Mathematical modeling of direction-finding characteristics of four-element circular antenna array taking into account the influence of carrier

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Abstract. The main problem arising in the development of mobile-based antenna arrays is the problem of taking into account the influence of the carrier body on the characteristics of such an antenna array. Unmanned aerial vehicles are one of the most popular directions of modern aviation development. It is aimed to consider a quite simple in design four-element annular antenna array and to analyze the influence on the bearing direction finding characteristics and radiation patterns of such a mobile carrier which is an unmanned aerial vehicle. Comparison of some absolute bearing direction finding errors obtained by the phase correlation method for the cases of placing the antenna array in free space and on the array carrier is given. The results of the calculation of the RMS values dependence on the frequency, averaged over all the analyzed angles of the radio wave direction of arrival, are presented. The radiation patterns of the synthesized array for the worst case are shown. The dependences of the RMS value on the azimuth angle of the radio wave direction of arrival for the cases of the antenna array placement on the carrier body and in the free space averaged for all the analyzed signal frequencies were calculated.

Keywords: unmanned aerial vehicle, antenna array.

1 Introduction

Business informatics as a practical activity is distinguished by work not only in the field of information technology, but also in the field of mathematical, economic and management tasks, such as: system analysis (system diagnostics of the organization, improvement of management systems); management of information and telecommunication infrastructure (planning of hardware resources of information systems for business processes, support for the continuity of information and telecommunication services); service management (support and service delivery management business with the use of information technology, calculation of their efficiency and cost, service engineering); life cycle management of information system (from design and development to termination of operation) and many others. All corporate information

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and telecommunication systems at the present stage of technology development can be built using wireless access networks.

In mobile radiobroadcasting, telecommunication, radiomonitoring, panoramic-direction finding systems, the antenna system is located on the carrier body [1]. In this case, as a result of secondary radiation when the radio waves are reflected from the carrier parts, the pattern of the antenna system is distorted [2]. This phenomenon, called radio deviation, leads to an increase in the direction finding error, which may in some cases exceed (20-30)° [3]. Theoretical consideration of the effect of the carrier body on errors in direction finding usually reduces to the problem of diffraction of electromagnetic waves on conducting objects [4].

The developers of vibrator antenna arrays used to solve the problems of radio monitoring and radio direction finding often use the apparatus of the Hallen integral equations [5] or the integro-differential Pocklington equations [6]. Such an approach allows us to estimate with a high degree of accuracy the systematic component of the direction finding error when performing numerical analysis, but it requires solving a system of equations with complex unknowns of a rather high order (up to several hundred for each discrete value of the azimuth angle of the radio emission source).

A device of this type can be used in the design and implementation of corporate information and communication systems as a research vehicle to obtain the most complete information on the coverage of a corporate wireless network. In addition, the device can be used as a backup signal source to maintain the continuous provision of information and telecommunication services.

2 Methodology

As discussed earlier, the theoretical account of the effect of the carrier body on the errors of direction finding can be reduced to a simpler method – to the problem of diffraction of electromagnetic waves on conducting objects [4]. The main section planes of the cylinder (the principal curvature planes, Fig. 1) can be chosen on the basis that the vector $\hat{U}_1$ is tangential to the cylinder in the XY plane, and the vector $\hat{U}_2$ is directed along the Z axis of the cylinder. The radius of curvature in the XY plane for an elliptical cylinder can be defined as:

$$a_1 = \frac{\left(a_2^2 \cos^2 v + a_1^2 \sin^2 v\right)^{\frac{3}{2}}}{a_1 a_2} \tag{1}$$

The incidence plane can be defined as a plane containing the unit vectors $\left(\hat{s}^i, \hat{n}\right)$. In the general case, the radius of curvature in the plane at angle α from the basic surface axes is given by Euler's theorem as:

$$\frac{1}{a_t} = \frac{\sin^2 \alpha}{a_1} + \frac{\cos^2 \alpha}{a_2} \tag{2}$$

