide to rectangular) with horizontal native polarization coinciding with the longitudinal axis $O'X_C$ of the aircraft, *C* – constant value that takes into account the beacon transmitter potential, the distance from the transmitter to the aircraft, and the receiver sensitivity.

After performing the necessary matrix transformations in formula (2), we get

$$\mathbf{E}_{вых}=C\begin{bmatrix}\cos(\alpha\pm\xi)\\ 0\end{bmatrix}. \tag{3}$$

Taking into account formula (3), the signal at the receiver input as a function of the orientation angle a of the polarization plane can be described by the expression

$$\mathbf{E}_{вх}(\alpha)=C\cdot\cos(\alpha\pm\xi). \tag{4}$$

The signal amplitude at the output of the receiver with logarithmic amplitude characteristic and linear detector equals

$$A(\alpha)=\lg C+\lg\left|\cos(\alpha\pm\xi)\right|. \tag{5}$$

After transformations of expression (5), considering that the signal level in the case of a logarithmic receiver is usually measured in decibels, at $\alpha=\Omega t$ we get

$$A\,(\Omega\,t\,)[\text{dB}] = 20\lg C + 10\lg\{0.5\,(1+\cos(2\,\Omega\,t\pm 2\xi))\}. \tag{6}$$

Relation (6) allows us to calculate the dependence of the logarithmic receiver output signal amplitude on the angular position of the polarization plane α for different values of the pitch angle ξ. The calculation results are shown in Fig. 2. Curves *1 – 3* correspond to pitch angle ξ values equal to 0°, 15°, - 15° .

Fig. 2. Dependencies of the output signal amplitude of the logarithmic receiver on the orientation angle of the polarization plane α of received signals...

In Fig. 2, it can be seen that the signal amplitude at the receiver output is modulated by twice the frequency of rotation of the polarization plane of the received beacon signals, with the amplitude modulation of the signal reaching 100% depth.

At the same time, the pitch angle does not affect the shape of this dependency and the depth of amplitude modulation, but only determines its phase shift by twice the pitch angle of the aircraft. Therefore, in the envelope spectrum of the logarithmic receiver output signal, there is a spectral component at a frequency of 2Ω. Its amplitude $A_{2\Omega}$ can be found using the Fourier transform of the form

$$A_{2\Omega}\left[\text{дБ}\right]=\frac{1}{\pi}\cdot\int\limits_{0}^{2\pi}A\left(\Omega t\right)\cdot\cos 2\Omega t d\left(\Omega t\right), \tag{7}$$

i.e. $A_{2\Omega}=8.69$ дБ ($A_{2\Omega}$ does not depend on the pitch angle of the aircraft), the phase $\varphi_{2\Omega}$ taking into account formula (6) is related to the pitch angle ξ of the aircraft by the relation

$$\xi\left[\text{рад}\right]=\pm\frac{\varphi_{2\Omega}}{2}, \tag{8}$$

where the "+" sign corresponds to a positive pitch angle ξ, and the "-" sign corresponds to a negative pitch angle ξ.

The phase $\varphi_{2\Omega}$ is measured relative to the phase of the reference signal, determined by the angular position of the polarization plane of the received beacon signal.

It should also be noted that, taking into account formula (6), the amplitude $A_{2\Omega}$ and phase $\varphi_{2\Omega}$ of the spectral component at frequency 2Ω do not depend on the transmitter potential, receiver sensitivity, and the distance from the aircraft to the beacon. Energy parameters determine the constant component of the signal at the output of the onboard logarithmic device.

3. EXPERIMENTAL MODEL OF THE POLARIZATION-MODULATION RMS

To verify the results of theoretical studies and obtain experimental estimates of the accuracy of determining the pitch angle ξ, a model of the polarization-modulation RMS was created. The functional diagram of the model is shown in Fig. 3. The model included a ground-based beacon located at a point with known coordinates, as well as onboard receiving equipment implemented on the basis of the "Groza-26" aircraft radar operating in passive mode for receiving beacon signals.

