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WYSOKOŚCIOMIERZ LOTNICZY Z SYGNAŁEM DŹWIĘKOWYM MODULOWANYM PRZEZ JEDNO-TONOWE OSCYLACJE HARMONICZNE

Streszczenie: W artykule omówiono metody mierzenia wysokości. Dla proponowanych metod zestawiono ich zalety oraz wady. Szczególną uwagę zwrócono na wysokościomierz z zastosowaniem idei FM (modulowania częstotliwości) tj. sygnału modulowanego poprzez jedno-tonowe oscylacje harmoniczne

Słowa kluczowe: transport, awiacja, nawigacja w przestrzeni powietrznej, radiolokacja, radiowy wysokościomierz

AVIATION ALTIMETER WITH SOUNDING SIGNAL, WHICH IS FREQUENCY MODULATED BY A SINGLE-TONE HARMONIC OSCILLATION

Summary: Methods of height measurement are considered, their advantages and disadvantages are noted. Special attention was paid to the altimeter with an FM signal modulated by a single-tone harmonic oscillation.

Keywords: transport, aviation, air navigation, radiolocation, radio altimeter

1. Height measurement methods

In conditions of high intensity of air traffic, the performance of safe and regular flights of aircraft requires the use of a large number of radio technical devices. In connection with the growing role of flight control automation, the creation of high-precision devices for measuring the coordinates of aircraft is an urgent task of modern aviation. One such device is a radio altimeter.

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The principle of operation of radio altimeters is based on the property of radio waves to reflect from objects and spread in space in a straight line and at a constant speed. When numerically determining the height, the moments of emission of the sounding signal and reception of the signal reflected from the target (ground) are fixed and the time interval between these events is compared. The value of this delay can be contained in the amplitude, phase and frequency of the signal of the radar station. There are three methods of height measurement, which are based on the determination of the time delay of the sounding signal in space: amplitude, frequency and phase.

1.1. Amplitude method of height measurement

The amplitude (pulse) method of height measurement is based on the direct measurement of the delay time of the reflected radio pulse relative to the emitted one [1]. Fig. 1 shows the structural diagram of the pulse radio altimeter [2].

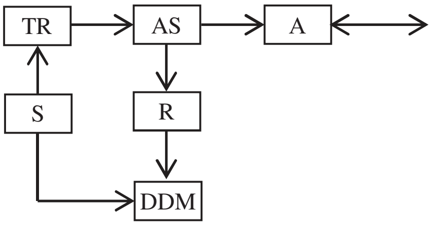

Figure 1. Structural diagram of the amplitude radio altimeter

where: TR – transmitter, AS – antenna switch; A – antenna; S- synchronizer; R – receiver; DDM – digital delay meter.

The synchronizer triggers the transmitter and the digital delay meter at the same time. The transmitter forms a periodic sequence of rectangular radio pulses with the required amplitude and power. From the output of the transmitter, these pulses are fed to the input of the antenna through the antenna switch, and sounding signals are emitted into space. During the radiation, the receiver is disconnected from the antenna. At the end of the emission of radio pulses, the antenna switch connects the antenna to the receiver for the duration of the tracking pulse period. Oscillations of the transmitter and the signal reflected from the target with a delay time arrive at the receiver. The reflected radio pulses have a much smaller amplitude than the transmitter signal. The delay time is measured in a digital meter. The distance to the target D depends on the delay time $t_d$and is determined by the following formula [2]:

$$D = \frac{c \cdot t_d}{2} \tag{1}$$

Since only one antenna is used in radio altimeters with a pulse height measurement method, such altimeters have a minimum distance to the target that they can measure ("dead zone") [3]. This phenomenon is explained by the fact that the antenna switch disconnects the receiver from the antenna for the duration of the pulse.

After the emission of the probing signal is over, the switch needs some time to restore its performance. Thus, the minimum range to the target that can be measured by the pulse radio altimeter is equal to [2]:

$$D_{min} = 0{,}5c(\tau_i + t_r) \tag{2}$$

where: τ_i is the duration of pulses, t_r is the recovery time of the receiver sensitivity.

