A System for Measurement of Electromagnetic Wave Scattered by Small UAVs

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Abstract—In this paper we describe a system for measuring the amplitude and spectrum of reflections from small-size UAVs. Experimental results of amplitude and spectrum electromagnetic wave scattered by small UAV with RCS since 0.01 m² are presented. Made direct measurements in an anechoic chamber at frequency of 9 GHz. Effectiveness of the parasitic leakage suppression technique at small RCS measurements it has been shown.

Index Terms—Radar cross-section, spectral characteristics, unmanned aerial vehicles, RCS measurement technique.

I. INTRODUCTION

Recently much attention is given to calculation and measuring of radar cross-section (RCS) of UAV in [1-4]. The method for fast calculation of the characteristics of scattering of electromagnetic wave (EMW) by UAV is considered in [1]. The work [2] is devoted to the calculation of RCS of UAVs having the same design. It has been shown that the main contribution to the RCS value is made by metal parts of the structure. In [3] considered the rotation of the propeller causes a significant periodic fluctuation of the radar echo. This phenomenon is studied by means of anechoic chamber measurements and numerical simulations. Numerical and experimental radar cross section analysis of the quadcopter at frequency of 10 GHz is presented in [4]. Major goal of the study is to evaluate the suitability of simplified quadcopter models for numerical radar cross section (RCS) investigations.

The measurement of electromagnetic wave scattering characteristics by small-size objects of the UAV type are relevant, since their designs are constantly being changed as well as onboard communications and navigation systems of UAVs are being complicated. Technical solutions aimed on the reduction of RCS by replacing metal parts with elements made of carbon materials are applied [5].

This paper describes measuring setup for experimental research on amplitude and spectral characteristics of EMW scattering by UAVs. Computational and experimental data that can be used in the development and further optimization of radar methods for detection of small UAVs with RCS from 0.01 m² under real-life conditions have been obtained.

II. DESCRIPTION OF THE MEASUREMENT SETUP

It is required high sensitivity of the receiving channel for the measurement of characteristics of the targets with RCS from 0.01 m², that is determined by the effectiveness of the interference compensation from its own probing leakage signal. It is known [6-8] that the signal reflected by the absorber of the AEC, as well as the leakage signal penetrating from the transmitting to the receiving antenna, is the main interference when measuring in the AEC. We shall evaluate the power of interference signals in comparison with the useful signal scattered by the target.

The power of the useful signal scattered by the target can be found from the radar range equation (1) [9, 10]:

\[ P_o = (P_t G_r G_s \sigma \lambda^4) \left( \frac{4\pi}{\lambda} \cdot R^2 \right)^{-1}, \]

where \( P_t \) is the transmitter power; \( G_r \) and \( G_s \) is the gain of the transmitting and receiving antennas respectively; \( \sigma \) is the RCS of the target; \( \lambda \) is the wavelength; \( R \) is the distance from measuring antennas to the target. Let us set the transmitted power value equal to 10 mW (+10 dBm), typical for laboratory standard microwave signal generators [11]. Gain values of the both wideband horn measuring antennas at frequency of 9 GHz are equal to \( G_r = G_s = 11 \text{ dB} \) [12]. The AEC dimensions are 4×6×3 m that meet requirements of far-field zone and allow diversity from measuring antennas to the measured target up to 4 m. We shall consider the frequency of 9 GHz and the target RCS equal to 0.01 m². Using these parameters at (1) we obtain an estimate of the useful (direct) response power \( S_o = -75 \text{ dBm} \).

Magnitude of the interference signal coming directly from the transmitting to the receiving antenna depends on mutual arrangement and orientation of directed antenna elements (AE). If receiving and transmitting antennas are identical and their apertures are parallel to each other, the isolation between the antennas is equal to the square of the side lobe level (SLL) of antenna patterns for the angle of incidence of EMW on the adjacent antenna element. From the value of SLL of the used measuring antennas equal to –23 dB at angle of 90° at frequencies above 5 GHz [12] follows expected calculated value of the isolation between the antennas for the direct penetration at a frequency of 9 GHz equal at least –46 dB. For the transmitted signal with a power of 10 dBm, the power of the direct leakage signal is \( S_p = -36 \text{ dBm} \).