Fig. 3. Functional diagram of the polarization-modulation RMS model for determining the pitch angle.

The ground-based radio beacon included a transmitter (TXMTR), first and second rotating waveguide joints (RWJ1, RWJ2), and a horn transmitting antenna (HTA). The TXMTR was a standard high-frequency signal generator of the G4-83 type, operating in pulse mode. The pulse repetition frequency F_n was 400 Hz, and the pulse duration τ_n was 3.5 μs. The carrier frequency value f_n was 9370 MHz. The radiation power P_n was 10 mW. RWJ1 allowed changing the radiation direction in the horizontal plane, while RWJ2 enabled setting the inclination angle of the polarization plane of the radiated signals through $1°$ in the vertical plane to simulate changes in the aircraft pitch angle.

The radio beacon's HTA had horizontal native polarization with an effective aperture area of 80 cm^2. The external view of the ground-based radio beacon model is shown in Fig. 4.

Fig. 4. External view of the ground-based radio beacon model .

To implement the proposed polarization-modulation method, the standard feed with a polarization plane rotator (PPR) of the onboard parabolic receiving antenna (OPRA) of the "Groza-26" radar (Fig. 5) operated in continuous rotation mode of the polarization plane with a frequency of Ω=20 Hz for the received radio beacon signals.

Fig. 5. External view of the standard OPRA feed with PPR.

The OPRA had a directional pattern width $3°$ and was a parabolic mirror with a diameter of 760 mm. The antenna gain was 25 dB, and the logarithmic receiver sensitivity was 120 dB/W. The external view of the onboard equipment model for the polarization-modulation radio beacon system is shown in Fig. 6.

Fig. 6. External view of the onboard equipment model for the polarization-modulation radio beacon system.

The ground-based radio beacon emitted horizontally linearly polarized electromagnetic waves. The initial position of the electric field vector **E** of the emitted waves coincided with the horizontal plane. The radiation direction in the horizontal plane was set using RWJ1.

The signals from the ground-based radio beacon were received by the BZPA, from the output of which the signal was fed to the input of the FVPP. The rotation frequency of the polarization plane

W was set by the ZG frequency. From the output of the FVPP, which is a transition from a circular cross-section waveguide to a rectangular cross-section waveguide with horizontal native polarization, the signal was fed to the input of the LP. From the output of the LP on the rectangular waveguide side, the signal went to the input of the LFP.

As a result of the polarization plane rotation at frequency Ω, a sequence of pulses amplitude-modulated by the doubled frequency of the polarization plane rotation 2Ω was formed at the output of the LFP. From the LFP output, the signal was fed to the BS and then to the PD, where the signal amplitude was memorized for the period of the emitted pulses repetition. The bandpass filter PF isolated the spectral component at frequency 2Ω, contained in the spectrum of the envelope of the LFP output signal. Its phase $\varphi_{2\Omega}$ was measured in the PD relative to the phase of the reference signal $\cos 2\Omega t$ coming from the FOS. The AD measured the amplitude of the spectral component $A_{2\Omega}$, and the value of the pitch angle ξ, determined by the phase of the spectral component $\varphi_{2\Omega}$, was displayed on the pitch angle indicator.

4. EXPERIMENTAL RESULTS

To verify the operability of the proposed method for measuring the pitch angle, the experiment was conducted on a ground-based inclined path with a length of 1300 m. The radio beacon model was located on the earth's surface. The model of the onboard receiving equipment was installed at a height of 18 m. The onboard receiving antenna BZPA was aimed at the radio beacon.

Simulation of the aircraft pitch angle change was carried out by rotating the orientation angle of the polarization plane of the emitted signals. The orientation angle of the polarization plane was set by VVS2 with a step $1°$ within the range $\pm 15°$ relative to the initial position, corresponding to the horizontal orientation of the polarization plane. The horizontal position of the electric field vector **E** of the emitted signals corresponded to the zero value of the pitch angle.

