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Radio Altimeter with J-correlation Signal Processing

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Abstract
A new approach to the construction of a radio altimeter based on J-correlation processing is proposed. Its operation is based on the transformation of the modulation index of the probing signal into a functionally dependent on the space-time delay. The structural scheme of the device is given, and the signal processing of the device is analyzed. The characteristic of the altitude meter is obtained. For the radio altitude meter of low altitudes (1500 m) the FM signal modulated by a single-tone harmonic oscillation with the following parameters is used: modulating frequency 70 kHz; width of the signal spectrum not more than 1 MHz, measurement accuracy not worse than 0.15 meters.

Keywords: the radio altimeter, modulation index, delay line, adjustable delay line, quadrature detector, Bessel functions, correlation, detector, spectrum.

INTRODUCTION

Three methods of range measurement are known: pulse, frequency, phase. All range (altitude) meters are based on the determination of the spatial delay of the signal. In aviation, the method with frequency linear modulation is widely used for height measurement. Despite the widespread use of this method, it has a number of disadvantages, which are expressed in the requirements of high linearity of the probing signal frequency change, to have a wide bandwidth of the frequency spectrum. Realization of such a method while ensuring acceptable accuracy of measurements is difficult [1]. This paper proposes a new method for measuring height, the structural scheme of which is shown in Fig. 1.

Using the example of a block diagram of a radio altimeter with J-correlation signal processing, it is necessary to analyze the operation of the proposed height measurement and identify the features of the device's signal processing. Based on the results obtained, the task is then to determine the characteristics of the meter, obtain basic relationships, and give recommendations on the selection of parameters of individual components.

1. INITIAL DATA

The structural diagram of the proposed aviation altitude meter is shown in Fig. 1.

Probing is a signal modulated in frequency by a harmonic oscillation with frequency Ω and modulation index β. The device consists of a transmitting An.1 and receiving An.2 antennas, a transmitter and a receiver. The transmitter consists of a power amplifier (PA), frequency converter (FC), modulator (Mod), low frequency generator (LFG).

The receiver in its composition contains: reference oscillator (RG), quartz oscillator (QG), linear path (LP), adjustable delay line (ADL), first, second, third delay lines (DL), mixer (Mix), first, second bandpass filters (BF), first, second and third multipliers (M), quadrature detector (QD), narrowband filter (NBF), low-pass filter (LPF), control and processing unit (CUO).

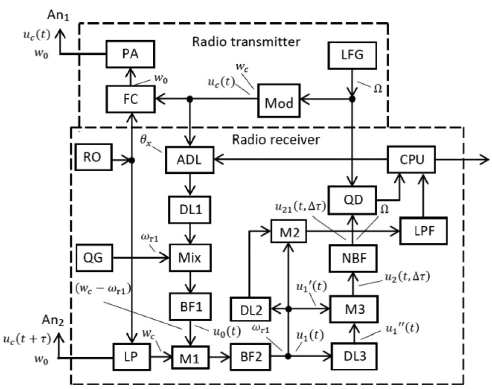

Fig.1. Structural diagram of a radio altimeter

2. MAIN PART

In the transmitter of the radio altimeter of Fig.1. at the output of the modulator (Mod), there is formed a signal modulated by frequency harmonic oscillation with frequency Ω and a given modulation index β, of the form:

$$u_c(t) = U_{c0}\cos\left[\omega_c t + \beta\sin\left[\Omega t + \varphi_0\right] + \gamma_0\right] \quad (1)$$

where U_{c0} is the signal amplitude; ω_0 is the carrier frequency; β is the modulation index; φ_0, is the initial phase of the modulating oscillation; γ_0 is the initial phase of the carrier oscillation.

The signal $u_c(t)$ (1) is converted to the frequency ω_0 □ ω_C with the help of the oscillator RO, amplified by power, thus forming the probing oscillation $u_{зн}(t)$.

At the same time, via a device containing delay lines DL1 and ADL, quartz oscillator QG, mixer Mix and filter BF1 with an average frequency ($w_c - \omega_{r1}$), reference oscillation is formed. The signal $u_c(t)$, is converted to the frequency ($w_c - \omega_{r1}$), with the help of the oscillator QG, amplified by power, and thus the probing oscillation $u_{зн}(t)$ is formed.

At the same time, via the device containing delay lines DL1 and ADL, quartz oscillator QG, mixer Mix and filter BF1 with an average frequency ($w_c - \omega_{r1}$), reference oscillation is formed:

$$u_0(t) = U_0 cos[(w_c - \omega_{г1})t + \beta sin(\Omega(t + \theta_x) + \varphi_0) + \gamma_1], \quad (2)$$

Where $u_{зн}(t)$ is the signal amplitude; is the frequency QG; τ is the delay in the ADL; is the initial phase including the QG phase - and the phase obtained in the ADL.