Real attenuation of an interference reflected by the AEC is difficult to evaluate by calculation, so it has been determined experimentally. For the arrangement of targets and antennas
used in measurements the attenuation was –55 dB. For the transmitted signal with a power of 10 dBm the interference power reflected from AEC walls will amount to \( S_p = – 45 \) dBm.

The sum of reflected signal received by the measuring device can be determined as sum of three components (2):

\[
S_r = S_o + S_i + S_p.
\]  

where \( S_o \) is the power of the useful received signal reflected from the UAV; \( S_i \) is the power of the first interference received signal reflected from the absorber on the wall of the anechoic chamber; \( S_p \) is the power of the second interference leakage signal coming directly from the transmitting antenna to the receiving antenna[6-8].

To measure the target RCS the magnitude of useful response signal scattered by it must be much higher than sum of interferences. So the following condition must be satisfied:

\[
S_o \gg S_i + S_p. \quad (3)
\]

For the described case a set of values \( S_i, S_p \) and \( S_o \) does not meet requirement (3).

Often well known different compensation methods are used to separate a useful signal from interference components of the received signal [6-8]. We shall use a kind of compensation method, the essence of which is in the vector subtraction of interfering reflections, previously measured in the AEC, from the sum reflected signal (see (2)). This method allows to irradiate the target with a continuous signal and does not require expensive equipment.

Such method is a single-frequency and has a limitation on the compensation of interfering reflections. Fig. 1 exhibits a structural diagram of the measuring setup with the implementation of the compensating interference attenuation scheme. Fig. 2 presents the arrangement of real quad copter drone and measuring antennas in an anechoic chamber.

In the structural diagram, the continuous microwave sounding signal \( S_o \) is formed by a microwave generator G7M-40A [11] at a frequency from 1 GHz to 40 GHz.

The sounding signal from output of the microwave generator, follows to the directional coupler (DC) NO12-2-50 [11] via microwave cables where it is divided into the main signal \( S_o \) and the compensation signal \( S_i \), wherein the signal \( S_p \) is attenuated by 10 dB with respect to the signal \( S_o \). Then, the signal \( S_o \) is radiated by the antenna element. Three models of measuring antennas are used in the setup to cover full operating frequency range: Fairview Microwave INC. SH128-20 (26.5 GHz – 40 GHz), Defence Communication Engineering INC. 042-520 (18 GHz – 26.5 GHz), A-INFOMW LB-8180-NF (0.8 GHz – 18 GHz) [12]. A pair of antennas of the same type has always been used in transmitting and receiving channels. To measure the polarization characteristics of the target, the antennas of the setup are equipped with devices allowing its rotation about an axis coinciding with the direction of radiation.

The target was hanged up in the AEC on dacron slings having the negligible RCS reducing scattering EMW on them and therefore interference signal to the minimum possible. To attenuate the direct propagation signal \( S_p \), an absorbing material was laid between antenna elements (Fig. 2).

In the receiver, the reflected signal \( S_i \) is received by an antenna element. Then, it adds up in DC with the signal \( S_o \), and then it is processed by Tektronix 2782 spectrum analyzer.

In the compensation channel, the signal \( S_i \) is adjusted for

Fig. 1. The structural diagram of the system for measuring the absolute RCS in the frequency range of 3-33 GHz.
amplitude by a digital-controlled step attenuator to the power level of the sum of interference signals equal to \( S_p + S_i \). To fine-tune the interference compensation channel, the attenuator must have smooth and discrete adjustments with a small step and a wide range of attenuation.

Therefore, a three-stage attenuator was used, which stages (ATT1, ATT2, ATT3) have a different resolution and an adjustment range. The following attenuators were used: Agilent 33325-60009 (step 10 dB, range 60 dB), Agilent 84904L (step 1 dB, range 11 dB), (MITEQ 294301-10 with a smooth adjustment in the range of 32 dB).