Pulses of long duration are used to measure high altitudes, and pulses of short duration are used for low altitudes.

The advantages of the pulse height measurement method include range resolution and the need for only one antenna. However, the long minimum range, which is caused by the duration of sounding pulses and the time of transient processes in the antenna switch, does not allow the use of an amplitude radio altimeter for low altitudes.

1.2. Phase method of height measurement

The phase method of height measurement is based on determining the phase difference of radiated and reflected oscillations [1]. Fig. 2 shows the structural diagram of the phase radio altimeter [2].

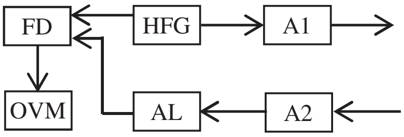

Figure 2. Structural diagram of the phase radio altimeter

Where: 2 FD – phase detector; HFG - HF generator; A1 – transmitting antenna; A2 – receiving antenna; AL – amplifier-limiter; OVM is an output voltage meter

The HF generator produces undamped oscillations that are fed to the input of the transmitting antenna. With the help of a transmitting antenna, oscillations are emitted into space. After reflection from the target, the signal enters the receiving antenna, the output of which is connected to a limiting amplifier. From the output of the amplifier-limiter, the signal enters the input of the phase detector. In the phase detector, the phases of the received and reference signals are compared. The phase difference between these oscillations is proportional to the range to the target and is determined by the following ratio [2]:

$$\Delta\psi = \frac{4\pi}{\lambda}D - \psi_{ref} - \psi_{radar} \tag{3}$$

Where: λ is the wavelength, ψ_{ref} is the phase shift that occurs when the radio wave is reflected from the target, ψ_{radar} is the known phase shift that occurs in the devices of the radar station.

The advantages of the phase height measurement method include the low required radiation power and the simplicity of the structural scheme. A significant disadvantage is the lack of resolution.

1.3. Frequency method of height measurement

For height measurement in aviation, the frequency method is widely used, which is based on determining the increase in the frequency of the transmitter during the propagation time of the sounding signal from the radar station to the target and back

[3]. Since it is impossible to implement frequency modulation with a continuous change in frequency, several types of periodic frequency modulation are used in practice, for example: symmetric and asymmetric sawtooth laws, sinusoidal law. Fig. 3 shows the structural diagram of the frequency radio altimeter [2].

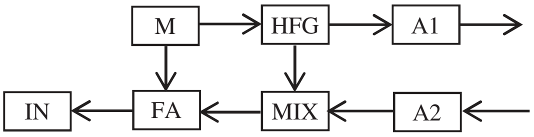

Figure 3. Structural diagram of the frequency radio altimeter

Where: M – modulator; HFG - HF generator; A1 – transmitting antenna; A2 – receiving antenna; MIX - mixer; FA – frequency analyzer, IN – indicator.

The modulator controls a high-frequency generator (HF generator), which produces oscillations with a frequency that varies according to a periodic law (Fig. 4, a, solid line). Oscillations of the HF generator simultaneously enter the input of the transmitting antenna and the first input of the mixer. The radiated sounding signal is reflected from the target and received by the receiving antenna, the output of which is connected to the second input of the mixer. The frequency of the reflected signal changes according to the law of the radiated radio pulse, but with a delay t_d (Fig. 4, a, dashed line).

