UDC 621.396.67: 629.735.45 (045)

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THE QUALITY ASSESSMENT OF THE DIGITAL COMMUNICATION CHANNEL WITH THE HELICOPTER

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—The cause-effect relations between the levels of pulsations of the antenna system, caused by main rotor rotating of the helicopter, and the probability of the bit error occurring in the digital data transmission channels were established. Graph-analytical method of error probability estimation was developed.

Index terms— Helicopter; antenna; directivity diagram; effective length; pulsation; bit error; dependent surveillance transceiver; protection ratio.

I. INTRODUCTION

The directivity diagram (DD) of on-board antenna (all other conditions being equal) depends on the design features of the aircraft body on which it is installed. If an aircraft is a helicopter, irregular DD produced hybrid system “standard antenna – conductive body aircraft” becomes pulsating. This is explained by the fact that the outline of the helicopter body is changed periodically according to the positions of its main rotor blades being changed. At the same time in the “standard antenna – conductive body of the helicopter” the effective length $h_e(t)$ is the parameter depending on the time which is the dimensional coefficient of proportionality between the electric field intensity at point placing antenna the potential difference that arises on its terminals. The directivity diagram pulsation, that is, its dips relative to the maximum value of $F_{\max}$, is the result of periodic changes effective length $h_e(t)$ of hybrid antenna. The frequency and depth DD pulsations depend on the speed of the main rotor rotation, its design features and placement standard dipole antenna on the body of the helicopter. The hybrid helicopter antenna system being formed acquires the properties of passive linear parametric circuit. Any signal radiated or perceived by the system is subjected to additional amplitude modulation (AM) at the frequency of main rotor rotating. In the spectrum of the output signal hybrid antenna the satellites – incidental components at the combination frequencies – arise. They exist due to the energy of the useful signal, acting on antenna. Satellites accompany every high-frequency spectral component of the input signal, as their lateral ones, arising from AM on respective sum-difference frequencies. Satellites reduce its average power energy donor and the average power of the useful signal in general, thus increasing overall noise power acting on the antenna device. External interference arriving at the input of the helicopter-receiving device is subjected to the same parametric transformations. However, redistribution of power noise between existing and emerging in its new spectral components does not effect on the value of its average power [1]. The signal power reduces, at the same time the average power of united noise increases simultaneously at the input of the receiving device. As a result the qualitative indicators of the digital data channel deteriorate. Therefore, in the digital channel, for example, automatic dependent surveillance – broadcast (ADS-B) which implements the principle of “everyone sees each”, probability of occurrence bit error rate (BER) may exceed the allowable unadjusted values 10^{-4} [2]. The risks of possible aircraft collisions in the air space will increase. The situation becomes more complicated if there will be, for example, two helicopters in the general airspace with functioning ADS-B onboard systems. In this case, the ADS-B signals systems, circulating in digital radio channels VDL-4 format or other formats, are modulated twice by amplitude and attenuated largely. The probability of bit error increases.

II. PROBLEM STATEMENT

In the known sources of literature, there is no information about the features of the ADS-B functioning system, installed on board of the helicopter, and BER estimation capabilities in the respective radio channels. Therefore there is a need to develop a method of quality evaluation of digital parametric data channel.

III. THEORETICAL BACKGROUND

We take the ratio [1] as a mathematical model of the effective length of a parametric antenna system (PAS), consisting of the whip antenna and the conductive body helicopter:

$$h_e(t) = h_{eo} - \Delta h_e(t) = h_{eo}\left[1 - \frac{\Delta h_e(t)}{h_{eo}}\right] \qquad (1)$$

where h_{eo} is effective length of PAS without pulsations $\Delta h_e(t)$. The instantaneous values pulsations $\Delta h_e(t)$, i. e, periodic deviations from values h_{eo} are determined by the angular frequency $v = {}^{\pi n N}\!/_{30}$. It depends on the n – number of revolutions of the shaft helicopter main rotor per minute (240 to 350) and N is the number of blades in the main rotor construction (2 to 8):

$$\begin{aligned}\Delta h_e(t) &= \Delta h_e \sum_{k=-\infty}^{\infty}\left|\cos\frac{v_1}{2}(t+kT)\right| \\ &= \frac{2}{\pi}\Delta h_e\left[1+\sum_{p=1}^{\infty}2\frac{(-1)^p}{1-(2p)^2}\cos pt\right].\end{aligned} \qquad (2)$$