Phase measurement $\varphi_{2\Omega}$ was conducted for each angular position of the polarization plane of the emitted signals during a thirty-second time interval with subsequent averaging. At the same time, the average level of received signals and the amplitude of the spectral component $A_{2\Omega}$ were recorded.

Measurement results $\varphi_{2\Omega}$ when changing the pitch angle are shown in Fig. 7 (curve 2). The same figure shows the theoretical dependence (curve 1) obtained in accordance with expression (8). The root-mean-square deviation of the measured pitch angle from the specified one was $\sigma_\xi = 0.92°$.

Fig. 7. Dependencies of the phase j_{2W} on the pitch angle ξ: *1* – theory, *2* – experiment.

5. CONCLUSION

1. A polarization-modulation method for measuring the pitch angle of an aircraft using horizontally polarized signals from a ground-based radio beacon has been proposed and tested.

2. The relationship between the phase of the spectral component at the frequency $2W$, contained in the spectrum of the envelope of the received signals, and the pitch angle for the studied polarization modulator in the form of a FVPP has been theoretically investigated and experimentally confirmed.

3. Using the created model of a polarization-modulation RMS, experimental estimates of the accuracy of pitch angle measurement were obtained.

4. The method can find application in aircraft orientation systems during landing approach, and its joint use with inertial navigation means will increase the reliability of the obtained navigation information.

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FIGURE CAPTIONS

Fig. 1. Explanation of determining the pitch angle ξ of the aircraft.

Fig. 2. Dependencies of the output signal amplitude of the logarithmic receiver on the orientation angle of the polarization plane α of received signals at pitch ξ equal to: 0 – curve *1* , 15° – curve *2* , -15° – curve *3* .

Fig. 3. Functional diagram of the polarization-modulation RMS prototype for determining the pitch angle: TRNSM – transmitter, RWJ1 and RWJ2 – first and second rotary waveguide joints, HTA – horn transmitting antenna, BOMA – board-mounted mirror receiving antenna, FPPR – Faraday polarization plane rotator, LGR – logarithmic receiver, MG – master generator, SU – strobing unit, RSF – reference signal former, PD – peak detector, PHD – phase detector, BPF – band-pass filter, PAI – pitch angle indicator of the aircraft, AD – amplitude detector.

Fig. 4. External view of the ground-based radio beacon prototype: *1* – RWJ1, *2* – RWJ2, *3* – HTA, *4* – TRNSM (G4-83).

Fig. 5. External view of the standard BOMA feed with FPPR: *1* – BOMA feed, *2* – FPPR.

Fig. 6. External view of the on-board equipment prototype of the polarization-modulation RMS.

Fig. 7. Phase dependencies $\varphi_{2\Omega}$ on the pitch angle ξ: *1* – theory, *2* – experiment.