The total signal delay in DL1 and filter BF1 compensates for the signal delay in the transmitter devices: converter FC, power amplifier PA and linear path (LP) of the receiver, so they are not considered in the further analysis.

The probing signal $u_{зн}(t)$, having received a spatial delay τ, having passed the transformation in LP of the receiver, at the input of the multiplier M1 will be defined by the expression. [2]

$$u_c(t+\tau) = U_c \cos\left[\omega_c\left(t+\tau\right)+ \right.$$
$$\left. +\beta \sin\left[\Omega\left(t+\tau\right)+\varphi_0\right]+\gamma_0\right] \quad (3)$$

From the result of multiplication of the signal $u_c(t+\tau)$ (3) with the reference oscillation $u_0(t)$ (2), the PF2 filter extracts a signal with a carrier frequency ω_{r1} of the form:

$$u_1(t) = U_1 \cos\left[\omega_{\text{r}1}t + \beta_1 \sin\left[\begin{matrix}\Omega t + 0.5\Omega\left(\tau+\theta_x\right)+ \\ +\varphi_0 + \Omega\tau_{\text{ф}2}\end{matrix}\right] + \gamma_2\right] \quad (4)$$

U_{c0}
ω_0
β
φ_0,
0
u^{r_1}
$u(t)\ \omega_0$
$\omega_C\ u_{зн}$
τ
$(w_c - \omega_{r1}$
$u_{зн}(t)$

where is the signal amplitude; $\tau_{\varphi2}$ – signal delay in BF2; $\beta_1=2\beta\sin[0{,}5\Omega(\tau-\theta_x)]$ – modulation index; $\gamma_2=\omega_c(\tau-\theta_x)+\omega_{r1}\tau_{\varphi2}-\varphi_{r1}$ is the initial phase of the signal.

In the obtained expression, the newly formed modulation index β_1 is functionally dependent on the time delay difference $(\tau-\theta x)=\Delta\tau$. Therefore, the Bessel functions are modified and become functionally dependent on $\Delta\tau$. Dependences of functions $J_n\left(\beta_1\right)$ at $\beta=3.1$ are shown in Fig. 2.

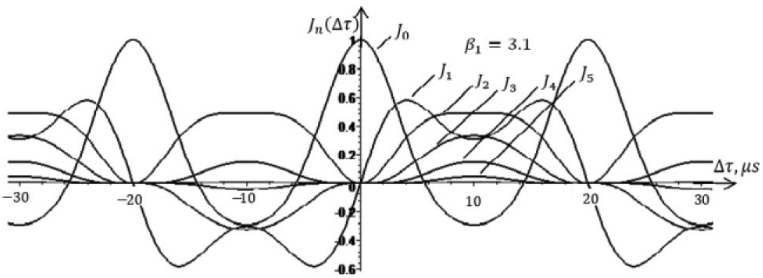

Fig.2. Transformed Bessel functions.

From the graphs a strict periodicity of the transformed Bessel functions is obvious, which is determined by the value of the modulating frequency Ω, and since for the construction of the time delay (distance) meter the modulation index should be β=3.1 [3], then the number of Bessel functions is chosen equal to (Fig.2) number of spectral components of the probing signal.

The correlation function of the signal $u_1(t)$ (4) is determined by the constant component, which is described by the zero-order Bessel function $J_0(\beta_1)$ Fig. 2. Hence, by changing the time delay θ_x in the ADL, the signal delay in space τ can be determined. If, when establishing some value of the time delay $\theta_x=\theta_0$, the maximum of the correlation function $J_0(\beta_1)=1$, which is achieved when $\Delta\tau=0$, then the spatial time delay will be equal to $\tau=\theta_0$.

However, in this case, the measurement accuracy will be low, because the steepness of the characteristic $J_0(\beta_1)$ at the measurement point ($\Delta\tau=0$) and some of its vicinity is small. It is possible to increase the accuracy of determining the time delay τ if we form a correlation function, which in the vicinity of the point ($\Delta\tau=0$) , will have a pronounced extremum. For this purpose, it is necessary to extract from the signal $u_1(t)$ (4) the spectrum component with the modulating oscillation frequency, the amplitude of which functionally depends on the difference $\Delta\tau$ and is determined by the first-order Bessel function $J_1(\beta_1)$.

