Microwave Radar Sensors for Active Defense Systems

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Abstract — **Modern anti-armor missiles represent enormous threat for any military vehicle. Simple hand-held missiles are able to penetrate 300 mm, more sophisticated missiles up to 1000 mm of the best steel armors. Active defense methods seem to be promising ways how to face this problem. Systems of active defense are based on sensors able to detect and measure approaching threat missile and generate signals that activate a suitable counter-measure. The paper describes several different designed radar sensors tested in active defense configurations. This concerns narrowband sector sensor, "microwave curtain" and a new wideband sensor with a distance measurement capability. All practical tests were performed using real missiles at army shooting ranges.**

Index Terms — **Active defense, missile detection and measurement, microwave curtain, wideband radar sensor.**

I. Intoduction

Protection of military vehicles based on standard steel armors seems to be less and less effective. The main reason for that is an easy availability of missiles that are able to destroy even very thick armors. For example, hand-held and low cost (under 60 USD) cumulative missiles are able to penetrate 300 mm thick armors, 1000 mm long kinetic energy missiles are able to destroy up to 1000 thick armor. Systems of active defense are based on sensors capable of detecting the threat missiles and activating the suitable counter-missiles. The latter should destroy, deactivate or at least deflect the threat missile. Military vehicles equipped with the active defense systems are supposed to be lighter, faster, easier to maneuver, cheaper and, above all safer.

Usually, the detection sensors are based on microwave radars, optical detection sensors or lidars. Optical systems can provide the most exact information on the position of the missile, but suffer from a low sensitivity in presence of a heavy dust or rain. That is why the majority of active defense systems employ microwave radar sensors as primary or at least secondary detection sensors. Generally, microwave radars are able to detect these missiles and to measure their radial speed and, in some cases, also their distance or track their trajectory.

Radar sensors described in this article were designed to detect and measure especially the two the most dangerous types of anti-armor missiles. This concerns PG-7 cumulative missiles and 30x173APFSDS kinetic energy missiles, see Fig. 1. These missiles were also used in all practical tests.

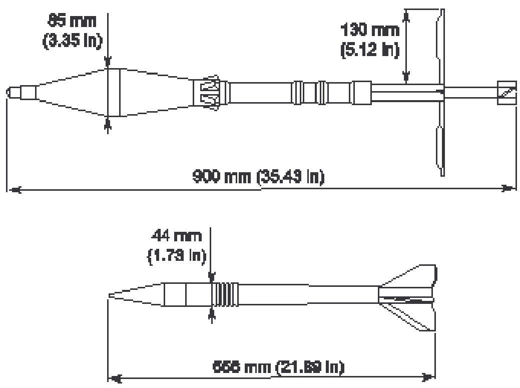

Fig. 1. Two types of anti-armor missiles tested – cumulative missile (upper figure) and kinetic energy missile (lower figure).

More detailed description of parameters and behavior of these missiles can be found, for example, in [1] and [2]. For the detection task they represent relatively small metallic objects flying with a speed between 150 m/s (cumulative missiles) and 1700 m/s (kinetic energy missiles). Values of their radar cross section (RCS) are relatively low ($10^{-2} \div 10^{-3} m^2$ in the X-band) and strongly frequency dependant, see Fig. 8.

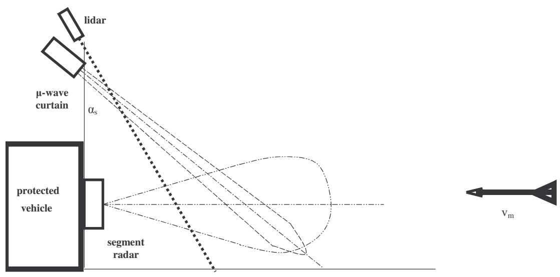

Fig. 2. Set of sensors used in tested active defense system

In the active defense systems many different scenarios are used. The one used in this paper supposes the detection and measurement of the threat missiles in a relatively near zone (20 to 30 m) and activation of the suitable counter-measure in a very close distance (around 2 m) from the protected vehicle. For this scenario, two basic types of sensors are required, see Fig. 2. The sector sensors monitor wider space angles and detect as well as measure any approaching missile. The main purpose of these radars is to prepare other sensors for the arrival of the threat missile and to perform its preliminary identification. The second set of microwave sensors should act as a microwave “curtain”. In fact they detect missiles flying through a definite plane. The aforementioned sensor, together with the lidar, should provide information on the exact position of the missile with respect to the protected vehicle.

