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16. ON THE USE OF MICROWAVE SIGNALS AND ACOUSTIC EFFECTS FOR MISSILE DETECTION

16.1. Introduction

Various types of shields and armor are used to protect objects against classic and anti-tank missiles. Another way to defend against missiles is to neutralize (destroy) attacking missile with anti-missile systems [1] or quickly leave the place of fire (hide). Due to the small dimensions of the missile attacking the protected object, its radar cross-section (RCS) is relatively small [2, 3]. This, in turn, influences, among other things, the potential detection capability and the range of its (i.e. attacking missile) detection by the active defense radar [11, 12] and by the microwave sensors [4] that can be installed on the protected objects. The type, shape and dimensions of the attacking missile also determine the method of its neutralization. In turn, the speed of the threatening missile, especially when approaching the attacked object, affects the time requirements for analysis and control units of protection systems. During combat mission, the radar or other sensor of the security system observes the area around the protected object. When an object is detected, the radar (sensor) checks whether it is a missile going towards the protected object. If so, the tracking process starts. When the attacking missile approaches the protected object at a distance considered dangerous, then anti-missile projectiles may be fired at it. At the same time, attempts are made to locate and neutralize (destroy) the shooter or the firing vehicle. The classic way of locating the shooting object i.e. shooter, tank, launcher or cannon is to use active radar [5, 9, 11, 12] of short or medium range.

The launch (shot) is associated with the detonation (explosion) of the propellant, which is accompanied by the strong (loud) sound effects. The speed of propagation of the sound wave v_s in the air is a physical quantity determined by the air temperature T_a. The value of v_s can be approximately determined from the relation (1) [10].

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$$v_s = 331.3 + 0.606 \cdot T_a \text{ [m/s]}, \tag{1}$$

where T_a – air temperature in degrees Celsius (°C).

The above relation shows that, for example, at an air temperature of 20°C, the speed of sound will be approximately 343.4 m/s. The speed of attacking missile depends on its construction and purpose. The phenomena accompanying missiles flying slower than the sound (subsonic missiles) and with velocities greater than the speed of sound in the air (supersonic missiles) were analyzed. In the first of these cases, the fired missile reaches the target later than the sound of the shot. In the second case, however, the missile will reach the target first, followed by the sound wave generated at the moment of the shot. In both of these cases, if the time Δt between the time of arrival of the missile and the moment of catching the sound of the shot is measured, and the missile velocity v_m is determined, it will be possible to estimate the distance d from which the missile was fired. The value of the distance d can be estimated using the formula (2).

$$d = \Delta t \cdot \frac{v_s \cdot v_m}{|v_s - v_m|} \tag{2}$$

Information about the distance d may be useful for taking actions aimed at withdrawing of protected object from the field of fire or trying to locate a hostile object and then neutralize (eliminate) it.

Detection, and even direction finding of the sounds of a shot can be performed using typical methods and devices, such as those described in [6-8]. The detection of missiles passing near the protected object can be carried out by radiolocation methods with the use very complex systems or light microwave detection heads. Microwave devices of this type can detect passing missiles and measure their speed. During the experiments it was found that microwave detection heads could also effectively detect acoustic signals coming from the surrounding space. This may be because the detection head components vibrate under the influence of the sound wave. This problem was discussed in more detail below in Section 2.

16.2. Structure and principle of operation of an active microwave detection head

An example of the block diagram of an active microwave detection head was presented in Fig. 1. The main parts of this device are transmitting and receiving channels.