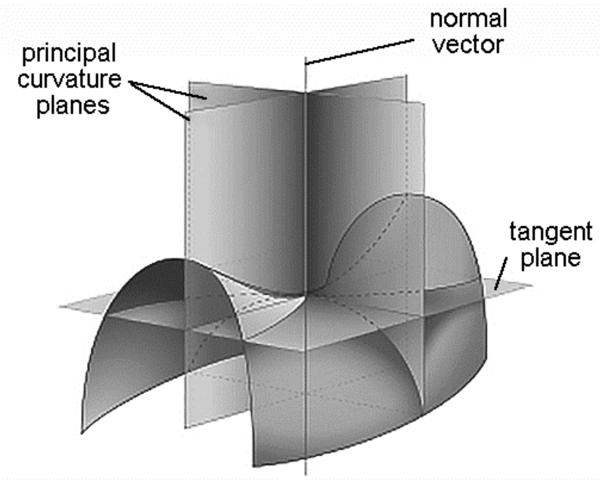

Fig. 1. Radius of curvature in the main planes (planes of symmetry).

For cylinder a_1, equation (1) corresponds, while $a_2 = \infty$. The angle α is calculated as:

$$t1 = -\hat{s}^i \cdot \hat{U}_1$$

$$t2 = -\hat{s}^i \cdot \hat{U}_2 \tag{3}$$

$$\alpha = \tan^{-1}(t1/t2)$$

Finding the length of the geodetic path (trajectory) can be produced as finding the distance along the surface of the cylinder from the elliptical angle $v1$ to $v2$ in the given direction. The arclength is calculated as:

$$\text{arcLength} = \frac{\int_{v1}^{v2} \sqrt{(a_1^2 \sin^2 \alpha + a_2^2 \cdot \cos^2 \alpha)} d\alpha}{\sin \theta} \tag{4}$$

where θ – the angle of elevation of the path traversed within $v1$ and $v2$.

In Fig. 2 the layout of the model under investigation and direction-finding antenna array is presented. All elements of the model, except the protective covers of the screws and the screws themselves, are perfectly conductive. Rings of protective covers are made of material with $\varepsilon = 2.5$. Screws, which can also be made of plastic, are not shown, it is believed that their rotation averages the observed situation. Other design variants of unmanned aerial vehicles are also possible [7].

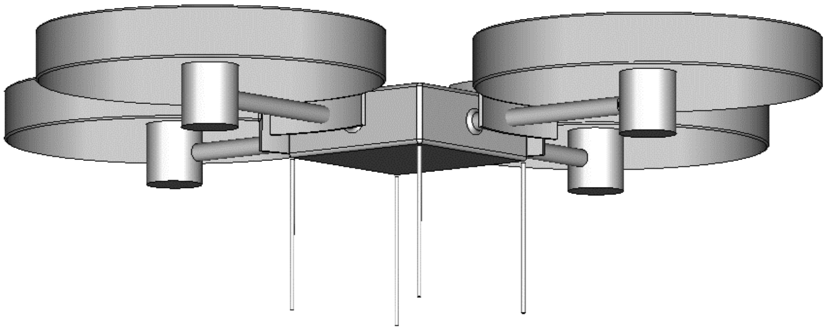

Fig. 2. 4-element antenna array and carrier.

3 Results

3.1 Analysis of absolute errors

In Fig. 3 shows the dependence of absolute errors of direction finding on the frequency of a signal without a carrier for angles of 0-40 degrees. Other angles of the electromagnetic wave arrival were not analyzed because the model is quasisymmetric with a period of 45 degrees horizontally. Based on the obtained data, it can be said that at almost all frequencies for all analyzed angles, except for the lowest frequencies (approximately from 100 MHz and below) for an azimuth angle of 20 degrees, the absolute error of direction finding does not exceed 5 degrees in the absence of an antenna array carrier.

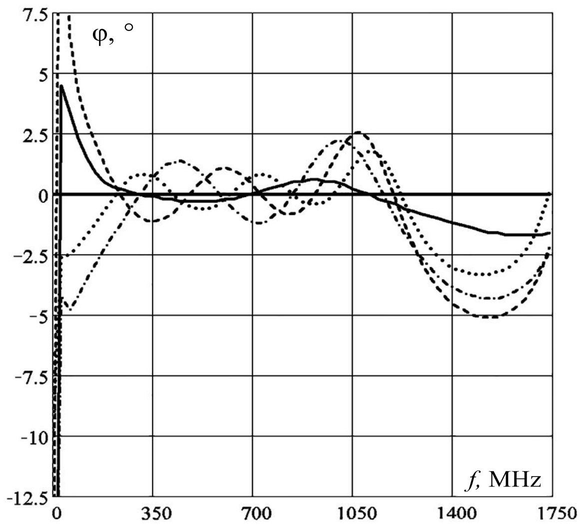

Fig. 3. Dependence of absolute errors of direction finding on the frequency of a signal without a carrier: solid line – 0°, dotted – 10°, dashed – 20°, dashed-dotted – 30°, fine line – 40°.