In ratio (2): Δh_e are pulsations amplitude ($\Delta h_{e\max} \le h_{e0}$); $T_N = {}^{2\pi}\!/_{v} = {}^{60}\!/_{nN}$ is the period recovery geometric configuration PAS; k is the integer. Cyclic pulsation frequency $F_N = {}^{1}\!/_{T_N}$ is between eight to forty-seven hertz for the indicated values n and N. Therefore, the combinational frequencies of satellites, which distort the useful signal, are very small different from the high frequencies in spectrum modulated input signal and cannot be practically filtered. The relative average power of satellites, i. e, the average power losses of signal, which circulates in the communication channel between the two helicopters, is determined by the ratio [1]:

$$\frac{\Delta P_{av}}{P_{Sav}} = 0{,}5\left[\left(\frac{\Delta h_e}{h_{e0}}\right)^2 + \left(\frac{\Delta l_e}{l_{e0}}\right)^2 + 0{,}25\frac{\Delta h_e}{h_{e0}}\frac{\Delta l_e}{l_{e0}}\right], \qquad (3)$$

where P_{Sav} is the average power of an undistorted signal (with no pulsations); ΔP_{av} is the average power of satellites; $\frac{\Delta h_e}{h_{e0}}$ and $\frac{\Delta l_e}{l_{e0}}$ are relative amplitude of effective lengths PAS pulsations of the first and second helicopters. Depending on the possible values of $0 \le \frac{\Delta h_e}{h_{e0}} \le 1$ and $0 \le \frac{\Delta l_e}{l_{e0}} \le 1$ relative useful signal power consumption for the maintenance of the satellites (3), arising in the communication channel between the two helicopters, is in the range 0 … 0.875.

If the communication channel is formed between the helicopter and an object of a different type (an airplane or ATC), then ratio (3) is simplified and written by the following patter:

$$\frac{\Delta P_{av}}{P_{Sav}} = 0{,}5\left(\frac{\Delta h_e}{h_{e0}}\right)^2$$

In this case the relative power, that consumed for the formation satellites, is in the range 0 … 0.5.

IV. GRAPHIC-ANALYTICAL METHOD VERIFICATION FOR EVALUATING BER IN DIGITAL DATA TRANSMISSION CHANNEL FROM THE BOARD AND TO BOARD OF THE HELICOPTER

Bit error rate values, with other things being equal, depend on the type of modulation useful signal and the ratio (signal (*S*)) / (noise (*I*)) at the input of radio receivers. If the channel contains PAS, this ratio can be expressed as:

$$\frac{S}{I} = \frac{P_{Sav} - \Delta P_{av}}{Q + \Delta P_{av}}, \qquad (4)$$

where Q is the noise power in the radio link; I is the noise power in the radio channel.

Let's assume that there is a known protective ratio of the receiver $q = \left({}^{S}\!/_{Q}\right)_{\min}$ [3] at which the BER $\le 10^{-4}$. Then, formula (4) can be expressed for a possible worst case as:

$$\frac{S}{I} = \frac{1 - \frac{\Delta P_{av}}{P_{Sav}}}{\frac{1}{q} + \frac{\Delta P_{av}}{P_{Sav}}}. \qquad (5)$$

In ratio (5) information about the classes of possible signals S and noise Q, applied to the input of the receiving device, is contained in an implicit form. According to the formula (5) the ratio S/I diminishes with increased values $\frac{\Delta P_{av}}{P_{Sav}}$ (3) and reduced values of the protection ratios q. Graphs of appropriate functional dependencies (5) are shown in the lower right field in Fig. 1. The graph arguments axis is graduated on a linear scale, and the values S/I are displayed in logarithmic units $\left({}^{S}\!/_{I}\right)_0 = 10\log\frac{S}{I}$ dB. Such a method of graphic representation functional dependencies (5) is caused by the simplification procedure of their further use. When $\frac{\Delta P_{av}}{P_{Sav}} = 0$ then value $\left({}^{S}\!/_{I}\right)_0 = q_0 = 10\log q$ dB. The graph shows that the values q >100 (20 дБ) have practically no effect on the level of relations $\left({}^{S}\!/_{I}\right)_0$.