II. Narrowband Sector Sensor

Narrowband sector radar was the first designed and realized test sensor. Its block diagram can be seen in Fig.3.

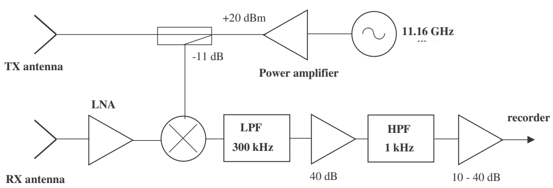

Fig. 3 Block diagram of test narrowband sensor

The 11.16 GHz operating frequency corresponds to the local maxima of both RCS plots, see Fig. 8. The sensor employs two identical 3.5 dBi patch antennas with a circular polarization or 10 dBi antennas with linear polarization. The test system was built in a strong metallic box that can withstand occasionally rough conditions at army shooting ranges, see Fig. 4.

Fig. 4 Test narrowband sensor

A series of practical measurements at army shooting ranges was performed. The cumulative missiles were shot off a simple launcher standing 33 m apart from the sensor and 43 m from the target. Examples of the measured signals in the time domain and calculated spectrogram can be seen in Fig. 5 and Fig. 6.

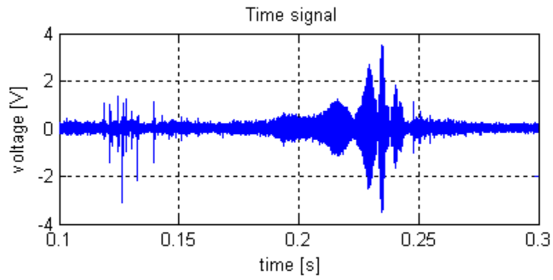

Fig. 5 Flight of cumulative missile – measured signal in time domain

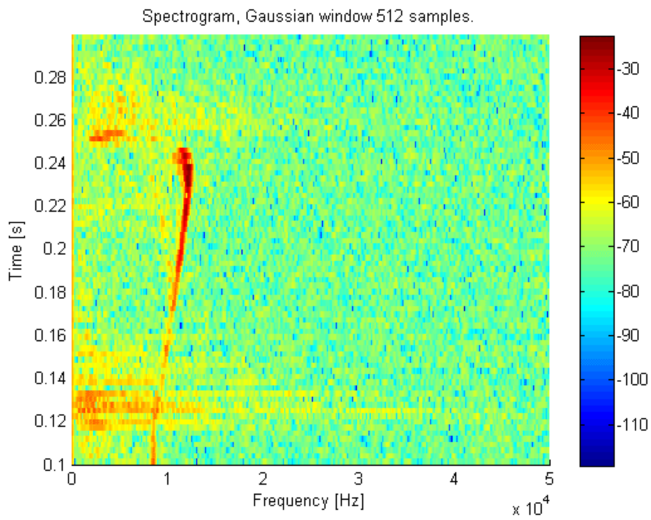

Fig. 6 Flight of cumulative missile – calculated spectrogram

The spectrogram shows the initial Doppler frequency around $f_d \approx 9\,kHz$, which corresponds to the velocity of the missile leaving the launcher. After a short time, the reactive engine is activated, and the velocity of the missile increases. The Doppler frequency drops to zero when the missile flights directly above the sensor. The measured peak Doppler frequency $f_d \approx 12\,kHz$ is in harmony with the expected velocity of this missile $v_m \approx 150\,ms^{-1}$. The measurement also shows a relatively strong parasitic signal caused by an acoustic wave vibrating sensor antennas. These interferences will be suppressed by better mechanical construction and by digital signal processing.

