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Electromagnetic image of small UAV in very low frequency range

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The article deals with the measurement, visualization and analysis of the magnetic field in the 3D space around a small quadcopter. The measurements were realized in the very low frequency (VLF) range, since this range is interesting because of the possible detection of the drone also in the fully automated flight mode (without telemetry transmission). A measurement equipment/device that allows mapping of the magnetic field of the multirotor drone based on the sensor elevation and the copters azimuth was realized. The magnetic field was measured with a small inductive sensor – the air coil. Frequency analysis (signal spectrum) and the spatial 3D analysis of the selected frequency components that brought interesting results were carried out on the recorded data.

K e y w o r d s: small UAV, VLF magnetic field, frequency analysis, spatial measurement and visualization

1 Introduction

After the large increase of the civil UAV applications in the second decade of the 21st century [1], in spite of the developed emergency procedures and safety equipment [2][3] many problems occurred concerning their misusage or the air traffic threatening. The reaction to this situation was quicker development of the small UAVs detection systems. Innovative methods of the UAV detection in the complicated terrain conditions based on the sensing of electromagnetic signals are used for example by systems like [4][5].

Based on our previous experiments [6] about the VLF radiation of various BLDC motors for small drones of a multirotor type the measurement methodology for the obtaining of their 3D electromagnetic image was elaborated. The electromagnetic radiation in the VLF band by the drones with an electric propulsion shows as one of the suitable detection method even in complicated terrain conditions, where radar and optical methods are not usable.

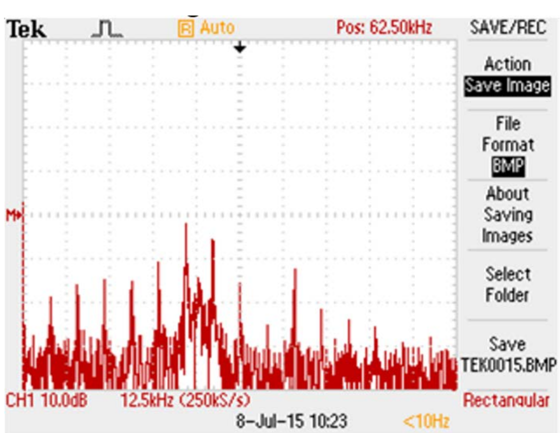

Fig. 1. Signal spectrum of RAY c2822 - 27 engine radiation with minimal revolutions [3]

2 Theory and methodology

The previous measurements of the small UAV with the RAY c2822-7 BLDC motors mentioned in the introduction that were realized in one selected axis had shown that radiation of the engines is real and from the frequencies point of view the significant harmonic components are determined by the fundamental operation frequency of the PWM regulators – commonly designated ESCs (Electronic Speed Controllers). The result obtained from the measurements is shown in Fig. 1. Based on the results the spatial measurements of the UAV radiation the VLF band was selected. This implies expected dominant frequencies at 8 kHz and 16 kHz (http://pelikandaniel.com/dld/RAY_ESC_manual_SBEC_v2013.pdf).

The drone was considered to be a special radiation source, which was positioned into many defined azimuths during the measurement in the 3D coordinate system with its origin in the center of the drone. The directional sensor of the VLF signal is based on the induction principle and it is positioned on the arm to create the elevation

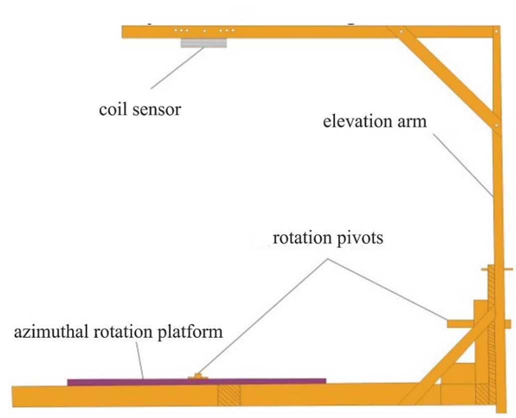

Fig. 2. Drawing of the measurement equipment

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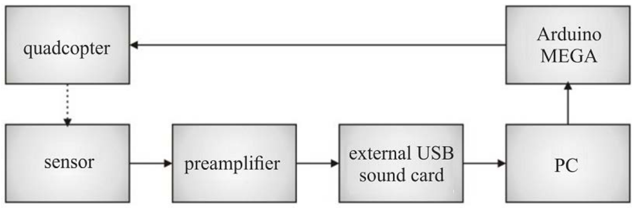

