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Susceptibility of Civilian UAV to Wideband High Power Electromagnetic Pulses

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Abstract—As unmanned aerial vehicle (UAV) is widely used in many civilian fields and wideband (WB) high power electromagnetic radiation devices development, whether the WB radiation would influence the civilian UAV to fulfil its tasks needs to be analyzed. Therefore, the radiated susceptibility of three models of DJI UAVs is studied in the paper. A decimetric wave oscillator with the power of over 500 MW was introduced as the radiation source. In experiment, adjusting the distance between radiation antenna and UAVs to change the electric field and the testing antenna was employed to measure the electric field on line. The three models of UAVs can be shot down by the electric field of 10 kV/m, 20 kV/m, and 30 kV/m, respectively. Besides, as electric field reached up to over 35 kV/m, the rotor motor, electric control system, and inertial measurement unit (IMU) in Mavic Air and Mavic Air 2 were easier to burn down. Except that, energy accumulation effect has been proved in the experiment. In conclusion, the UAVs should fulfill tasks in the WB electromagnetic environment whose electric field is much less than 10 kV/m, and some shielding methods are needed to make UAV survive.

1. INTRODUCTION

Unmanned aerial vehicle (UAV) was first made in 1917 [1]. Because UAVs can ensure safety of operator and have the characteristics of low expense, low-requirement for on-land guarantee, strong mobility, and strong viability, they are widely used in many civilian fields, such as ground mapping, geological examination, disaster monitoring, air traffic control (ATC), message transmission, and aerial photo [2]. However, as application scenarios are expanded, civilian UAVs have to face tough challenges from the electromagnetic interference (EMI) in complex electromagnetic environment, especially intentional electromagnetic interference (IEMI) [3, 4].

According to the characteristics, the EMI can be classified into three main categories: high-altitude electromagnetic pulse (HEMP), nuclear electromagnetic pulse (NEMP), and high power electromagnetic (HPEM) pulse [5, 6]. Owing to the development of pulsed power sources, the HPEM pulses are becoming a new threat. In terms of frequency spectrum, the HPEM can be classified as narrow-band high power microwave (HPM), wideband (WB) HPEM radiation, and ultra-wideband (UWB) transient.

However, most studies in the field of IEMI have only focused on radiated susceptibility of electronic equipment to narrow-band HPM or UWB transient [7–13]. Far too little attention has been paid to WB HPEM radiation because of the slow development of WB microwave generator. In recent years, nonlinear transmission line (NLTL) oscillators and other transmission line oscillators have been widely used, which will be used in the WB IEMI environment. Besides, radiated devices usually include cars, computers, missiles, tactical radio link, army radio, circuit modules, etc., but the susceptibility of civilian UAV has not been studied in details. In [14], the susceptibility of the UAV toward continuous wave has been studied, and the results proved that the date link used to communicate with the ground control

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station is easily disrupted when frequency of the IEMI is close to that of the date link. Nevertheless, the research method is injection way, which may be different from the real IEMI environment.

Therefore, considering complexity of the UAVs, we carried out the experimental research on the radiated susceptibility to WB high power radiation. The paper is organized as follows. Section 2 will give the output characteristics of the WB oscillator and the influence of the ground reflection on the electric field at the UAVs. Introduction of the tested UAV and the experimental setup will be illustrated in Section 3. Besides, the experimental results and discussion are given in Section 4. Finally, Section 5 will summarize the paper briefly.

2. CHARACTERISTICS OF THE WIDEBAND HIGH POWER RADIATION SOURCE

The spectrum bandwidth of WB microwave is about 10% [15], and its radiation field spectrum is generally between 100 and 1000 MHz. Compared with UWB microwave (bandwidth > 25%), the WB microwave has higher energy spectral density and directional radiation ability. At the same time, different from narrowband microwave (bandwidth < 1%), WB microwave does not need a priori understanding of the target, has lethality to many targets at the same time, and generally does not need relativistic electron beam to generate microwave, which is easy to realize miniaturization.