The kinetic energy missiles were shot off the standard long tank barrel. The recorded signals show Doppler frequency $f_d \approx 120\,kHz$, which is sufficiently in line with the expected velocity of this missile $v_m \approx 1700\,ms^{-1}$. The detection range using 10 dBi antennas and optimum operating frequency is, again, around 30 m.

The measured results prove that narrowband radar sensors can be used for detection and measurement of anti-armor missiles. The most significant problem is represented by strong dependences of both radar cross-section and detection ranges on the frequency and type of the missile. These phenomena are described and explained in more detail in [1]. Other measurements using the 3.5 dB antennas are presented in [2].

III. Microwave Curtain

In order to verify possibilities of the microwave "curtain", the narrowband sensor was equipped with two antennas designed according to [3]. Their radiation patterns show approx. 70° beam-width in a horizontal plane and 15° in a vertical plane, see Fig. 7.

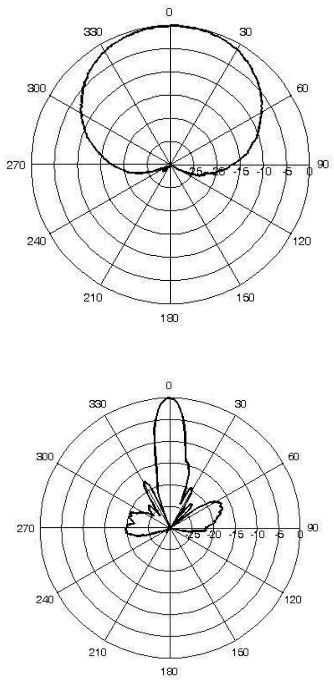

Fig. 7 Radiation patterns of antennas used in the "microwave curtain", horizontal plane (top), vertical plane (bottom)

The main purpose of this "curtain" is to generate electric signals that can be used for activation of the counter-missile when the thread missile intersects a definite plane in a vicinity of the protected vehicle. The example of the measured output time-domain signals is depicted in Fig.7. For generating signals able to activate the counter-measures, digital filtering and thresholding is performed.

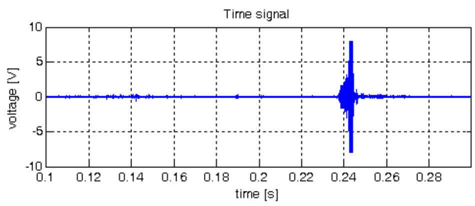

Fig. 7. Output signals of "microwave curtain"

Microwave curtain has been repeatedly used for efficient activating of counter-missiles.

IV. Wideband Sector Sensor

As it has been already mentioned, the frequency dependences of radar cross section *RCS* (see Fig. 8) and consequently also of radar detection range, represent the main problems of detection and measurement of anti-armor missiles.

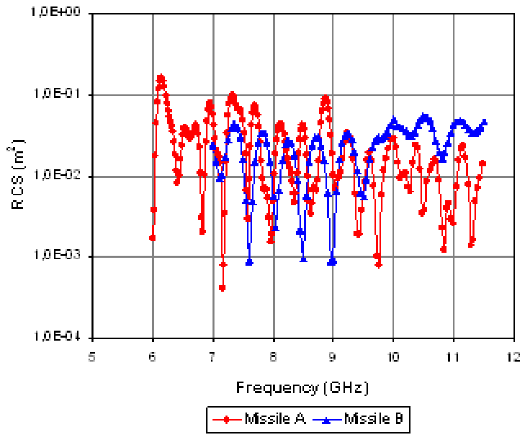

Fig. 8 Radar cross-section *RCS* as function of frequency and type of missile (A is cumulative missile, B stands for kinetic energy missile)

The 11.16 GHz operating frequency of the narrowband sensor was chosen, this corresponds to a frequency point, where plots of *RCS* values of both types of missiles used during test have their local maxima. For another type of missile, the detection range of this narrowband sensor can fall under a value required for a proper operation of the active defense system. This phenomenon was verified in [2]. Consequently a new wideband sensor was designed and realized, see Fig. 9.