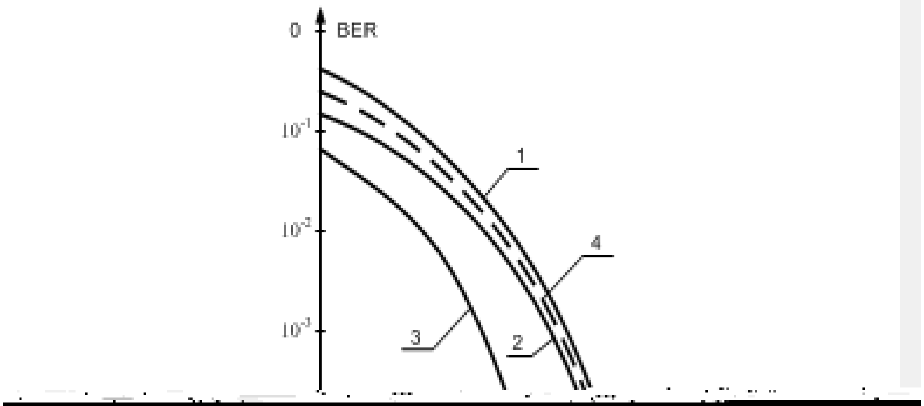

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Fig. 1. Graphs mediated dependence BER from

During BER calculating in digital channels on the relations given, for example, in [4] and [5], under model of noise I, which is consists essentially from a additive mixture of a plurality narrowband and broadband random processes, white Gaussian noise is meant to simplify the mathematical analysis. This noise model allows using already known graphs dependencies BER = $f\left(\frac{E_b}{G}\right)$ without any special calculations. Here E_b is the energy needed to transmit one bit of information; G is the power spectral density of white noise in the transmission channel. The values of S / I and the corresponding values E_b / G_0 are associated by known ratio:

$$\frac{E_b}{G}=\frac{B}{R}\frac{S}{I}. \qquad (6)$$

In ratio (6) B is the bandwidth of the digital channel, the R is bit rate.

On the upper field of graph Fig. 1 shows a plot BER from the values $\left(\frac{E_b}{G}\right)_0$, dB for different types of manipulation of signals [5]: curves *1* and *2* are frequency shift keying (FSK) with incoherent and coherent detection, curve *3* is quadrature phase shift keying (QPSK). If the curves are compared with each other, their obvious geometric similarity is observed. If all the curves are focused at one point, for example, for BER ≤ 10^{-4}, normalizing them by axis $\left(\frac{E_b}{G}\right)_0$ (Fig. 2), we can find that for BER $\leq 10^{-2}$, irrespective of manipulation signal decrease, ratio $\left(\frac{E_b}{G}\right)_0$ 2 dB (1.6-fold) accompanied by increasing BER at least by an order, and increasing it at the same value results in a decrease BER by two orders. When a maximum allowable value BER decreases, for example, to a value of 10^{-6}, this effect becomes more prominent. Such legitimacy is specific for almost all types of manipulation signals, because a Gaussian error is common for them being integral for the basis of known and have not yet identified computational ratios for BER.

The Gaussian signal binary frequency shift keying (GFSK) is used for ADS-B system creation that operates in the VDL-4 protocol format. The theoretical dependence BER = $f\left(\frac{E_b}{G}\right)$ is not known for such a signal as well as adjusted for parametric conversion in helicopter PAS. But, on the basis of the foregoing, it can be assumed that hypothetical curve corresponding to this signal of BER from the ratio $\frac{E_b}{G}$ will fit into the region occupied by the curves *1* and *2* (shown in Fig. 2), or be close to it. The curves intersect at a point of permissible corrected value BER = 10^{-4}, which is defined by a document [2].

The curve 4 being constructed on the basis of curves *1* and *2* (shown in Fig. 1) is used to estimate the BER of the channel ADS-B system with the same values of the bit error probabilities by averaging respective arguments $\frac{E_b}{G}$. The normalized curve *3* is almost identical to this curve, being specific for QPSK – quadrature phase of shift keying.