The decimeter wave WB oscillator used in this paper is composed of a multi-channel switch, a coaxial transmission line, and a single cone horn. When the main switch of the pulse power source is turned on, the generated high-voltage pulse is introduced into the multi-channel switch of the coaxial structure through the charging inductor to form a quarter wavelength transmission line oscillator. Due to the open structure of the single cone horn, part of the energy of each oscillation is radiated into the free space to form damped oscillation radiation [16, 17].

Its center frequency is about 380 MHz; 3 dB bandwidth is about 60 MHz; max pulse repetition frequency (PRF) is 25 Hz; and the pulse number can reach up to 250 at one shoot. To get the electric field at the tested UAVs exactly, the output of the WB oscillator and influence of the ground reflection need to be tested and discussed.

2.1. Output of the WB Device

In experiment, a triangle antenna was used to carry out the examination, and the whole layout of the testing experiment is shown in Fig. 1. Considering that the ground reflection may influence the testing results, the microwave generator was lifted up, and the corresponding height above the ground

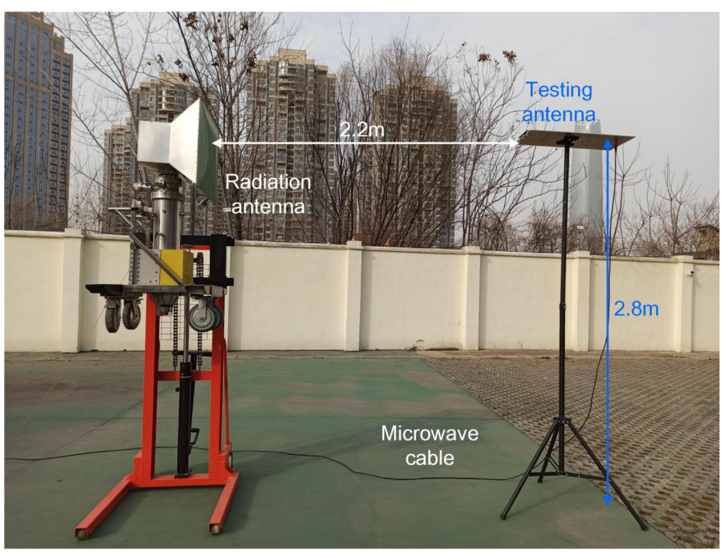

Figure 1. Layout of the testing experiment.

is 2.8 m. The distance between radiation and testing antennas was set to be 2.2 m to satisfy the far-field condition. The acquired signal observed by the testing antenna was transmitted to the oscilloscope, and there were some attenuators between them, whose total attenuation is over 60 dB.

The classical observing time-domain waveform and its Fourier transform (FFT) waveform are illustrated in Fig. 2. The time-domain waveform is obviously WB microwave, and the center frequency is about 380 MHz. Besides, the 3 dB bandwidth is about 60 MHz, and the relative bandwidth is about 16%. After 30 pulses, the average outputted power can be calculated to be over 500 MW, and the center frequency ranges from 350 MHz to 390 MHz, which proves that the produced microwaves from the oscillator are unstable.

Figure 2. Time-domain waveform and the corresponding FFT waveform of the single pulse.

In addition, the multiple pulse waveforms at one shoot are observed in Fig. 3. It can be seen that the repeatability is good, but the amplitudes for different pulses are different. After many times of tests, the maximum amplitudes for different pulses at one shoot are almost the same.

Figure 3. Multiple waveforms at one shoot.

2.2. Influence of the Ground Reflection

Considering instability of the output from the WB oscillator, to prove how the ground reflection influences the tested results, we tested the microwaves at different distances between radiation antenna and testing antenna. The result is given in Table 1. If the ground reflection is little, the rE value should be the same, and the integral power would not change. However, the rE value and the power are different at different distances, which proves that the ground reflection is a sever issue for WB microwaves testing. Anyhow, the electric field will decrease as the distance increases, so the electric field was selected as the parameter to measure the radiation level.

Table 1. Observed microwaves at different distances.

Distance (m)	Electric field (kV/m)	rE value (V)	Integral power (MW)
2.2	140	294000	600
5.0	60	310000	520
7.9	40	318000	550

In addition, setting the distance between radiation antenna and testing antenna to be 7.8 m, the microwaves at different angles are observed in Table 2. Here, the angle is between the line that connects the center of the oral surface of the radiation antenna and the testing antenna and the line normal to the oral surface of the radiation antenna. The difference between the values at different angles is less than 6%. For the electric field at ±10%, the electric field difference is no more than 4%. Therefore, if the testing antenna and the target are mirror symmetry about the normal face of the radiation antenna, the electric field at the testing antenna can be regarded as the electric field at the target, which is the foundation of on-line test.