The phase shift of the compensating signal \( S_c \) was adjusted via two controllable phase shifters PhS1 and PhS2 from Filtronic Sage Laboratories 6705K in a way to compensate the interference \( S_p + S_i \) by anti-phase addition (subtraction) of equal-amplitude signals \( S_p + S_i \) and \( S_c \). A pair of phase shifters provides for phase rotation on 360° at lowest frequencies, which provides the required adjustment range of the compensation channel by phase.

The computer that controlling setup reads data recorded by the spectrum analyzer, and controls the microwave generator and attenuators.

Phase shifters and attenuators are designed for a frequency range of 3 - 33 GHz. This factor determines the frequency range of the setup, though all other components, including the AEC, operate in a frequency range of 1 - 40 GHz.

The following are the results obtained at a frequency of 9 GHz.

### III. Measurement Results

The measured isolation between the receiving and the transmitting antenna was \( S_p = -52 \text{ dBm} \). The interference component, due to a direct leakage \( S_p \), was attenuated by –10 dB to the level \( S_i \) by introducing an absorber between the antenna elements (Fig. 2). The level of signals \( S_p \) and \( S_i \) corresponds to the calculations taking into account the signal attenuation in microwave cables by –15 dB.

Spectrograms of the interference signal before and after compensation are shown in Fig. 3. It can be seen that the depth of the interference compensation was 35 dB.

A reference isotropic solid aluminum sphere (Fig. 4) with RCS equal to 0.01 m² was used to calibrate the level of signal scattered by UAV. The sphere's RCS and its radius of are related by expression [7, 13]:

\[
\sigma_r = \pi r^2, \tag{4}
\]

here \( r \) is the sphere radius, for RCS equal to 0.01 m², a radius \( r = 0.056 \text{ m} \).

The spectrogram of the signal reflected by the reference is shown in Fig. 4, which shows that the power of the reflected signal was –89.1 dBm, which is in good agreement with the calculation taking into account the signal attenuation in microwave cables –15 dB.
The RCS of an arbitrary target can be calculated from the ratio of powers of the received signals reflected from the reference and the target under the formula obtained from (1):

\[ \sigma_d = \frac{P_{rd}}{P_{rr}}, \]

(5)

where \( P_{rd} \) is the power of the received signal reflected from the UAV, \( P_{rr} \) is the power of the received signal reflected from the etalon metal sphere.

Fig. 5 and Fig. 6 present the measured characteristics of EMW scattering of the quad copter Cheerson-CX-20 at a frequency of 9 GHz with a horizontal polarization of antennas and a bistatic angle among the antennas of 3°. Consequently, Fig. 5 shows the spectrum and the power level of the reflected signal when quad copter engines are off and Fig. 6 shows the spectrum and the power level when propeller engines are on.

From Fig. 5 we can see that the power level of the response from UAV was equal to –90.6 dBm. Then the estimate of RCS of the quad copter from (5) is equal to 0.007 m². Fig. 6 shows that in the spectrum of emerged lateral petals with the level of -22 dB relative to main lobe.

Fig. 6 shows that in the spectrum of emerged lateral petals with the level of -22 dB relative to main lobe arising from the rotating elements (propeller) quad copter with Doppler frequencies lying in the range from ± 125 to ± 500 Hz. Additionally, when you enable the rotation of the propellers of the UAV then RCS has been increased by 5.2 dB to 0.023 m², which is associated with a change in angular position of the UAV.

IV. CONCLUSION

1. Measurements of the characteristics of the EMW scattering by the target with low RCS of 0.01 m² are possible in the AEC using the known selected method of the interference compensation from in the main signal. Moreover, the estimating accuracy of not less than –10 dB relative to 0.01 m² is achieved.

2. The carried out numerical calculation of the RCS of a real UAV satisfactorily agrees with the experimental data, that allows collecting the statistics of EMW scattering from different types of UAVs without resorting to laborious and expensive experimental measurements.

3. The electromagnetic calculation can be used as a tool in the evaluation of radar visibility of designed UAVs in a wide frequency range.

4. Spectral components of the radar response, formed by rotating elements of the quad copter, are in 20-25 dB weaker than the reflections from its stationary element. Therefore, their use in the detection at distances close to maximum permissible is problematic.

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