Microwave Radar Sensor for Detection of Anti-Armour Missiles

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***Abstract* — Anti-armour missiles represent one of the biggest threads for any military vehicle, both in a standard combat or e.g. during UN humanitarian actions. Millions of extremely dangerous missiles, able to break-through tank armour-plates, are widely spread even in the most dangerous areas of the world. Standard lighter vehicles or helicopters by themselves do not have any chance against them. That is why more efficient methods of defense are under development. Active defense methods are based on detecting the thread missiles and activating an efficient counter-measure. Presented paper describes parameters of two the most dangerous missiles and calculates parameters decisive for their detection in microwave frequency region. Practical measurements confirm calculated detection parameters.**

***Index Terms* — Anti-armour missiles, missile detection and tracking, Doppler radar, radar cross section, wideband radar.**

I. INTRODUCTION

There are two basic types of probably the most dangerous anti-armour missiles, the kinetic energy missiles and the cumulative missiles, see Fig. 1.

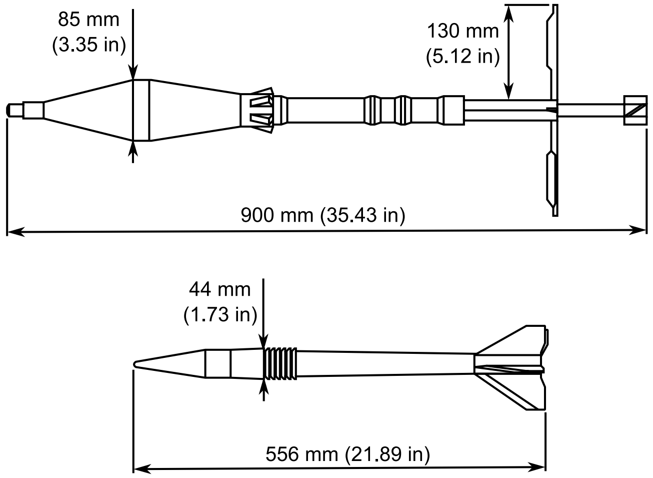

Fig. 1. Analyzed anti-armor missiles – the cumulative missile A (up), the kinetic energy missile B (down).

The cumulative missiles consist of a head with an explosive stuff placed around a small copper cup and a small reactive engine. The missile can be fired of relatively short and simple man-carried launchers. The reactive engine accelerates the missile to velocity v_m ranging from 100 m/s up to 600 m/s. When hitting the target, the explosion presses the copper cup from outside and form an approx. 10 mm thick copper rod with an extreme velocity around 10000 m/s. This relatively small and light man-carried missile is able to break through up to 350 mm of the best steel armour-plate. Nowadays, approx. 20 millions of cumulative missiles are expected to be spread worldwide, very often they are used by terrorist groups in the most dangerous 3-rd world countries.

The kinetic energy missiles are formed by a relatively thin wolfram arrows and usually are fired of standard long barrels (typically from tanks). Typical velocity of these missiles is 1500 to 1700 m/s and their kinetic energy is so high that they are able to break through as thick steel armour-plates as is their length. A 500 mm long kinetic missile used in practical tests is able to destroy 500 mm thick armour, a modern 1000 mm long kinetic energy missile can break through 1000 mm of the best armour.

Standard steel armours are heavy, expensive and vulnerable. Enlarging their thickness seems to be both inefficient and impractical. That is why new concepts of defense are under development. Nowadays, substantial effort is devoted to development of methods of an active defense. These methods are based on detection of thread missiles and activation of a suitable counter-measure able to destroy, deactivate, break or at least deflect the thread missile. Military vehicles equipped with an active defense system should be lighter, faster, cheaper and above all more safe.

II. DETECTION RANGE

Detection of thread missiles can be performed in an optical or microwave region. Simple microwave radar sensors can detect the missiles and measure their radial speed. More complex radar systems can also measure distance of the missiles from the sensors or track the missile. Measurement of the distance or tracking are often complicated by very high missile speeds and relatively short detection ranges. Between detection of the missile and activation of the counter-measure usually only units or tens of milliseconds are available.