A correlation detector (CD) is used to extract this component. The CD consists of the multiplier M2, delay line DL2 for the time τ_2 and LPF with the average frequency $\Omega_{cp}+\Omega$, bandwidth $\Delta\Omega\leq\Omega$, which has some time delay $\tau_{y\varphi}$.

The signals $u_1'(t)=u_1(t)$ and $u_1''(t)=u_1(t+\tau_2)$ act on the inputs of the multiplier M2. The decomposition of the signal $u_1'(t)$ at the first input of the multiplier M2 can be represented in the following form [2]:

$$u_1'(t)=U_1\sum_{n=-5}^{5}J_n(\beta_1)\cdot\cos\Big[(\omega_{\text{г}1}+n\Omega)t+ \\ +0.5n\big[\Omega(\tau+\theta_x)+2\varphi_0+2\Omega\tau_{\text{ф}2}\big]+\gamma_2\Big] \tag{5}$$

At the second input of the multiplier M2 after a delay in DL2 by τ_2

$$u_1''(t)=U_1\sum_{n=-5}^{5}J_n(\beta_1)\cdot\cos\Big[(\omega_{\text{г}1}+n\Omega)t+ \\ +0.5n\big[\Omega(\tau+\theta_x)+2\varphi_0+2\Omega\tau_{\text{ф}2}\big]+\gamma_3\Big], \tag{6}$$

where $\gamma_3=\gamma_2+n\Omega\tau_2+\omega_{r1}\tau_2$- determines the initial phases of the spectral components of the signal $u_1''(t)$.

As a result of multiplication of $u_1'(t)$ (5) and $u_1''(t)$ (6), the signal $u_2(t,\Delta\tau)$ is formed at the output of X2 in the low frequency region. The spectral composition of the signal is determined not only by the modulation index but also by the initial phase $\omega_{r1}\tau_2$. When $\omega_{r1}\tau_2 = \pi/_2$ the spectrum of the modulation frequency Ω, which ensures their maximum level. These spectral components are formed by summing the voltages obtained from multiplication of the corresponding spectral components of the signals being multiplied. Thus, as a result of multiplication of the n -th harmonic component of the signal $u_1'(t)$ (5) with $(n \pm 1)$ -th harmonic of the signal $u_1''(t)$ (6), provided that $|n-(n \pm 1)| = 1$, at a frequency Ω is formed harmonic component, which at the output of the UPF, is written in the form of:

$$u_{21}(t,\Delta\tau) = U_2 F(\Delta\tau)\cdot\cos\Big[\big(\Omega t + +0.5\Omega\big(\tau+\theta_x+\tau_{\text{ф}2}+\tau_2+\tau_{\text{уф}}\big)+\varphi_0\big)\Big], \quad (7)$$

where $U_2 F(\Delta\tau)$ is the amplitude of the signal; $F(\Delta\tau) = \sum_{n=0}^{6} k_n \cdot J_n(\beta_2)\cdot J_{(n+1)}(\beta_2)$ is a function of $\Delta\tau$ that determines the amplitude of the first harmonic of the signal $u_{21}(t,\Delta\tau)$; k_n are coefficients, $k_0 = 1$, $k_1 = k_2 = ... = k_5 = 2$, $\beta_2 = 2\beta_1 \sin[0.5\Omega\tau_2]$ is the newly formed modulation index.

The signal from the NBF output enters the quadrature detector (QD), in which the modulating oscillation from the output of the low-frequency generator (LFG) is taken as a reference. As a result of detection at the output of the QD a signal in the form of a constant component is extracted, depending on the difference of time delays $\Delta\tau = (\tau - \theta_x)$.

$$u_{21}'(\Delta\tau) = U_2 F(\Delta\tau) \quad (8)$$

where $F(\Delta\tau)$ - defines the law of change of the constant voltage level depending on the difference of time delays $\Delta\tau$.

Attitude $\frac{U_2 F(\Delta\tau)}{U_2 F(\Delta\tau_{\max})} = \Phi(\Delta\tau)$ is a characteristic of the altimeter and at

$F(\Delta\tau_{\max}) = 1.33$ and $\sin[0.5\Omega\tau_2] = 0.25$ take the form

$$\Phi(\Delta\tau) = 0.75\sum_{n=0}^{5} k_n \cdot J_n\big(\beta\sin[0.5\Omega\Delta\tau]\big)\cdot \cdot J_{(n+1)}\big(\beta\sin[0.5\Omega\Delta\tau]\big). \quad (9)$$

Fig. 3 shows the characteristic $\Phi(\Delta\tau)$ for the probing signal with modulation index $\beta = 3.1$, modulating frequency $F_0 = \Omega/2\pi = 70\text{kHz}$. From the graph: the characteristic has a monotonically varying section of 11 μs, which corresponds to unambiguously measured height of more than 1500 m.