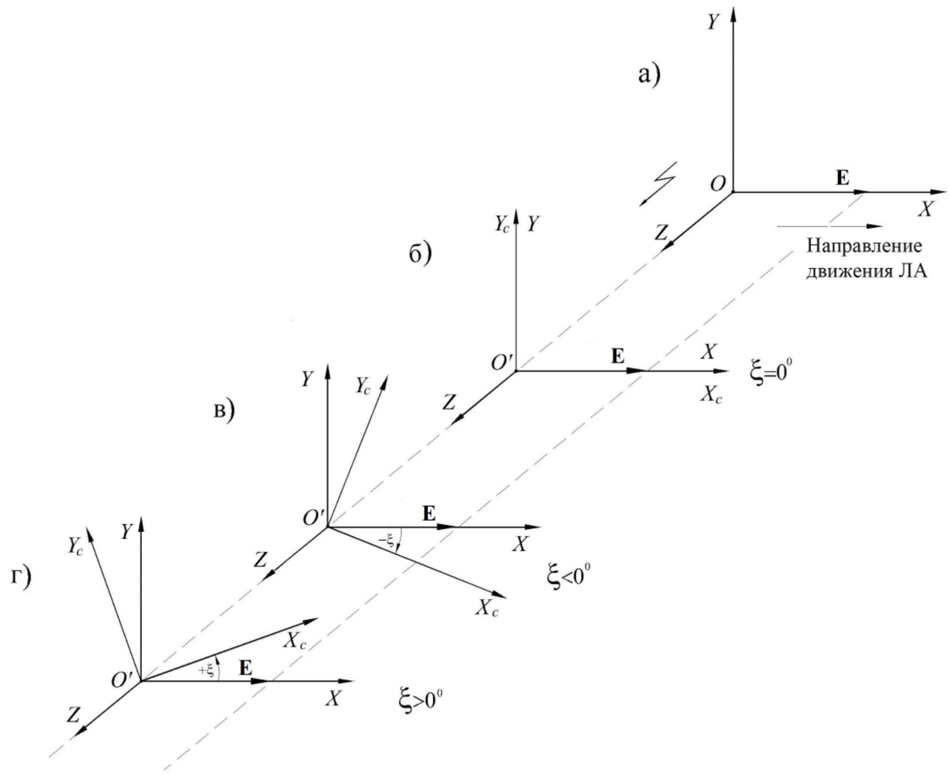
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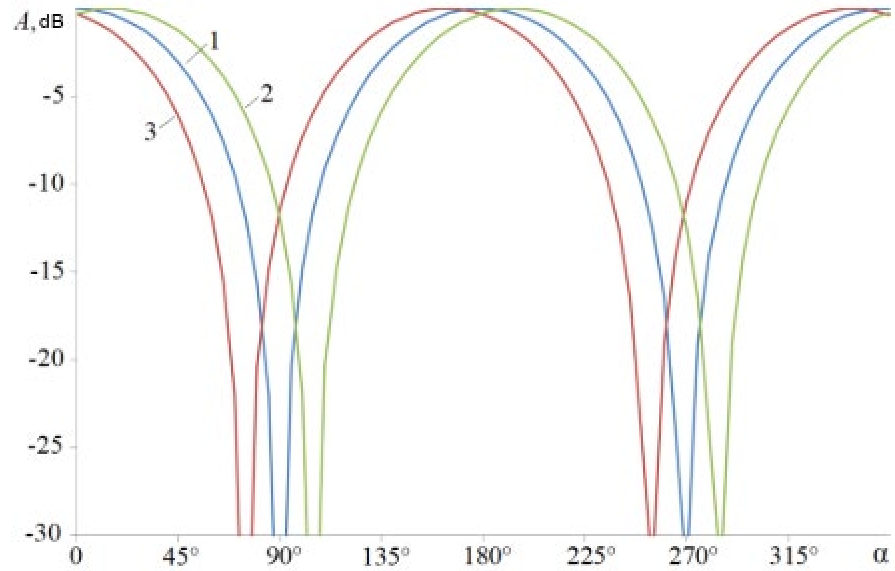
Fig. 1.