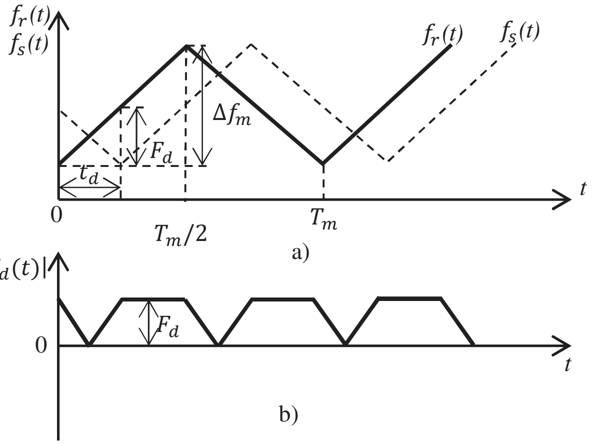

Figure 4. Change in the frequencies of radiated and reflected signals with a symmetrical sawtooth frequency modulation law (a) and change in the beat frequency (b)

As a result of the mixer's output, an oscillation with a difference frequency F_d, which is proportional to the distance to the target, will be formed at its output. This frequency is determined by the following ratio [2]:

$$F_d = F_{rad} - F_{ref} = \frac{4F_m\Delta f_m}{c} D \tag{4}$$

where: F_m is the modulation frequency, Δf_m is the frequency deviation of the transmitter.

From the output of the mixer, the oscillation of the difference frequency enters the frequency analyzer. The range to the target with the frequency measurement method is characterized by the following equality [2]:

$$D = \frac{cF_d}{4F_m \Delta f_m} \tag{5}$$

The frequency method can be used to measure low altitudes, however, a significant disadvantage of such a radio altimeter is the need for high linearity of the frequency change [1].

1.4. J-correlation method of height measurement

Currently, the J-correlation method of distance measurement has been developed [3, 4]. The structural diagram of the radio altimeter that implements this method is shown in Fig. 5. In fig. 5 An.1 – transmission antenna; An.2 – receiving antenna; PA – power amplifier; FC – frequency converter; FM – frequency modulator; LFG is a low-frequency generator that generates a harmonic oscillation with a frequency of Ω; ADL - adjustable delay line with time delay θ_x; QH – quartz heterodyne with a generation frequency of ω_h; MIX - mixer; CH – common heterodyne; LP – linear path of the receiver; BF1 and BF2 – band filters; X1 and X2 are multipliers; DL1 – delay line for time constant τ_1; NBF - narrow-band filter; CPU - control and signal processing unit.

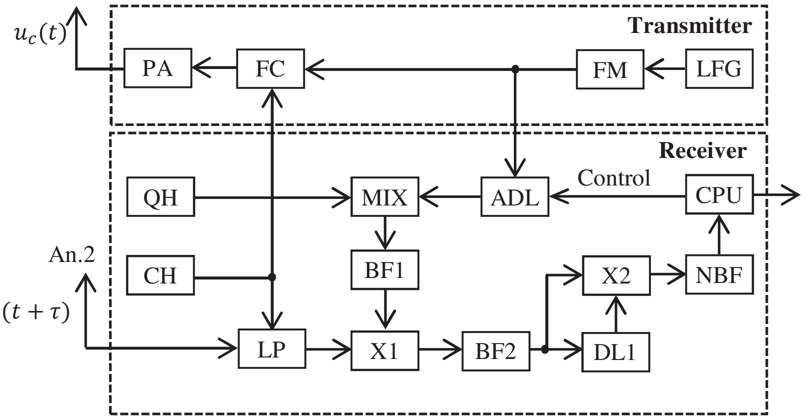

Figure 5 Structural diagram of the radio altimeter

In the device under consideration, the probing signal is an FM signal with a modulating harmonic oscillation of frequency Ω. It is formed at the output of the modulator and has the form:

$$u_c(t) = U_{c0} \cdot \cos[w_c t + \beta \cos(\Omega t + \varphi_0) + \gamma_0] \tag{6}$$

where: U_{c0} is the signal amplitude; w_c – carrier frequency; β is the modulation index; φ_0 – initial phase of modulating oscillation; γ_0 is the initial phase of the generated signal.