Table 2. Observed microwaves at different angles.

Angle (°)	Electric field (V/m)	rE value (V)	Integral power (MW)	Se (W/cm^2)
−10	34000	261300	390	330
0	35200	251000	400	340
+10	35150	261000	420	310

3. TARGET OBJECTS AND EXPERIMENTAL SETUP

3.1. The UAVs under Test

Three different types of civilian UAVs from the same brand (DJI) were selected as the target objects, whose parameters are shown in Table 3. Phantom 4 is larger than Mavic Air and Mavic Air 2, and Mavic Air 2 is the improved model of Mavic Air. Besides, the max flight time is only about half of the time in Table 3 in experiment, which will decrease the experimental efficiency.

Table 3. Parameters for different target objects.

Models	Phantom 4	Mavic Air	Mavic Air 2
Weight (including battery)	1388 g	430 g	570 g
Max flight altitude	6000 m	5000 m	5000 m
Max flight time	$\sim$ 28 min	21 min	34 min
Communication frequency	2.4–2.483 GHz	2.4/5.8 GHz	2.4/5.8GHz

These UAVs system includes aircraft, ground control station, and communication link. The aircraft is mainly composed of four rotor motors, electronic speed control (ESC), batteries, pan-tilt and highly integrated motherboard. The shell material of the fuselage is usually light plastic, which has no ability to shield electromagnetic waves. Therefore, all components and communication links of the aircraft may be affected by electromagnetic waves.

As we all know, there are two ways that the microwaves energy couples to the interior electronics of a system: front-door coupling and back-door coupling. Front-door coupling is the microwave radiation couples to equipment intended to communicate or interact with the external environment, and back-door coupling is coupling through imperfections (apertures) in an electromagnetic shield. In other words, the frequency of the radiation coincides, at least partly, with the working frequency of the equipment. The communication frequency of the selected UAV is 2.4 GHz or 5.8 GHz in Table 2, and the frequency range of WB oscillator is 350 MHz to 390 MHz. The frequency-hopping spread spectrum is usually adopted by the 2.4 GHz communication. Theoretically, it may coincide with the frequency of WB oscillator, so the irradiation of WB oscillator to UAV may be two coupling modes.

3.2. Experimental Setup

The experimental setup is as shown in Fig. 4. Here, the fiber optical control box was operated by an experimenter to adjust the output parameter of the WB oscillator, such as repetition frequency and radiated pulse number at one shoot. As the WB oscillator radiated, the testing antenna and target UAVs were placed at the same distance from the radiation antenna, and the distance between testing antenna and UAV is usually less than 2.0 m to ensure that we can get the electric field at UAVs precisely. The remote control was to control the flight of the UAVs, and the mobile phone was used to report errors and show the pictures that camera of the UAV photographed. Besides, the acquired signal by the testing antenna was transmitted through microwave cable and attenuators, and finally reached the oscilloscope. To avoid the effect of the WB microwaves on devices as well as experimenters, all the devices and experimenters are placed behind the oscillator, and the distance ranges from 5 m to 10 m.

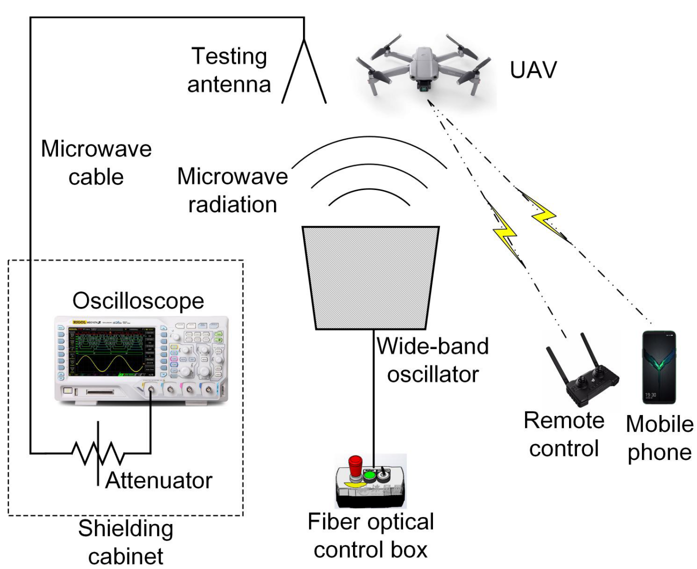

Figure 4. Layout of the experiment.