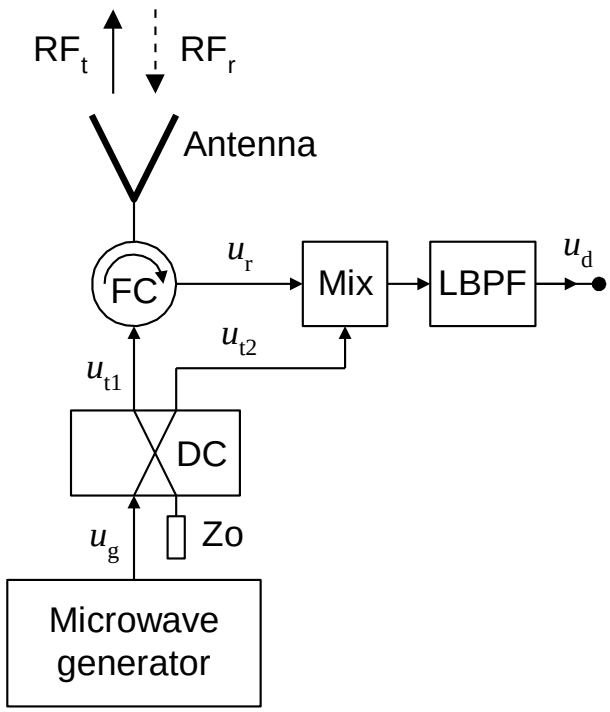

Fig. 1. Scheme of an active microwave detection head working with the continuous wave signal
Rys. 1. Schemat aktywnej, mikrofalowej głowicy detekcyjnej pracującej z sygnałem ciągłym

The microwave generator, the directional coupler (DC), the ferrite circulator (FC), and the antenna form the transmit channel of the detection head. The receiving channel of the detection head consists of an antenna and a ferrite circulator, which are the common elements with the transmitting channel. In addition, the receive channel comprises a frequency mixer (Mix) and a low-frequency band-pass filter (LBPF). The continuous wave (CW) signal u_g from the microwave generator is delivered to the directional coupler (DC). In this device, the DC works as a splitter that distributes the u_g signal into two components u_{t1} and u_{t2} of equal strengths. The u_{t1} signal is fed to a ferrite circulator (FC). The ferrite circulator separates the transmit and receive channels that cooperate with a common transmit-receive antenna. The microwave signal from the output of the ferrite circulator is emitted into the air through the antenna. The emitted signal is described as RF_t in the Fig. 1. The received signal marked as RF_r in the Fig. 1 is the RF_t signal, but reflected by an object situated in front of the microwave detection head. The microwave signal RF_r reaching the antenna is fed to the ferrite circulator and then appears as a signal described as u_r at the input port of the frequency mixer. A bandpass filter of low-frequencies, but greater than zero (LBPF), is connected after the mixer. A low-frequency u_d voltage is obtained at the LBPF output port. When the reflecting object is moving with velocity v, the carrier frequency f_r of the RF_r signal differs from the frequency f_t of the RF_t signal. The difference in these frequencies is called the Doppler frequency shift [5] and is denoted as f_d. The value of f_d is described by the formula (3) given for example in [5].

$$f_{\mathrm{d}} = \frac{2 \cdot v}{c} \cdot f_{\mathrm{t}}\,, \tag{3}$$

where: v – object speed, c – speed of electromagnetic wave in the air, f_{t} – frequency of transmitted microwave signal.

Due to this phenomenon, the voltage u_{d} has the shape of sinusoidal type with a frequency f_{d} and thus contains information about the object velocity v. As a consequence, the microwave detection head shown in Fig. 1 can be used to detect moving objects and determine their speed. The determination of the velocity v is based on the formula (4) obtained from the transformation of the relation (3).

$$v = \frac{c}{2} \cdot \frac{f_{\mathrm{d}}}{f_{\mathrm{t}}} \tag{4}$$

The value of the frequency f_{d} is determined using the fast Fourier transform (FFT) of the voltage u_{d} obtained at the output of the LBPF filter (Fig. 1).

During various experiments, it has been noticed that a low-frequency signal u_{d} also appears when hitting or shaking the microwave detection head, especially its antenna. This property results from the fact that the microwave elements, including antenna, are subjected to vibrations when acoustic signals impact on the microwave detection head. As a result, signals modulated with acoustic frequencies, reflected inside the antenna and from local objects, reach the receiving path of the detection head. Thus, if the shaking is caused by acoustic waves (vibrations) propagating through the air, the microwave detection head can work as a microphone and may be called a microwave-acoustic microphone or microwave-acoustic sensor. Such properties of the microwave detection head are very useful, e.g. for detecting missiles, the launching of which is accompanied by a loud acoustic firing signal.

16.3. Results of subsonic missile detection tests

The experiments with a subsonic missile were carried out in the scenario shown in Fig. 2.