The sensor employs frequency hopping (FH) techniques and a double-side band operation. The direct digital synthesizer (DDS) generator generates short frequency hops in the 100 – 300 MHz frequency band. The DDS signals are up-converted using a 11 GHz local oscillator and a double-balanced mixer. The resulting output signal has two 10.7 - 10.9 GHz and 11.1 - 11.3 GHz frequency bands with the carrier attenuated by the balanced up-conversion, see Fig. 10. The received reflected signal are amplified by LNA and processed by a image-reject mixer which separates signals corresponding to the lower and upper side-bands. A couple of IF mixers converts the separated signals to the baseband. After A/D conversion, the FPGA based circuit performs digital filtering and signal processing.

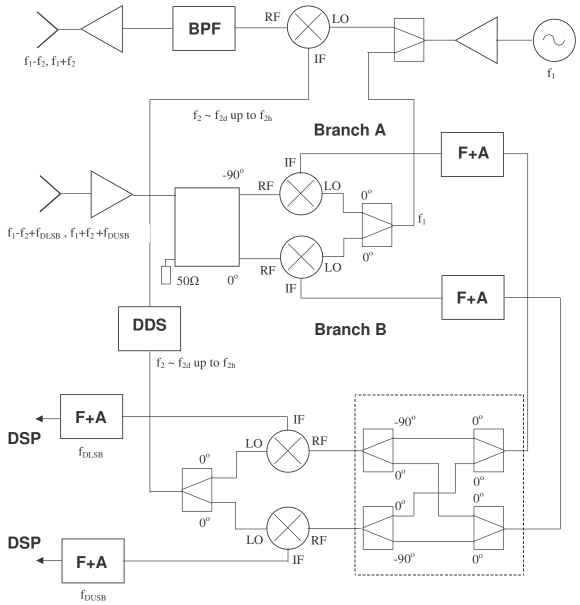

Fig. 9 Block diagram of wideband sensor

Fig. 10 shows transmitter output spectrum recorded using the spectrum analyzer with help of the MAX HOLD function.

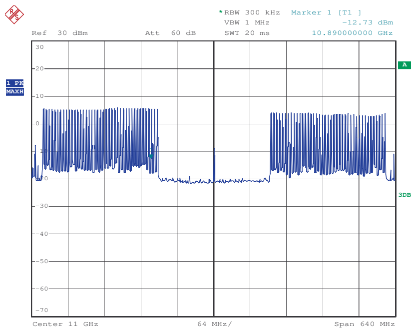

Fig. 10 FH transmitter output spectrum

Such frequency range can guarantee that all types of missiles should be "visible" with approximately the same detection range.

The designed wideband measurement procedure also generates enough information for calculation of the distance of the missile with respect to the sensor. The $\Delta\varphi$ phase difference of baseband signals corresponding to upper and lower side-band outputs can be expressed as:

$$\Delta\varphi = -4\pi f_2 (1 - \frac{2v_r}{c})\tau$$

Where f_2 stands for the DDS generator frequency and v_r represents the radial part of the velocity of the missile. Since $v_r << c$, the time delay τ and distance d of the missile with respect to the sensor can be expressed as:

$$\tau \cong \frac{-\Delta\varphi + 2k\pi}{4\pi f_2}$$

$$d = \frac{c\tau}{2}$$

The k parameter that describes the phase ambiguity can be set by measurements on more frequencies. A new version enabling substantially wider hopping range is under development.

V. Conclusion

Microwave radars seem to be very good candidates for sensors applicable in the active defense systems. Even simple narrowband sensors are able to detect approaching missiles and measure their speed. The main problem is represented by the sensitivity of their detection range on the operational frequency and type of the approaching missile. That is why a new type of wideband sensors will have to be used. The narrowband sensors can also be used as a "microwave curtains" that detect flights of the thread missiles through a certain plane and generate signals used for activation of suitable counter-measures. Practical tests show very good behavior of radar sensors in the above-described active defense arrangements.

References

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