That is the inherent error of the antenna system of this type and size is approximately 5 degrees and, without complicating the construction a less error, cannot apparently be achieved. This is a rather strange and poor result, although it corresponds to the concept given in [8] that arrays with an even number of vibrators have a greater error relative to arrays with an odd number of them. The least error from the presented ones is characterized by a direction of 40 degrees, the phase on two vibrators of four for these angles of incidence should theoretically almost coincide, because the electromagnetic wave front reaches them almost simultaneously, and for the other two ("front" and "rear" for convenience) they should differ as much as possible. However, no complete coincidence is observed, this can be explained by the fact that the angle of full coincidence is 45 degrees. Here, except for frequencies below 100 MHz, the errors do not exceed 2 degrees.

In Fig. 4 shows the dependence of absolute errors of direction finding on the frequency of a signal with a carrier for angles of 0-40 degrees. In the presence of a carrier, the situation considerably and quite unexpectedly changes. Errors, as in the case of the three-element array [9], tend to have a negative character, although the average value practically does not shift relative to 0, and their maximum absolute value for all analyzed angles exceeds 5 degrees.

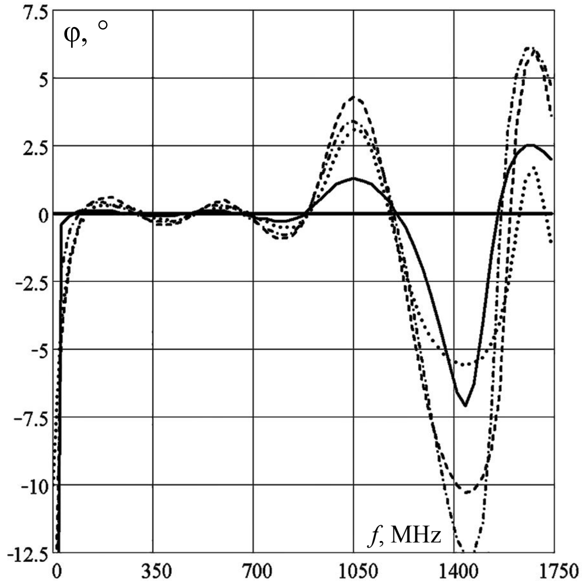

Fig. 4. Dependence of absolute errors of direction finding on the frequency of the signal with the carrier: solid line – 0°, dotted – 10°, dashed – 20°, dashed-dotted – 30°, fine line – 40°.

In addition, the nature of the distribution of the error in frequency and angles of incidence changes. The maximum error except for the lowest frequencies is achieved at frequencies of the order of 1450 MHz, as in the case of free space, apparently there is a resonance of the antenna system itself. In this case, the error value exceeds 12.5 degrees for the angle of incidence of the electromagnetic wave of 30 degrees. Due to

the influence of the carrier, there was a change in the angle with the maximum absolute deviation and the angle of 20 degrees, leading in the previous figure, is now only the second with an error of the order of 10 degrees. The minimum error of the order of 5.5 degrees from the maximum errors for a given frequency belongs to a direction of a wave arrival of 10 degrees closest to the metal rod with the engines. There are also two significant positive deviations, at frequencies of the order of 1050 MHz the error does not exceed 4 degrees, at frequencies of about 1650 MHz the error does not exceed 6 degrees, and a number of smaller ones at lower frequencies. At frequencies below 100 MHz, unlike the previous case, only negative deviations up to 7.5 degrees are observed for the angle of the wave arrival of 20 degrees.
Based on the results of the analysis of absolute errors for the cases of the three-element and four-element antenna arrays, can say the following: in the presence of a carrier with metal parts elongated in the direction of possible azimuth angles of electromagnetic wave arrival, the measured bearing "distorts" towards these metal parts.

3.2 Analysis of radiation patterns

Let's analyze the directional functions of the synthesized four-element circular antenna array for the worst of cases, corresponding to the maximum absolute deviation under the action of the carrier by more than -12.5 degrees, at a frequency of approximately 1450 MHz. In Fig. 5 shows the radiation pattern for the analyzed four-element antenna array.