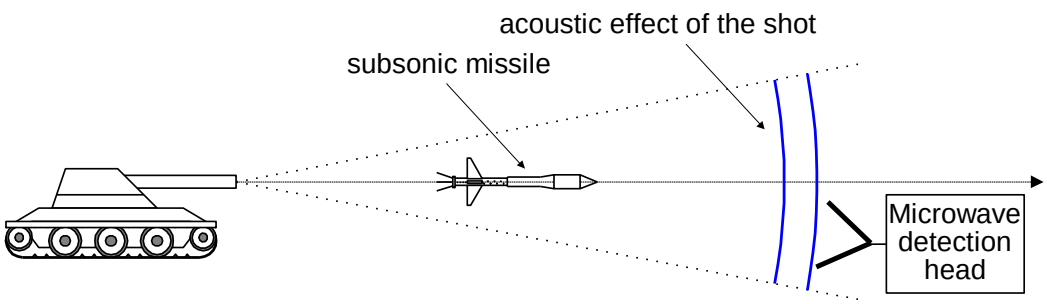

Fig. 2. Illustrative scenario of the subsonic missile detection tests
Rys. 2. Poglądowy widok stanowiska do badań wykrywania pocisków poddźwiękowych

The subsonic missile was fired using launcher. The microwave detection head was placed very close to the trajectory of the missile. The antenna of the detection head was aimed almost parallel to the missile trajectory. The u_d signal was recorded with a fast acquisition unit. The registration process was synchronized with the shot.

The results of the chosen two tests were presented in Figs 3 and 4.

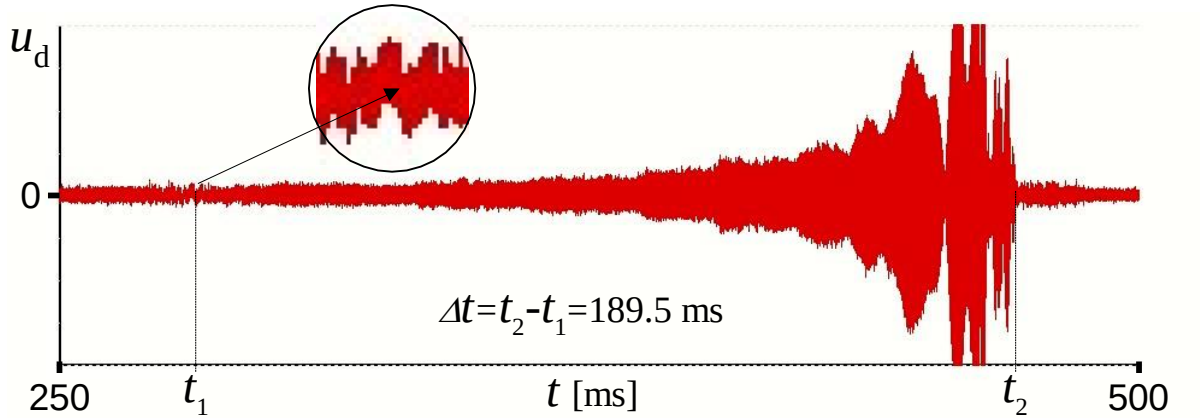

Fig. 3. Microwave detection head output signal u_d versus time recorded while observing a subsonic missile (test PD03)
(t_1 – the moment when the acoustic effect of the shot reaches the microwave detection head, t_2 – the moment when the flying missile passes the microwave detection head)

Rys. 3. Sygnał wyjściowy u_d mikrofalowej głowicy detekcyjnej w funkcji czasu, w warunkach obserwacji pocisku poddźwiękowego (próba PD03)
(t_1 – chwila, gdy akustyczny efekt wystrzału dociera do mikrofalowej głowicy detekcyjnej, t_2 – chwila, gdy lecący pocisk mija mikrofalową głowicę detekcyjną)

As one can see, the acoustic effect of the missile launch first reaches the detection head (moment t_1). The signal at this moment is very weak, but its shape is very clear and characteristic in both Figs 3 and 4. The graph of voltage u_d before and just after the t_1 moment has a noise-shape. This is the internal noise of the detection head. In the middle of the time interval between t_1 and t_2, amplitude of the voltage u_d begins to increase. Up to the moment t_2, the increase in the voltage u_d level is due to the fact that the detection head receives the signal reflected from the missile at an increasingly shorter distance. Before the moment t_2, the deformations of the u_d plot are visible. They are caused by the shape of an antenna directive pattern and by the reflection of the microwave signal from the ground, because the missile was flying at a relatively low height. The flattening of the graphs in Figs 3 and 4 is an effect of the saturation of the last chain of amplifiers in the receiver channel. This saturation was intentional and allowed to see the weak signals more clearly.