The transition from the graphs, depicted in the lower right field of Fig. 1, to graphic *4* on the upper field, is based on the relation (6) after its taking logarithms in accordance with the rule, dB:

$$\left(\frac{E_b}{G}\right)_0 = \left(\frac{B}{R}\right)_0 + \left(\frac{S}{I}\right)_0 . \tag{7}$$

For ADS-B system in the format VDL-4 $B =$ = 25 kHz and R = 1920 bit/s, which corresponds to the value signal base $\frac{B}{R} = 1.32$. In the equation (7) $\left(\frac{B}{R}\right)_0 = 1$ dB. A specific value of BER to for the value of the abscissa $\left(\frac{E_b}{G}\right)_0$ corresponds to curve *4* in the graph, mapped on the axis of ordinates.

Relative pulsations of effective antenna lengths $\frac{\Delta h_e}{h_{e0}}$ and $\frac{\Delta l_e}{l_{e0}}$ in the formula (3) and, consequently, in the formulas (5) – (7), can not be measured by direct methods. Therefore, for practical use of below graphs to evaluate BER are necessary replaced relative pulsations of effective antenna lengths by the corresponding relative pulsations DD antennas $\frac{\Delta F_{av}}{F_{\max}}$. Which power averaging over on interval time T_N for each DD angle and in azimuth plane full angle 2π.

Irregular DD pulsations can be determined by standard methods at the stage of equipping aircraft of antenna-feeder devices for this purpose using the possibility of physical or mathematical modeling [6].

Interconnection of relative pulsations effective length PAS $\frac{\Delta h_e}{h_{e0}}$ and pulsations DD $\frac{\Delta F_{av}}{F_{\max}}$ is based on formula of ideal radio broadcast and can be represented in the form:

$$\left(\frac{\Delta h_e}{h_{e0}}\right)^2 = \frac{\Delta F^{(h)}{}_{av}}{F^{(h)}{}_{\max}} . \tag{8}$$

In this case, the ratio (3) is converted into the formula suitable for graphing systems graphs shown in Fig. 1:

$$\frac{\Delta P_{av}}{P_{Sav}} = 0.5\left[\frac{\Delta F^{(h)}{}_{av}}{F^{(h)}{}_{\max}} + \frac{\Delta F^{(l)}{}_{av}}{F^{(l)}{}_{\max}} - 0.25\sqrt{\frac{\Delta F^{(h)}{}_{av}}{F^{(h)}{}_{\max}}\frac{\Delta F^{(l)}{}_{av}}{F^{(l)}{}_{\max}}}\right] . \tag{9}$$

Elements of the right side in formula (9) are known. Graphs include the baseline data needed to further assess BER.

The ratio (9) is simplified for two helicopters of the same type equipped with ADS-B systems (solid line in the lower left field in Fig. 1) and is simplified for one helicopter (the dotted line).

The examples and the results of mathematical modeling pulsating DD unidirectional antenna installed on conductive body of hypothetical helicopter are given in [7].

V. THE EVALUATION OF CONDITIONS WHICH MAKE PREDETERMINED VALUES OF BER

We mark predetermined value bit-error probability in the upper graph, for example BER = 10^{-4}. According to the curve *4*, we define the corresponding value $\left(\frac{E_b}{G}\right)_0$ = 12.4 dB. The line, drawn from this point parallel to the axis $\frac{\Delta P_{av}}{P_{Sav}}$, crosses the three curves corresponding to different values of protection ratios: $q = 20$ (13 dB); $q = 100$ (20 dB); $q = 200$ (23 dB). When we drop perpendiculars to the axis $\frac{\Delta P_{av}}{P_{Sav}}$ from these points, we define the values of relative powers satellites. When we will omit from these points perpendicular to the axis $\frac{\Delta P_{av}}{P_{Sav}}$, then will define the values of relative powers satellites. We define the permissible values of relative pulsations DD PAS and their corresponding relative pulsations of effective antenna lengths of helicopters (8), on the values which are defined on the previous stage, based on the point of intersection with lines, which are shown in the adjacent figure.