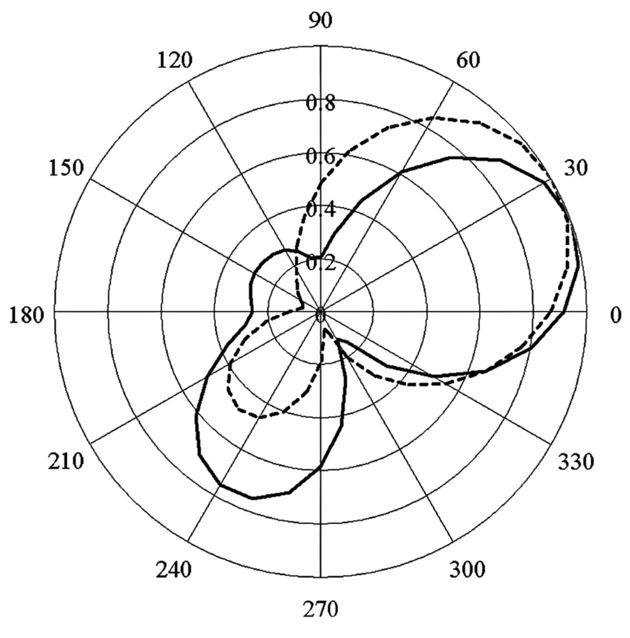

Fig. 5. The radiation patterns for the angle of arrival of the wave 30 ° and frequency 1450 MHz: solid line – free space, dashed line – on carrier.

It can be seen from the figure that the shape of the directional function under the action of the carrier is significantly distorted, the maximum really deviates by approximately -15 degrees, the back lobe increases approximately 1.5 times and more and more turns into the side lobe, moreover the second side lobe appears. In general, the distortion of the main lobe shape is positive (narrowing), but the appearance of the back (side) lobe up to 0.8 of the maximum spoils the whole picture.

3.3 Analysis of RMS

In Fig. 6 shows the dependence of the root-mean-square error of bearing detection on the frequency of the signal. The graphs as a whole repeat the situation for the dependence of the absolute errors of direction finding on frequency: for the case of placing the antenna array on the carrier, the root-mean-square deviation of the frequency dependence for high frequencies is much higher than for the case of placement in free space and at frequencies of the order of 1450 MHz it reaches 9.5 degrees, side maxima at frequencies around 1050 MHz (~ 3.5 degrees, duplicated for the case of free space with a maximum of less than 2 degrees) and at frequencies of 1650-1700 MHz of about 4.5 degrees are also shown. For the case of placing the antenna array in free space, the maximum does not reach 4 degrees and is somewhat shifted in frequency (about 1500 MHz). An interesting effect is that in the frequency range of 100-700 MHz, the antenna array placed on the carrier has a much smaller mean square error than the same array, but located in free space, in this range the RMS of the array with the carrier does not exceed 0.5 degrees, unlike the values of 1 degree or more for a solitary case.

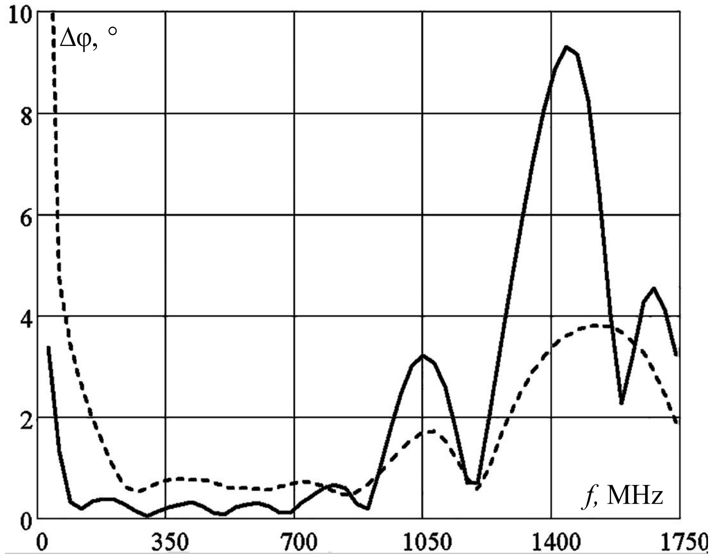

Fig. 6. Dependence of the root-mean-square error of bearing detection on the frequency of the signal: solid line – on carrier, dashed line – free space.