There is a number of different active defense scenarios, each of them requires a definite range of detection, ranging usually from several meters up to hundreds of meters. Maximum measurement distance of any radar sensor or system is defined by a well-known radar formula (1):

$$R_{max} = \left[\frac{P_t G_t G_r \ RCS \ \lambda^2}{(4\pi)^3 SNR_{min} k T_s B_e} \right]^{\frac{1}{4}} \qquad (1)$$

In this formula P_t represents radar transmitted power, G_t and G_r stand for gains of transmitter and receiver antennas, RCS is the radar cross-section of the target, λ is the operating wavelength, SNR_{min} represents a minimal value of signal-to-noise ratio that enables the receiver to measure the moving object correctly, k is the Boltzmann's constant, T_s represents radar system noise temperature and B_e stands for an effective system bandwidth. A closer analysis of the radar equation shows that, in this case, there are not many possibilities how to extend the detection range.

For this application, the transmitted output power cannot be too high so that the radar does not attract attention to the protected vehicle. Antenna gains correspond to antenna beam widths. Therefore, antennas that should monitor wider angles cannot have high gains. The standard value of the SNR_{min} parameter is usually between 10 and 20 dB and it is usually difficult to construct a radar receiver with a substantially lower T_s than 1000 K. Measurement of radial speeds of different missiles under different conditions usually requires B_e around 10^4 to 10^5 Hz.

The achievable R_{max} values are, therefore, strongly dependent on RCS values. The RCS is a parameter that describes an ability of the measured object to reflect wave incident from the radar transmitter back to the direction of the radar receiver. The RCS values of aerodynamically shaped missile front-ends are usually very low (down to 10^{-4} m^2), which can result in very low R_{max} values, especially in the case of required low P_t values and wide-beam antennas.

III. 3D EM FIELD SIMULATIONS OF RCS VALUES

A 3D electromagnetic field simulator was used for calculation of RCS values of the two above described types of anti-armor missiles. Since the missiles are large with respect to wavelengths used, it is not an easy task to perform their computer simulation. The most suitable method for solving electrically large structures is probably the multi-level fast multipole method (MLFMM) [2], which is a modification of the MoM. This method performs a manipulation with Green's functions in such a way that a group of sources that are close together acts as a single source.

The 3D electromagnetic field simulator FEKO equipped with the MLFMM method was used for the required RCS calculations. Both missiles were modeled as a piece of a perfect electric conductor (PEC), their models are shown in Fig. 2 and Fig. 3. The structure was excited by a linearly polarized plane wave and a bi-static RCS characteristic was computed. Values related to backscatter were then examined. The results are shown in Fig. 4.

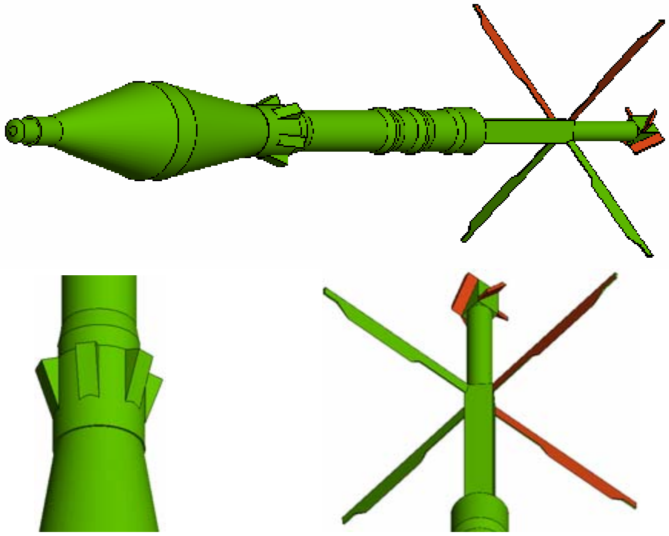

Fig. 2. Model of the cumulative missile A in FEKO.

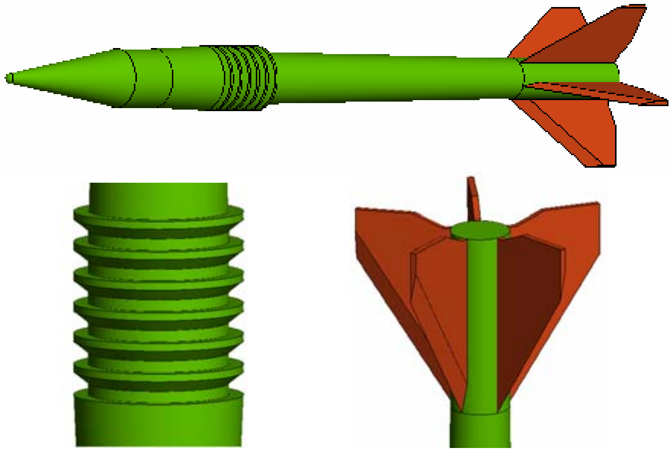

Fig. 3. Model of the kinetic energy missile B in FEKO.