Considering that radiating UAV at different directions may results in different results, the four radiation directions were defined as in Fig. 5. When the green signal light is almost opposite the microwave radiation, the direction is 0°, and seeing above the UAV, as the direction turns 90°, we can get 90°, 180°, and 270°, respectively.

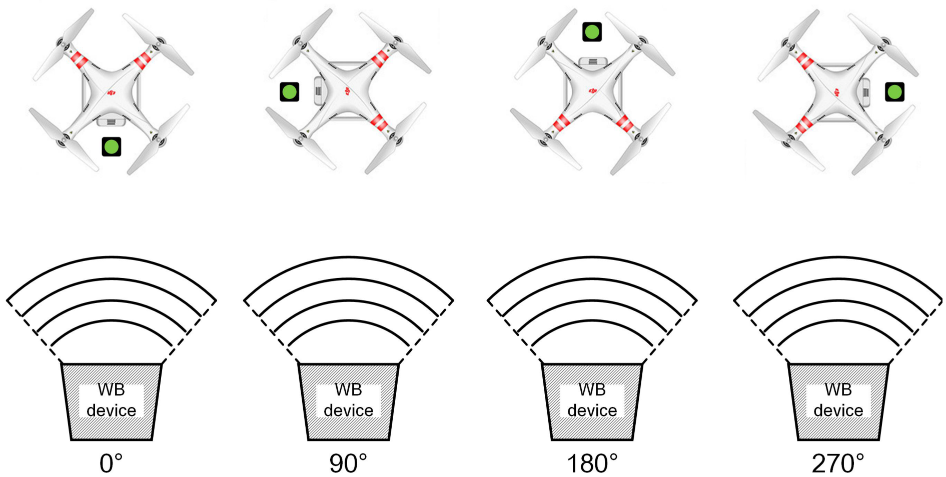

Figure 5. Radiation direction.

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1. Results

In experiment, since the output power of the WB radiation can be modulated, we changed the electric field at the target UAV by changing the distance between the WB oscillator and the UAVs. The distance between them usually ranges from 40 m to 9 m. In the experiment, some results have been observed as below.

1) The photograph system was disturbed by microwave, which results in the abnormal display of the pictures on the mobile phone as in Fig. 6.

Figure 6. Abnormal display of the pictures on the mobile phone.

2) The communication between remote control or mobile phone and UAV was cut off by the WB radiation, and only restarting the UAV can realize reconnection.

3) Abnormity of the sensor.

4) UAVs shook or their altitude varies. When the UAV was radiated, it may go up or down and return to its original position. This phenomenon usually means that the UAV was close to be shot down.

5) UAVs were shot down by the microwave. As in Fig. 7, there are three separate moments of the UAV. At moment 1, the UAV flights safely. When it is radiated, the UAV is shot down; moment 2 is the beginning of the falling; and moment 3 is almost falling on the ground. The direction of the UAV at moment 3 is different from that in moment 2 because the UAV rolled over in the falling process.

Figure 7. UAVs were shot down.

6) UAVs burned down. The experiment was carried out in a microwave unreflected chamber. When the distance between UAVs and the radiation antenna is close enough and the electric field at the UAV strong enough, the UAV may burn down, and some hardware modules may be destroyed. The results are shown in Fig. 8. Usually, when this phenomenon appears, the smell can be detected on the scene, and the UAV can no longer fly. The burned UAVs have been delivered to the testing organization, and three reports have been fed back as in Table 4. It needs to be noticed that some other damages resulting from collision between UAVs and something in the environment are not provided here.