In Fig. 7 shows the dependence of the root-mean-square error of direction finding from the azimuth of the arrival of the signal. When averaging over the angles of the wave arrival, a discrepancy of the RMS maxima is observed, in the case of finding the antenna array in free space, the error maximum, equal to 3 degrees, is observed for the azimuthal angle of the wave arrival of 20 degrees. For the case of finding the antenna array on the carrier, the maximum RMS is shifted towards one of the array elements and / or the angle of the carrier on which it is mounted, and is slightly less than 4.5 degrees for the angle of the wave arrival of 30 degrees.

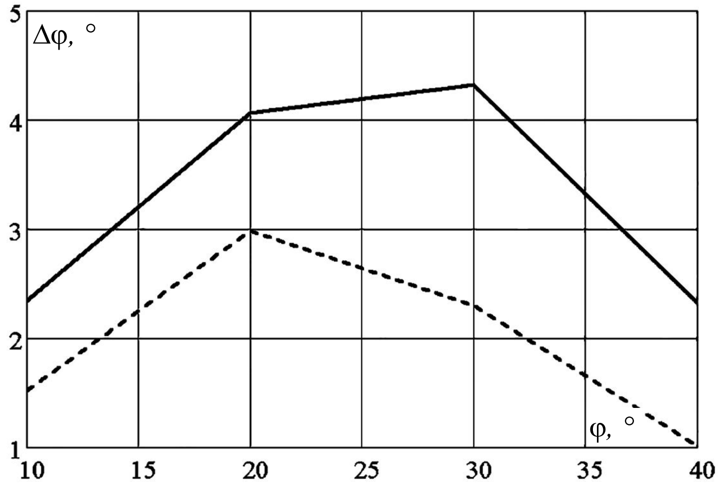

Fig. 7. Dependence of the root-mean-square error of direction finding from the azimuth of the arrival of the signal: solid line – on carrier, dashed line – free space.

Based on the results of the analysis of the dependence of the root-mean-square error of direction finding from the azimuth of the arrival of the signal, we can state the fact that for the case of placing a four-element antenna array on the carrier, the errors are small enough even for averaging over the whole range of the analyzed frequencies. They do not exceed 5 degrees, which is somewhat less than in the case of a three-element array [9], but also it does not allow the use of a four-element array directly for direction finding without further error correction. In this case, in order to use the antenna array together with the carrier, we can directly recommend a narrower range of operating frequencies of 50-1300 MHz, the RMS in which does not exceed 2 degrees, or even 50-1000 MHz, the RMS in which does not exceed 1 degree, if of course such a range satisfies other system requirements.

4 Conclusion

Regarding the absolute errors for the case of the four-element antenna array being analyzed, one can say about the unusualness of their values at high frequencies relative to the case of a three-element array, most likely this is related to the design of the antenna system itself and the aggravation of the resonance in the presence of the carrier. Due to it, the dependence of the RMS on the frequency has a similar character with a sharp increase in errors at frequencies of the order of 1400 MHz. The RMS, depending on the azimuth of the arrival of the signal, varies within 2.5-4.5 degrees for the case of positioning the array on the carrier while averaging over the whole analyzed frequency range, which is relatively small. By reducing the range of operating frequencies, it is possible to pick up variants with RMS of less than 1 degree in both cases.

In the frame of this publication, a comparison is not made between antenna array patterns for the angles being analyzed when it is in free space and on an carrier. Moreover, the errors for different vertical angles of signal arrival have not been taken into account, the influence of rotor rotation and the instability of the position of the aircraft in the air has not been taken into account. It is also desirable to analyze the errors for the vertical and horizontal angles of an electromagnetic wave arrival under all the above mentioned conditions, taking into account the noisy signal spectrum [10, 11].

The synthesized four-element circular antenna array with a mobile carrier can be used in such areas of business and business informatics as: design and implementation of corporate information systems; implementation, adaptation and development of application and communication systems (especially for corporate management tasks); audit of information technologies and systems (for example, wireless corporate communication network); in carrying out theoretical and applied research in the field of practical application of new information technologies; in the development of new methods and procedures information systems; with the support of the continuity of information and telecommunication services; in the mode of both reception and transmission (if there are sufficient power sources on board).

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