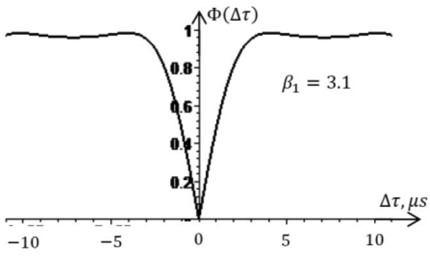

Fig.3. Characteristic $\Phi(\Delta\tau)$ of the probing signal.

The disadvantage of the device follows from the kind of characteristic: at $\Delta\tau = 0$, the signal disappears. To eliminate this shortcoming, a second correlator (M2, DL2) is used, which indicates the presence or absence of the received signal.

The accuracy of time delay measurement is estimated by the steepness of the measurement characteristic at the measurement point. The steepness the characteristic of altimeter in the vicinity of the point $\Delta\tau = 0$ is determined by the expression:

$$\begin{aligned} S(\Delta\tau) &= \Phi'(\Delta\tau) = 0.75k_0\left[J_1\left(\beta\sin[0.5\Omega\Delta\tau]\right)\right]' = \\ &= 0.75\cdot 0.5\beta\sin[0.5\Omega\Delta\tau] \approx 0.2\beta\Omega. \end{aligned} \tag{10}$$

Since the modulation index determines the maximum monotonically varying section of the characteristic (i.e., section of the characteristic unambiguity of measurement) and is limited by the maximum value $\beta = 3.1$ [3], the steepness of the meter characteristic can be changed by the choice of the modulating frequency Ω of the probing signal. This is confirmed by Fig. 4, where the characteristics of the altimeter for modulating frequencies of 50 kHz (Digit 2) and 70 kHz (Digit 1) are shown

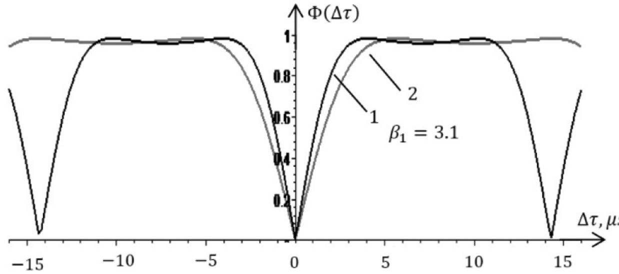

Fig. 4. Effect of modulating frequency

From Fig. 4, as the modulating frequency increases, the steepness of the characteristic of the meter increases and the monotonically varying section decreases, indicating a decrease in the measured height.

Modelling of the altimeter with modulating frequencies 50 and 70 kHz and modulation index of the probing signal β=3,1 was performed. The altimeter characteristic is shown in Fig.5.

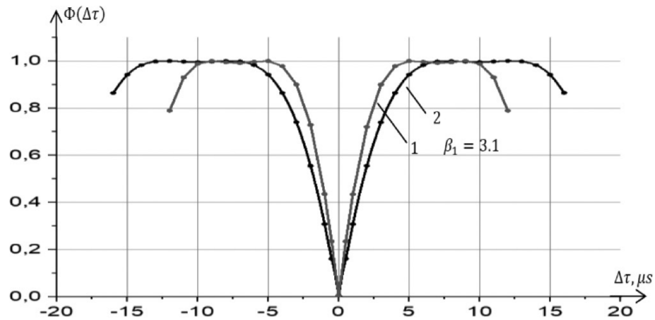

Fig.5. Characteristic of radio altimeter at modulation index of probing signal β=3,1 modulation frequencies 50 (Digit 2) and 70 (Digit 1) kHz.

CONCLUSION

In the radio altimeter, the altitude readings are taken at time instants given $\Delta\tau = 0$, and since $\Delta\tau = (\tau - \theta_x)$, in which the delay θ_x changes discretely by the amount $\Delta\theta_x = 10^{-9}s$, the altitude readings will be discrete. When the altimeter is built using FPGA chips with a maximum operating frequency of 1 GHz, it will allow to provide delay variation in the ADL with a step $\Delta\theta_x = 10^{-9}s$, which corresponds counting to the altitude after 0.15 m. Modelling of the radio altimeter confirmed the observed results. Hence, the measurement results will be accurate only at discrete points of the measured height where the condition $\Delta\tau = 0$ is fulfilled.

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