Fig. 3. Block diagram of the measurement chain

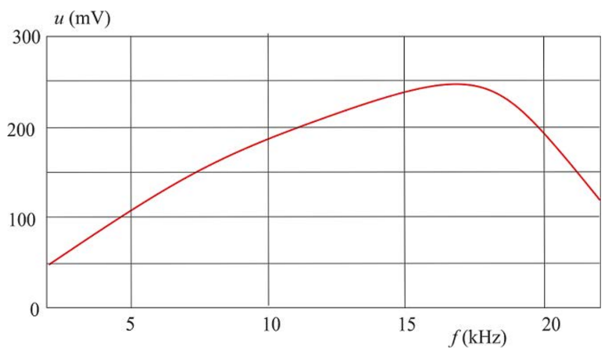

Fig. 4. Frequency characteristics of the measurement chain

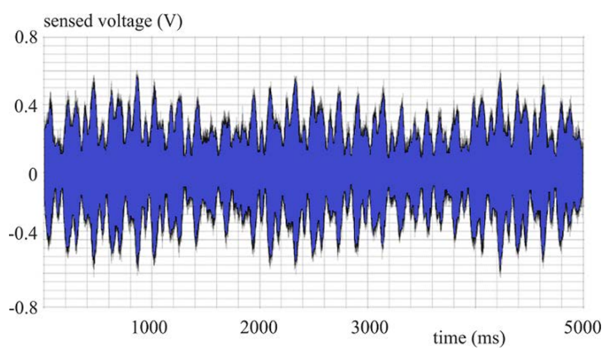

Fig. 5. Time development of the signal recorded in position (– 90 deg, 0 deg, 80 cm)

angle. The measurement equipment illustrated in Fig. 2 was designed without screws from wood only, so no ferromagnetic materials were used.

Based on the experiences with the spatial directional characteristics measurement of the aircraft antennas at the Faculty of Aeronautics at the Technical University of Košice [7] the methodology of the UAV radiation measurement was created. This method combines the UAV rotation on the azimuthal platform with the induction sensor positioning in elevation. The axis of the sensor pointed always to the XYZ coordinate system origin defined in the center of the UAV, so the winding of the sensor was always in the tangential plane to the imaginary spherical surface around the multirotor UAV. The measurement sequence can be imagined as the consecutive measurements on the parallels of the imaginary sphere.

The magnetic field sensor was realized as flat circular coil with 800 turns and had the diameter of 110 mm and height of 8 mm. The block diagram of the measurement chain is shown in Fig. 3. In Fig. 4 is shown the frequency characteristics of the measurement chain, the stimulation field was 6.5 nT.

The inverting circuit low noise amplifier OPA27GP was used as the preamplifier. The recording device consisted from the external audio card ASUS XONAR U7 with the 16-bit A/D converter and 192 kHz sampling frequency. The Zelscope oscilloscope software was used in the PC. The measurement with the selected step of 30 deg in both the azimuth and the elevation produced over 4 GB of the recorded data text files that were processed and visualized by scripts created in the Python programming language. The coil sensor was calibrated with the Helmholtz coils in the 2 kHz – 22 kHz range. At the frequency of 8 kHz it has the constant of 42 pT/mV.

The spatial image can be solved as the visualization of the radiated signal intensity in the form of the position vector magnitude or a pseudo-color spatial visualization on a spherical surface. In both cases it is so possible to visualize the amplitudes of the dominant frequencies.

3 Experiments and results

For the initial experiment with the measurement and visualization of the drone spatial radiation a small quadcopter made from the glass fiber composite with the 310 mm distance between the BLDC motors was used. The RAY R-20B ESCs with the maximum continuous current of 20 A with the 8 kHz PWM were used. The quadcopter was powered from its operational Li-Pol accumulator, which was recharged among the measurements to obtain relevant results. Also, for the purpose of the correct generation of the control signals (standard servo PWM) for the ESCs the ARDUINO platform with the ATMega2560 processor was used, because the quadcopter control boards correction signals based on its accelerometers and gyroscopes into the set throttle level were unwanted. The throttle level set for the ESCs corresponded to the hovering, which is the typical flight mode for the quadcopter operation. When setting the throttle level during the measurements the start up and stabilization of revolutions of the motors were taken into the account.

The measurements were done with the single motor running (X axis arm) and all four motors running at hover throttle level, both measurements in two distances of 80 cm and 90 cm. For the basic information about the measurements and analyses we present following selection of the results from the measurement with all four motors running.