In the transmitter, the generated signal $u_c(t)$ is transformed by the FC to the frequency $\omega_0 \gg w_c$, amplified by power in the PA and radiated into space. In space, the signal is reflected from the surface, receives a time delay τ, returns to the input of the receiver and, after conversion to LP, will be recorded

$$u_c(t+\tau) = U_c cos[w_c(t+\tau) + \beta\cos(\Omega(t+\tau) + \varphi_0) + \gamma_0] \qquad (7)$$

From the output of the LP, the signal enters the input of the first multiplier X1, where it is multiplied with the reference oscillation, which is formed from the output signal of the modulator with the help of ADL, QH, MIX and bandpass filter BF1, in the form

$$u_0(t) = U_0 cos[(w_c - w_{\text{г}})t + \beta cos(\Omega(t+\theta_x) + \varphi_0) + \gamma_1] \qquad (8)$$

By multiplying the reflected $u_c(t+\tau)$ and reference $u_0(t)$ signals at the output of the band-pass filter BF2 with an average frequency $\omega_{\text{г}}$ and a given band, a signal is isolated:

$$u_1(t) = U_1 cos[\omega_{\text{г}} t - \beta_1 sin[\Omega t + 0{,}5\Omega(\tau+\theta_x) + \varphi_0] + \omega_{\text{c}}\tau - \theta_x + \varphi_{\text{г}}] \qquad (9)$$

where: $\beta_1 = 2\beta sin[0{,}5\Omega(\tau - \theta_x)]$ is the newly formed modulation index; $\varphi_{\text{г}}$ is the initial phase of QH.

The transformed modulation index depends on the difference in time delays, that is, on $\Delta\tau = \tau - \theta_x$. A change in θ_x leads to a change in the differential time delay $\Delta\tau$, i.e. to a change in the modulation index β_1, hence to a change in the width of the signal spectrum. The difference $(\tau - \theta_x)$ is zero when the value of $\theta_x = \tau$ in the adjustable delay. In this case, $\beta_1 = 0$.

The isolated by BF2 signal goes to the input of the correlation detector, which consists of a multiplier X2, a delay line DL1 for the time constant τ_1 and a narrow-band filter with an average frequency Ω and a bandwidth $\Delta\Omega < \Omega$. As a result, a signal of the form is formed at the output of the X2 multiplier in the low-frequency region:

$$u_{21}(t) = U_2 \textstyle\sum_{n,m=1}^{5} J_n(\beta_2) cos[m\Omega t + 0{,}5m\Omega(\tau + \theta_x + \tau_1) + \varphi_0] \qquad (10)$$

Where: $\beta_2 = 2\beta_1 sin(0{,}5\Omega\tau_1)$ is the new modulation index; n is the order of the Bessel function; m is the number of the harmonic component in the signal spectrum at the output of the X2 multiplier.

The modulation index in the generated signal depends on the time delay τ_1, it is chosen from the condition of ensuring equality $\beta_2 = \beta_1$.

The spectrum of such a signal contains a number of harmonic components with frequencies $m\Omega$, $m = 1, 2, \ldots$ multiples of the frequency Ω. A narrow-band filter NBF isolates a harmonic component with a frequency Ω, which will be written as:

$$u_2(t) = U_2 \textstyle\sum_{n=1}^{5} J_n(\beta_1) cos[\Omega t + 0{,}5\Omega(\tau + \theta_x + \tau_1) + \varphi_0] \qquad (11)$$

The amplitude of this signal

$$U_{out}(\beta_1) = U_2 \textstyle\sum_{n=1}^{5} J_n(\beta_1) = U_2 \sum_{n=1}^{5} J_n(2\beta sin[0{,}5\Omega(\tau - \theta_x)]) \qquad (12)$$

determines the altitude of the flying object. The output voltage $U_{out}(\beta_1)$ goes to the control and processing unit CPU, one of the functions of which is to control the time delay θ_x in the delay line of the radar detector. By changing the delay θ_x, the equality condition $U_{out}(\beta_1) = 0$ is achieved. This is possible if the condition $(\tau - \theta_x) = 0$ is fulfilled. If the specified condition is fulfilled for some $\theta_x = \theta_0$, then the spatial delay determined by the height is equal to $\tau = \theta_0$, and the height of the aircraft is determined by the CPU as $D = 0{,}5c\theta_0$.