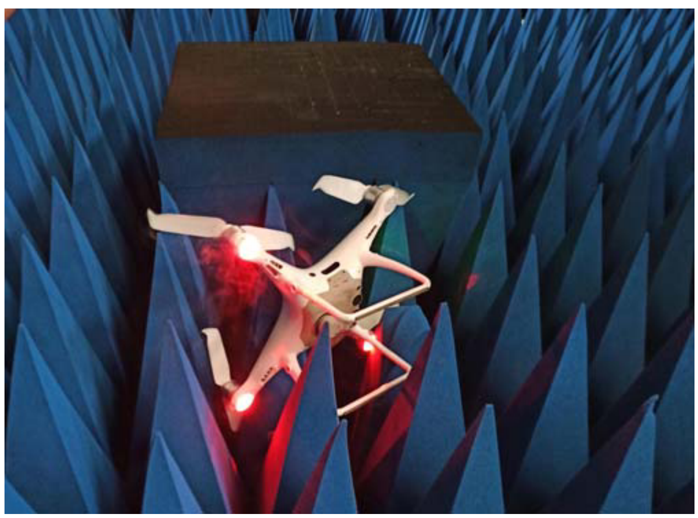

Figure 8. UAVs burned down.

4.2. Discussion

After thousands times of experiments and analyzing the experimental data carefully, although the phenomena and susceptibility may be different for different UAVs, some meaningful results can be obtained as below:

- When the UAV is attacked by strong electromagnetic pulse, the flight control system works abnormally under the electric field intensity of less than 10 kV/m, and sends wrong control commands to the steering gear, resulting in many violent and rapid changes in the flight course in a short time.
- Although the onboard electronic equipment such as satellite navigation module, gyroscope, accelerometer, barometric altimeter, and communication link may work abnormally due to the

Table 4. Testing results of the damaged UAVs.

Model of the damaged UAV	Testing results
Mavic Air	The power board burned down, which results in abnormity of the electric control system.
Mavic Air	The inertial measurement unit (IMU) was destroyed and M3 motor burned down, which resulted in breakdown of operation and flight control system.
Mavic Air 2	M1 and M4 motors burned down, and M2 abnormally sound. Besides, the UAV could not take off owing to the electric control component brook.

attack of strong electromagnetic pulse, even if the data of these electronic equipment is abnormal or even damaged, it will not directly cause the UAV to lose control of flight or even crash.

- The UAV can only be shot down or burned under the highest electric field. As the distance between UAV and radiation antenna was shortened and the electric field at the UAV increased, 1) to 4) phenomena may appear at random, but 5) or 6) are the last to occur.
- The radiation result is related to the radiation direction. When the electric field at UAVs was the same, the WB oscillator's radiation at a particular direction can lead to radiation result, and these phenomena would not occur at the other directions. In addition, as the distance decreased, and the electric field was improved, the radiation result may appear at any direction.
- The electric quantity of the UAV's battery will influence the radiation result. When the distance between UAV and radiation antenna was the same, in other words, the electric field at UAV was the same, and the radiation direction was the same, the UAV whose battery was close to full power (larger than 75%) was more likely to be affected by the WB microwave radiation.
- When the electric field and radiation direction were the same, more pulses at one shoot with certain PRF were more likely to result in server results than monopulse radiation and less pulses with the same PRF. The single pulse cannot shoot the UAV down, but the 5 pulses with 25 Hz can, which seems just a statistical effect. But in experiment, with 25 Hz PRF, 250 pulses shot the UAV down, which was not shot down by 100 pulses. In statistics, the probability of 100 pulses is very close to that of 250 pulses; therefore, this result is more likely to be the energy accumulation effect.
- Phantom 4 is easier to be shot down, and the needed electric field intensity is about 10 kV/m. Meanwhile, to shoot Mavic Air and Mavic Air 2 down, the susceptibilities are about 20 kV/m and 30 kV/m, respectively. Since the electric field is different, the Phantom usually flies everywhere and falls in the falling process, but Mavic Air and Mavic Air 2 will fall immediately in the process.
- The rotor motor, electric control system, and IMU are easier to burn down. All the burned UAVs were destroyed at these parts.