Waveform recording in the distance of 80 cm at the elevation –90 and 0 deg azimuth, Fig. 6. As the result of the different PWM frequencies of the ESCs and phases significant ELF effects occur in the sensed signal. To achieve the fine spectral analysis, the data were recorded in each

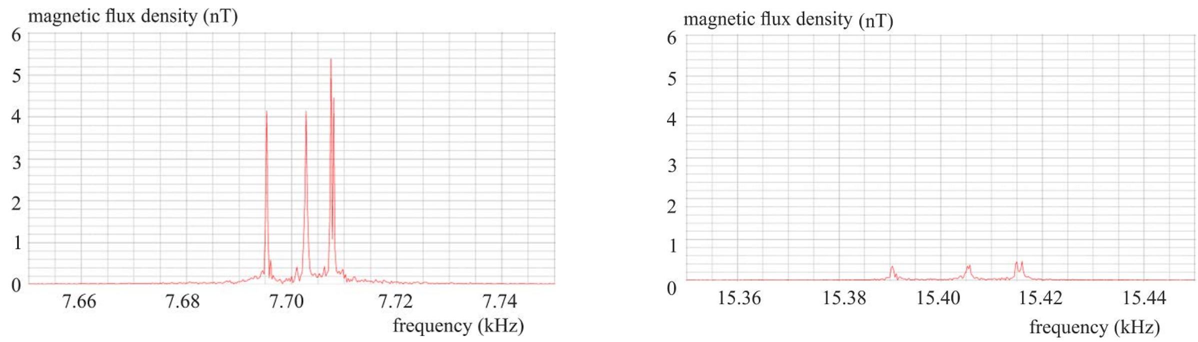

Fig. 6. Frequency analysis of the signal near the first and the second harmonic components

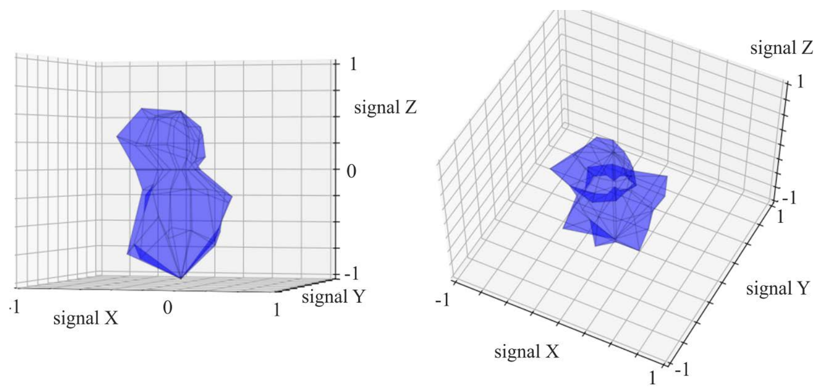

Fig. 7. Visualization of the directional characteristics at the first harmonic components range

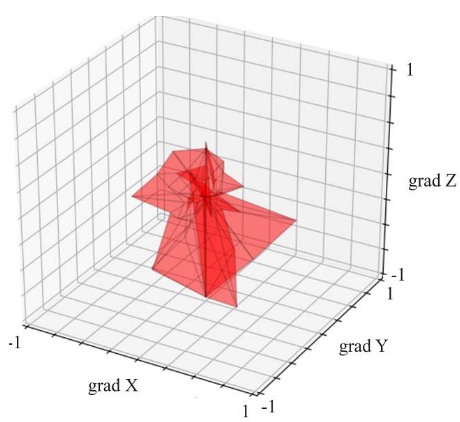

Fig. 8. Directional characteristics of normalized flux density gradient

measurement point for 4 s with the 192 kHz sampling frequency.

The result of the fine spectral analysis with the 0.25 Hz resolution is shown in Figure 7. The first harmonic component of the ESCs operating PWM frequency at approximately 8 kHz is dominant; the second harmonic component is also visible. The number of the spectral lines is corresponding to the count of the motors, since each ESC has slightly different PWM frequency. The variation of the PWM frequencies was in range from 7695 Hz to 7708 Hz.

From the obtained data in the elevation range from –90 to 90 deg and the azimuth range from 0 to 360 deg both with 30 deg measurement stepping it is possible to visualize the 3D directional characteristics and rotate them freely with the mouse. For these characteristics, the signal is normalized to 1 corresponding to the maximum of radiation. In this manner it is possible to analyze the directional properties of the radiation regardless to the absolute value of the radiation. In Figure 8 the directional characteristics for the first harmonic components range is shown. The reference value for the normalization was 0.1281697 V, what with the constant 42 pT/mV corresponds to the flux density of 5383.98 pT.

The measured quadcopter radiates more in the lower hemisphere, approximately twice the radiation in the upper hemisphere. The smallest (directional) radiation was measured in the XY plane when $z = 0$, in the plane of the quadcopter construction. The measured flux density values were relatively small, therefore common magnetometers are not suitable for the micro and small UAV magnetic fields measurement. On the other side, frequencies of the harmonic components 8 kHz, 16 kHz or 16 kHz and 32 kHz of the ESCs are frequencies from radio transmission bands, for example the formerly used worldwide navigation system OMEGA. This fact implies that it is sensible to seriously deal with this issue. As an interesting information we can mention that the first drone detection system operating among others also with the principle of detection of signals in the VLF band (from 9 kHz) was introduced into the market by Aaronia company [1] about one year after our measurements with the BLDC motors [3].