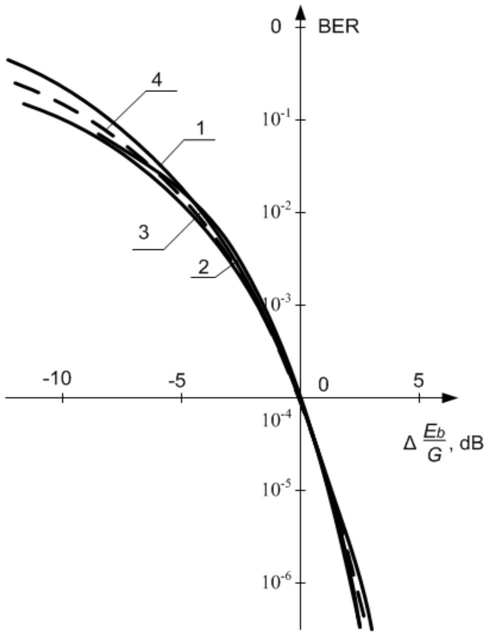

Fig. 2. Normalized BER parameters

If we use the same system graphs in reverse order, we can determine the values BER in digital data transmission channel, according to the known or presumed value of the relative pulsations $\frac{\Delta F_{av}}{F_{\max}}$ DD PAS.

It follows from the foregoing that the methods of reducing BER in a data channel with the bead or on board helicopter are:

– choosing an appropriate point of the antenna placing – at the stage of designing the aircraft;

– replacement of type frequency shift keying FSK (curves *1*, *2*, *4*) by the type of phase shift keying PSK (curve *3*) - ICAO competence;

– using of non-conductive materials in a design of main rotor blades.

If the condition $\frac{\Delta F_{av}}{F_{\max}} = 0$, based on given set of graphs, is met, we can estimate BER for the case when all aircraft – planes or ground objects are equipped with ADS-B systems.

VI. CONCLUSIONS

The quality of the on-board digital data transmission channel to the helicopter under otherwise equal conditions is always lower than for the plane.

If the ratio $signal/noise$ reduction at the entrance to the on-board transceiver ADS-B is on one and a half decibel then bit-error probability increases by about an order of magnitude.

The level of the ratio $signal/noise$ at the entrance to the on-board transceiver ADS-B is dependent on placing standard of no directional antenna on a conducting body of the helicopter.

Limit value BER = 10^{-4} is ensured with protection ratios transceiver q = 13 … 23 dB (q = 20 … 200 times). Further increase protection ratio is ineffective.

To ensure the maximum permissible values of BER = 10^{-4} the level of the averaged relative pulsations DD of the hybrid system “standard antenna – the body helicopter” when q_0 = 13 dB should not exceed values 0, 02 (–16 dB), and at q_0 = 23 dB – values 0.18 (–7 dB). Such small pulsations mean levels of DD is difficult to ensure.

Common standards of quality channel VDL-4 and ADS-B system can be impracticable with respect to helicopters (a helicopter is not a plane).

This graphic-analytical method can be used to mediate BER estimation in the system ADS-B, which operates in a digital radio channel 1090 ES format that implements noise-immune phase shift keying.

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Received February 21, 2016

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В. О. Іванов, О. С. Задорожний. Оцінювання якості цифрового каналу зв’язку з гелікоптером

Встановлено причинно-наслідковий зв’язок між рівнем пульсацій діаграми спрямованості антенної системи, які зумовлені обертанням несучого гвинта гелікоптера, та вірогідністю бітової помилки, що виникає в цифровому каналі передачі даних. Розроблено графо-аналітичний метод оцінювання вірогідності помилки.

Ключові слова: гелікоптер; антена; діаграма спрямованості; ефективна висота; пульсації; бітова помилка; залежні спостереження; транспондер; захисне співвідношення.

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В. А. Иванов, А. С. Задорожний. Оценка качества цифрового канала связи с вертолетом

Установлены причинно-следственные связи между уровнями пульсаций диаграммы направленности антенной системы, которые обусловлены вращениями несущего винта вертолёта, и вероятностью битовой ошибки, возникающей в цифровом канале передачи данных. Разработан графо-аналитический метод оценивания вероятности ошибки.

Ключевые слова: вертолёт; антенна; диаграмма направленности; эффективная высота; пульсации; битовая ошибка; зависимые наблюдения; транспондер; защитное отношение.

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