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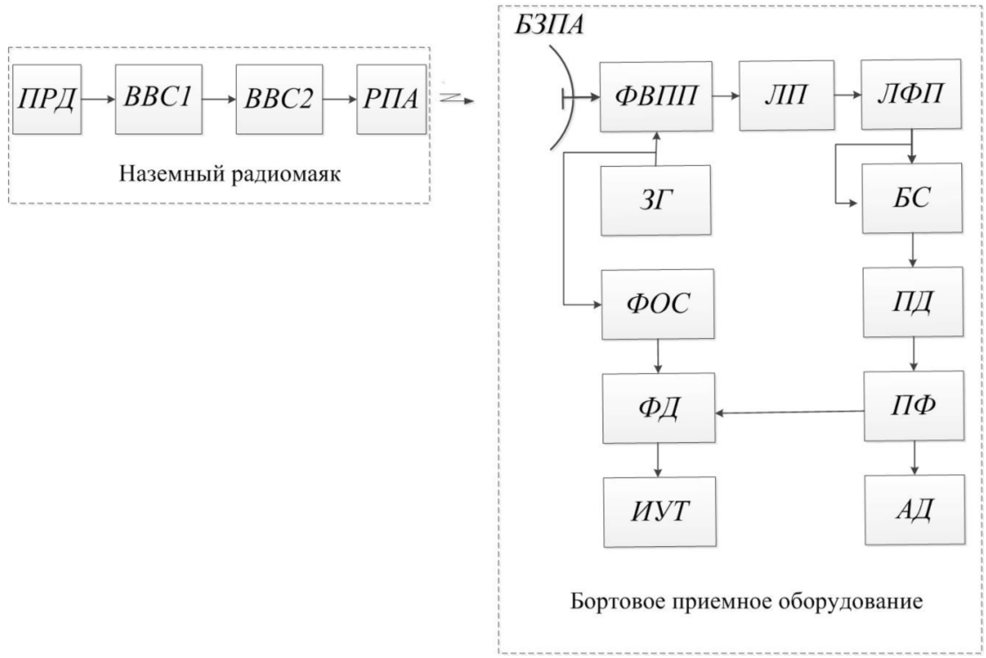
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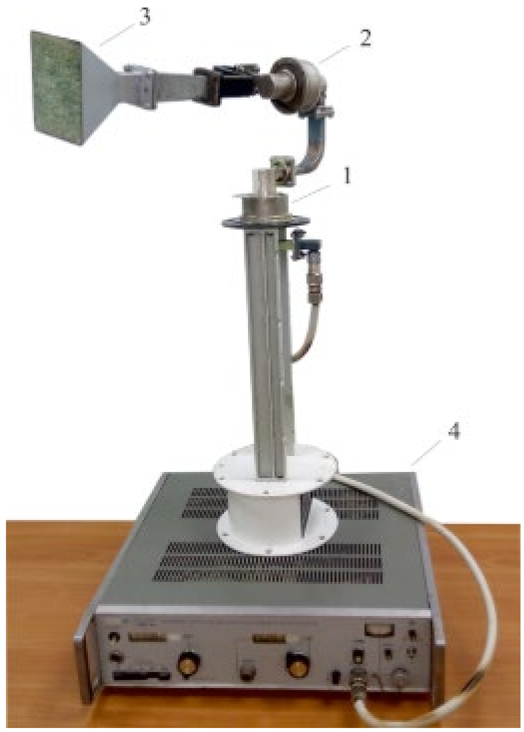
Fig. 3.



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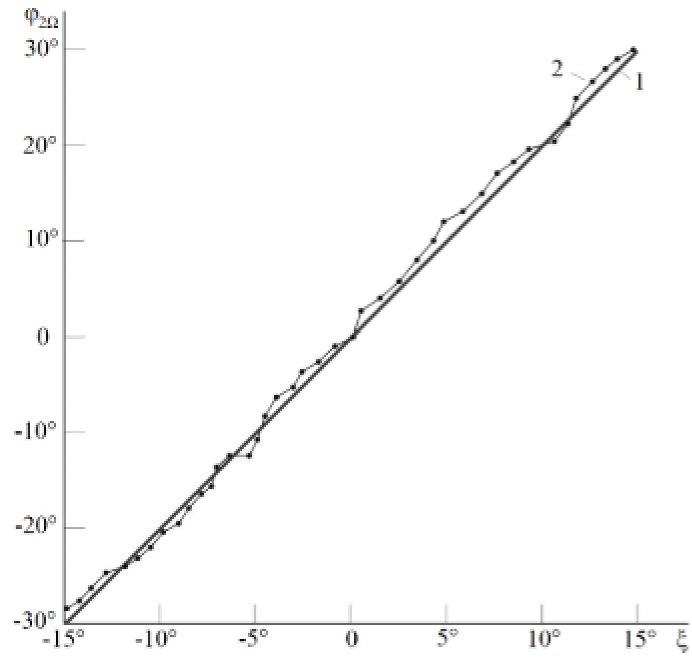

Fig. 7.