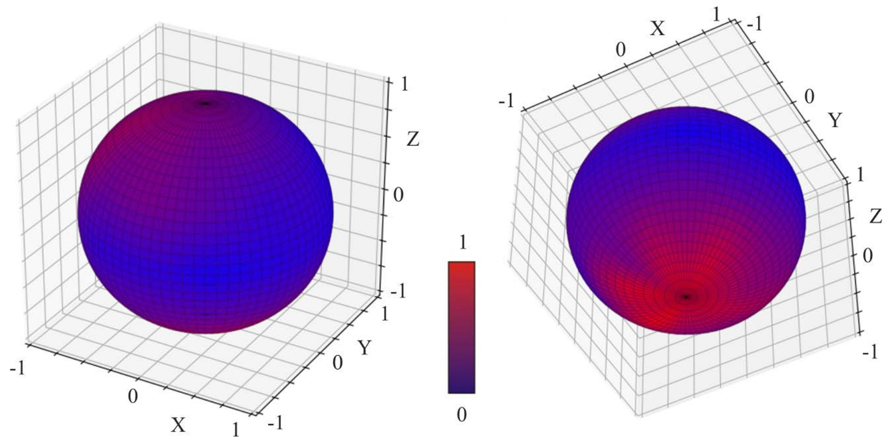

Fig. 9. Pseudo - color visualization on the surface of the unit sphere

As examples of other visualization types, the directional characteristics of normalized flux density gradient (since there were two measurement distances, 80 cm and 90 cm) are shown in Fig. 8. The reference value for the gradient normalization was 4136 pT/m. In Figure 9 another possible way to analyze spatial directional radiation of the UAV with the pseudocolor visualization on the surface of the sphere with radius equal to 1 is shown. To achieve this visualization, the data were interpolated using the bilinear interpolation.

4 Conclusion

Results presented in this paper confirmed that the measurement methodology using the rotation of the investigated UAV in the azimuth and positioning of the sensor in the elevation allows us to obtain the 3D image of its magnetic field. The measurement results can be visualized in the normalized 3D directional characteristics, when the maximum of the sensed signal is normalized to 1 (directional unit vector). Another useful graphical visualization type is the normalized pseudocolor visualization on the surface of the unit sphere.

The electrical drives of the UAVs with the BLDC motors and using the PWM are the source of the electromagnetic radiation. This can be a significant factor for the detection of the UAVs also in the fully automated flight mode. With the use of the fine spectral analysis of the measured signal components it is possible to visualize the objects radiation on the selected frequencies. The analysis has shown that the ESCs are operating on similar but not the same frequencies. So, the quadcopter UAV had recognizable four peaks around the 8 kHz frequency (given by the ESCs base frequency) and also on the other harmonic components. This fact can be used to distinguish the count of the UAV motors, what is valuable information for the UAV detection systems.

Based on the results, the next tasks include measurement of the UAV with more powerful BLDC motors, measurement with the ESCs with the 16 kHz PWM and also the measurement of the autopilot driven modes of the UAV. To achieve more sensitive measurement chain the sensor is going to be optimized and possibly used with the low noise ferromagnetic core, where also the influence on the sensitivity and directional characteristics will be investigated.

Acknowledgements

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References

[1] M. Jurková and K. Draganová, "History and Perspectives of Unmanned Aerial Vehicles Utilization", *Aeronautika 2013*, Košice: LF TU, 2013, p.85-90.ISBN 978-80-553-1416-7.

[2] K. Draganová, F. Kmec and V. Moucha, "Safety Equipment for Unmanned Aerial Vehicles", *Acta Avionica. vol. 14*, no. 25 (2012), p.116-120.ISSN 13359479.

[3] K. Draganová, V. Moucha and F. Kmec, "Safety Equipment and Emergency Procedures for UAV Control", *MOSATT 2013*, vol. 5.Košice: Perpetis, 2013.p.44-49.ISBN 978-80-971432-1-3.

[4] IsoLOG 3D Panorama Tracking Antenna http://www.aaronia.com/Datasheets/Antennas/Antenna-Array-IsoLOG-3D.pdf.

[5] R&S ARDRONIS-D, https://cdn.rohde-schwarz.com/pws/dl_downloads/dl_common_library/dl_brochures_and_datasheets/pdf_1/ARDRONIS_pro-fly_en_3607-4993-32_v0300.pdf.

[6] J. Blažek, "Leakage Magnetic Fields of the Electric BLDC Motors of Small UAV", *JEEEC*, Vol 66., NO 7/s, (2015), p.14-17.ISSN 1335-3632.

[7] M. Krchňák and J. Labun, "Measurements anechoic chambers ", *5th International Scientific Conference of PhD Students and Young Scientists and Researchers*, Košice: TU, 2016, pp.1-10.ISBN 978-80-553-2514-9.

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