The plot presented in Fig. 4 shows that the frequency dependences of RCS values exhibit significant sharp minima. In the case of the missile B, the minima are nearly equidistantly spaced with a 450 MHz distance between the neighboring two. In the case of missile A, the frequency dependence is more complicated. Distances between adjoining minima ranges from 220 to 420 MHz. The strong frequency dependence of the RCS value can cause that the measurement range at some frequencies can fall below a certain value where reliable reaction of an active defense system can not be guaranteed.

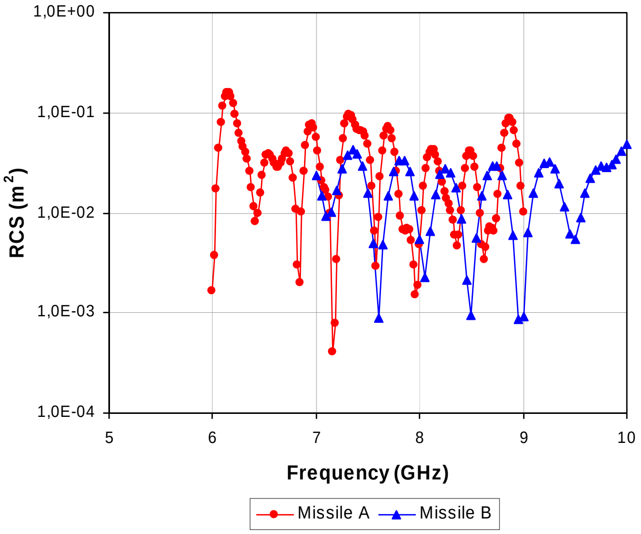

Fig. 4. RCS values of the analyzed missiles.

V. TEST DETECTION SENSOR

In order to verify the calculated RCS values and corresponding detection ranges, and get experiences with detection of both types of the described anti-armour missiles, an experimental detection sensor based on a Doppler radar concept was designed and realized, see Fig.5.

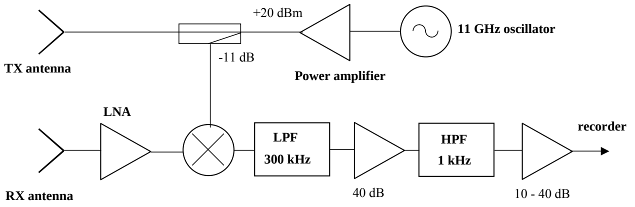

Fig. 5 Block diagram of the test detection sensor

The sensor operates at frequency 11 GHz and consists of a dielectric resonator oscillator, 20 dBm power amplifier, 11 dB directional coupler, low noise pre-amplifier, wideband mixer, 300 kHz low-pass filter, 40 dB low-noise low-frequency amplifier, 1 kHz high-pass filter and 10 - 40 dB additional LF switchable-gain amplifier. The sensor employs two identical 3.5 dBi patch antennas with a circular right-hand and left-hand polarization. The test system was built-in a strong metallic box that can withstand sometimes rough conditions at an army shooting range.

VI. MEASUREMENT RESULTS

A series of practical measurements at an army shooting range was performed. The microwave sensor was placed on a line between the launcher and the target (approx. 300 m apart, the sensor was situated 25 m in front of the target), approx. 1 m below the line of the flight. High sampling rate oscilloscope with a 1 Msa memory recorded the output voltage. Measured spectrogram of the B type kinetic energy missile is presented in Fig. 6.