The resulting dependence of the output voltage on the difference in time delays $(\tau - \theta_x)$ is a characteristic of the meter, the type of which is determined by the behavior of the sum of Bessel functions. To ensure the unambiguousness of the measurements, the obtained dependence should be monotonic. The analysis of the dependence $\sum_{n=1}^{5} J_n(\beta_1)$ conducted in [4] showed that this dependence satisfies the condition of monotonicity if the modulation index lies within $0 < \beta_1 \ll 3{,}1$. At the point $\beta_1 = 0$, i.e. at $\theta_x = \tau$, the value of the output voltage is equal to $U_{out}(\beta_1) = 0$.

An important parameter of any meter is the steepness of the characteristic on the outskirts of the measurement point, which determines the accuracy of the measurement. The measurement point is the value at $\beta_1 = 0$. In the vicinity of the extreme point, the dependence

$$U_{out}(\beta_1) = U_2 \sum_{n=1}^{5} J_n(\beta_1) \tag{13}$$

turns into a linear dependence on the modulation frequency:

$$U_{out}(0 < \beta_1 < 0{,}5) = U_2 J_1\{2\beta sin[0{,}5\Omega(\tau - \theta_x)]\} = 0{,}5U_2\beta\Omega(\tau - \theta_x) \tag{14}$$

It follows from the last expression that the steepness is determined by the modulating frequency Ω, which has no limits. In addition, it follows from the described features that the spectrum width, which is determined by the modulation index and the modulating frequency, will be significantly less than the spectrum width of a radio altimeter with a sawtooth frequency modulation law.

To confirm the obtained results, the simulation of a radio altimeter with J-correlation signal processing with the following sounding signal parameters was carried out in the System View software environment: the carrier frequency of the signal at the output of the modulator is 40 MHz, the modulation frequencies are 70 kHz and 51 kHz. The conducted experiments confirm the adequacy of the processes taking place in the scheme to the processes outlined in the work. Fig. 6 shows the characteristics of the meter.

From the experimental characteristics, it follows that for a modulation frequency of 70 kHz, the maximum monotonicity interval of the characteristic $\Delta\tau = 10$ μs, which corresponds to a maximum height of 1500 m. For a modulation frequency of 50 kHz, the maximum measurement height is more than 1800 m. At the same time, the practical width of the sounding signal spectrum is in the first case, it is less than 0.8 MHz, in the second case, it is less than 0.5 MHz, that is, with the increase in the measured height, the required width of the sounding signal spectrum decreases.

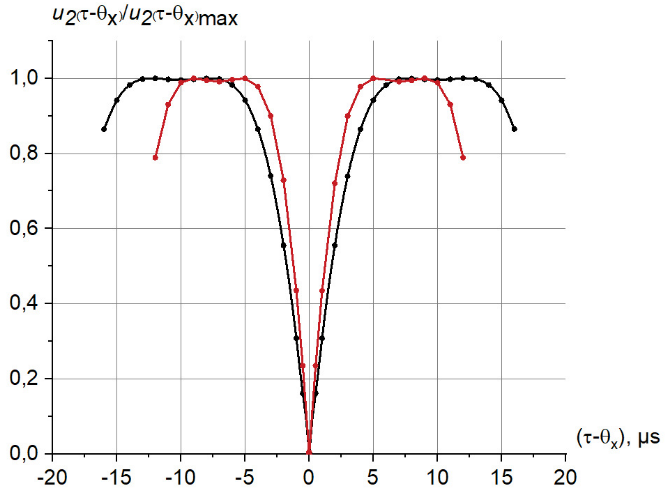

Figure 6. Characteristics of the altimeter: the black curve corresponds to the modulation frequency $F = 50kHz$*, the red curve corresponds to the modulation frequency* $F = 70\ kHz$

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