The reason for the interruption of communication between UAV and ground control station is that the frequency-hopping spread spectrum adopted by the 2.4 GHz communication mode uses pseudo-random code sequence for frequency shift keying, so that the carrier frequency is constantly hopping, and the spectrum is expanded [18]. When the communication frequency coincides with that of the WB oscillator, the data link is disconnected, and the aircraft cannot be connected with the ground control station [19].

The jitter of UAV is due to serious interference of attitude detection module and attitude settlement control module. In the attitude detection module, acceleration sensors, geomagnetic sensors and gyroscopes are vulnerable to electromagnetic interference. Among them, geomagnetic sensors directly provide the heading angle, pitch angle, and roll angle of the aircraft, which plays a key role in the attitude control of the aircraft. In the attitude settlement control module, the core is

STM32 single chip microcomputer, which executes the PID control algorithm program in the flight process. Electromagnetic interference and external electrical noise are formed under the action of strong electromagnetic field on the surface of electronic circuit, which makes the integrated circuit malfunction or function failure. For example, when the signal voltage or current reaches the interference threshold due to electrical noise, the core processing chip will not be burned, but the logic value of the output will change, that is, from "0" to "1" or vice versa, resulting in bit error. The error code of key signals may lead to opposite instructions or even unrecognized instructions, which may be fatal for aircraft flight. After the fault or reset of the circuit, the induced voltage will disappear or return to normal.

The direct cause of aircraft overturning and crash is that the lift torque provided by the four motors is unbalanced, and there is a huge torque in a certain axis. Even if the attitude balance control of the aircraft itself works normally, the attitude of the aircraft cannot be adjusted, resulting in aircraft overturning and crash. The electronic governor on UAV mostly uses a field effect transistor (FET) to drive brushless motor. The FET is connected with a pull-down resistor to ensure that the input signal of the FET is either high or low, and there is no uncertain third state. Then the motor has only two states, either rotating or not rotating. The FET is easily damaged in the environment of high-power electromagnetic pulse. Once the electronic governor is disturbed or damaged, the aircraft loses its balance and immediately capsizes and crashes.

When strong electromagnetic field acts on the ESC and semiconductor integrated circuit, the thermal effect of HPM will appear. In a wide frequency range, heated semiconductor device materials will exhibit resonance absorption and related dielectric constant changes due to a variety of molecular vibration modes. At this time, the local concentration of current may occur in the electronic component, which will increase the temperature in some areas. If the temperature reaches the intrinsic temperature of the electronic component material, the collector junction depletion layer will disappear, and the current will rise sharply, which in turn will lead to the continuous rise of the temperature at this point. When the melting point of the device material is reached, the material begins to melt, and the device is permanently invalid. The strong electric field on the surface will also cause dielectric breakdown between MOS gate oxide and metallized lines, resulting in circuit failure. If the processing chip of the ESC is burned, the aircraft will directly lose power and balance conditions, resulting in overturning and crash [20, 21].

From above results, the electric field in the electromagnetic environment should be much less than 10 kV/m to ensure the safety of the UAVs and make them to complete diversified tasks. In other words, the civilian UAVs should escape the strong WB electromagnetic environment.

5. CONCLUSION

The susceptibility of the civilian UAV to WB high power electromagnetic radiation was discussed in the paper. The $350 \sim 390$ MHz high power radiation source was used to radiate the three models of civilian UAVs (Phantom 4, Mavic Air and Mavic Air 2). Considering that the ground reflection would influence the electric field at the UAVs, the on-line testing antenna was employed to get the electric field precisely. Besides, in experiment, the amplitude of the electric field can be changed by adjusting the distance between UAVs and radiation antenna. As UAVs were radiated by the microwaves, some phenomena have been observed, and some meaningful laws have been obtained from the experimental data. For example, the microwaves with the electric field of 10 kV/m, 20 kV/m and 30 kV/m can shoot Phantom 4, Mavic Air and Mavic Air 2 down, respectively. Comparing the radiation susceptibility to multiple-pulse with that to the monopulse, it can be proved that there is energy accumulation effect for the radiation susceptibility. And the rotor motor, electric control system, and IMU were easier to burn down. Therefore, the electric field much less than 10 kV/m is safe for civilian UAVs to fulfill their tasks. Meanwhile, some methods need to be figured out to strengthen sensitive devices.

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