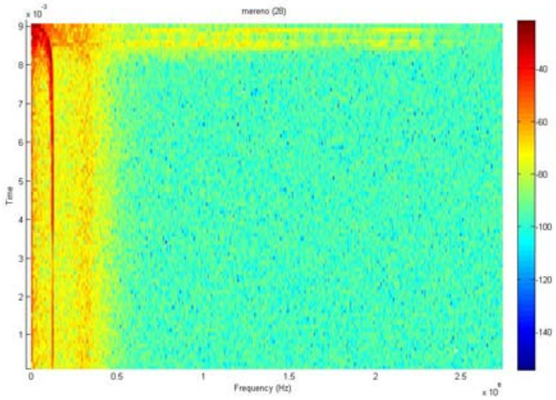

Fig. 6. Measured spectrogram of the B type kinetic energy missile

The sensor detects the missile at the time t = 0 ms and measures its frequency shift $f_d = 120\ kHz$ with respect to the 11 GHz carrier. The calculated velocity of the kinetic missile is $v_m = 1620\ ms^{-1}$, which accords well with the standard velocity of the missile used. At t = 9 ms, the Doppler frequency drops down to zero, which corresponds to the missile flying directly above the sensor (the radial component of $v_m = 0$). Output voltage drops to a low value in a short range around t = 3 ms. This accords with a multipath attenuation caused by a reflections from the ground. Performed measurements of the B type kinetic missile energy provide the following results:

measured missile velocity	1620 m.s^{-1}
calculated detection range	13.9 m
measured detection range	14.5 m

The type A cumulative missiles were measured with a shorter distance between the launcher and the sensor (60 m apart, the sensor was placed approximately in the middle). Recorded results provide substantially lower Doppler frequency $f_d = 9\ kHz$, which again very well accords with supposed velocity of this type of missile $v_m = 150\ ms^{-1}$. Measurement of the detection range was to a high degree obscured by the fact, that at the given distance from the launcher, the sensor also sees the plasma from the reactive engine (active approx. 200 m from the launcher). The plasma can be seen as a very strong wideband noise that obscure the measurement. Performed measurements of the type A cumulative missiles provide the following results:

measured missile velocity	150 m.s^{-1}
calculated detection range	6.8 m
measured detection range	6.0 m

Measured results confirm, that the accuracy of 3D simulations of RCS values is usable for system calculations.

They also confirm the strong RCS frequency dependences and their influence on the detection range. Narrowband detection of missiles cannot provide reliable results and, therefore, wideband methods will have to be used. A detection of plasma from the reactive engine of the A type cumulative missiles in a range up to approx. 200 m from the launcher represents another substantial problem.

VII. WIDEBAND MEASUREMENT

Based on performed RCS simulations and practical measurements, a wideband sensor structure was developed, see Fig. 7.

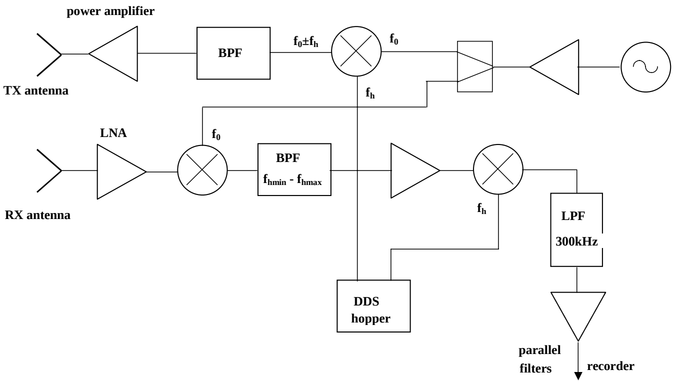

Fig. 7 Block diagram of the wideband detection sensor

The wideband sensor is based on a fast-tunable DDS unit and up-conversion. Transmitted frequencies are hopped in a 500 MHz wide bandwidth, which averages frequency RCS dependencies at the receiver. At the majority of hopped frequencies each missile will be well detectable. The DDS unit can switch its output frequency each 10 µs. Even in the case of the fastest missile, the frequency can be hopped each 16 mm of its trajectory. Output Doppler frequencies can be computer corrected with respect to the instantaneous transmitted frequency. The frequency hopping concept also enables operation of more independent sensors on one vehicle.

VIII. CONCLUSION

Detection and measurement of anti-armor missiles represent a difficult technical problem especially in the case of radar sensors with low output transmitted power and wide-beam antennas. Calculated RCS values show strong frequency dependencies, existing dips can reduce the measurement range below a certain value that is necessary for reliable operation of the sensor. The test microwave sensor operated at 11 GHz was designed and realized. Calculated detection ranges were verified by practical measurements at an army shooting range. The kinetic missile with a relatively smaller 44 mm diameter shows reasonable approx. 15 m detection range. The cumulative missile with a substantially larger 85 mm diameter is detectable hardly from 6 m. The newly designed wideband sensor, based on fast frequency hopping, should overcome the above described RCS problems and should provide more reliable detection of any type of anti-armour missiles. Practical tests will be conducted. An attention will have to be dedicated to analysis of accompanying plasma in detection ranges close to the launcher.

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