The difference Δt between the times t_2 and t_1 in Fig. 3 (test PD03) is about of 189.5 ms. Sound and missile velocities calculated from formulas (1) and (4) were, respectively, of

342.3 m/s and 198 m/s. Thus, according to the relation (2), the distance to the shot point was about of 89 meters.

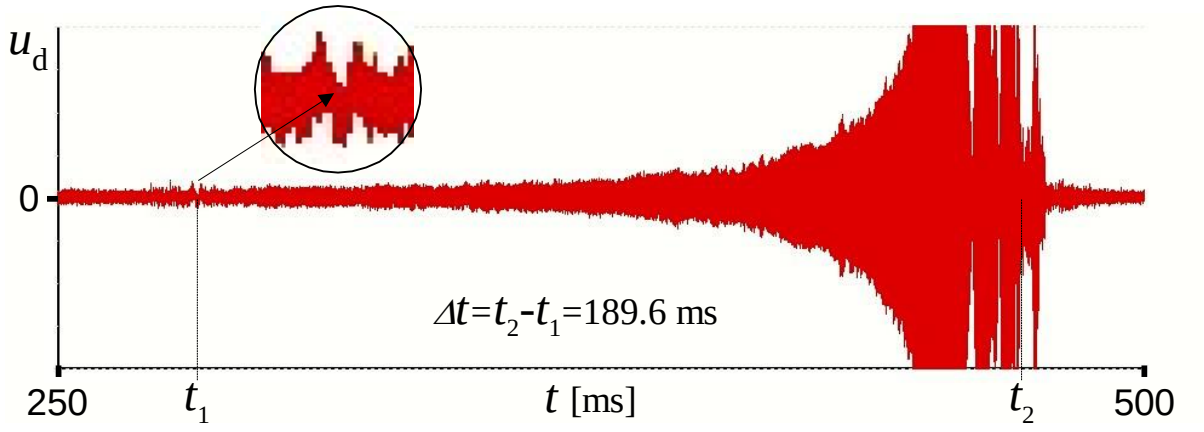

Fig. 4. Microwave detection head output signal u_d versus time recorded while observing a subsonic missile (test PD05)
(t_1 – the moment when the acoustic effect of the shot reaches the microwave detection head, t_2 – the moment when the flying missile passes the microwave detection head)

Rys. 4. Sygnał wyjściowy u_d mikrofalowej głowicy detekcyjnej w funkcji czasu, w warunkach obserwacji pocisku poddźwiękowego (próba PD05)
(t_1 – chwila, gdy akustyczny efekt wystrzału dociera do mikrofalowej głowicy detekcyjnej, t_2 – chwila, gdy lecący pocisk mija mikrofalową głowicę detekcyjną)

In the plot shown in Fig. 4 (test PD05), the difference Δt between the times t_2 and t_1 is approximately of 189.6 ms. Whereas the sound and missile velocities calculated from formulas (1) and (4) were, respectively, of 343.5 m/s and of 197 m/s. Thus, in these conditions, according to the relation (2), the distance to the shot point was about of 87 meters. The difference in the values of the distance d calculated in tests PD03 and PD05 may be due to the insufficient accuracy of the measurement of air temperature T_a and the Doppler frequency f_d.

16.4. Results of supersonic missile detection tests

Very interesting are the signals recorded during tests with supersonic missiles. Experiments with a supersonic missile were performed on the posts shown in Figs 5 and 7. Results of experiments are presented in Figs 6 and 8. In these experiments, the missile reached the plane of the microwave head installation earlier than the acoustic effect of the shot.

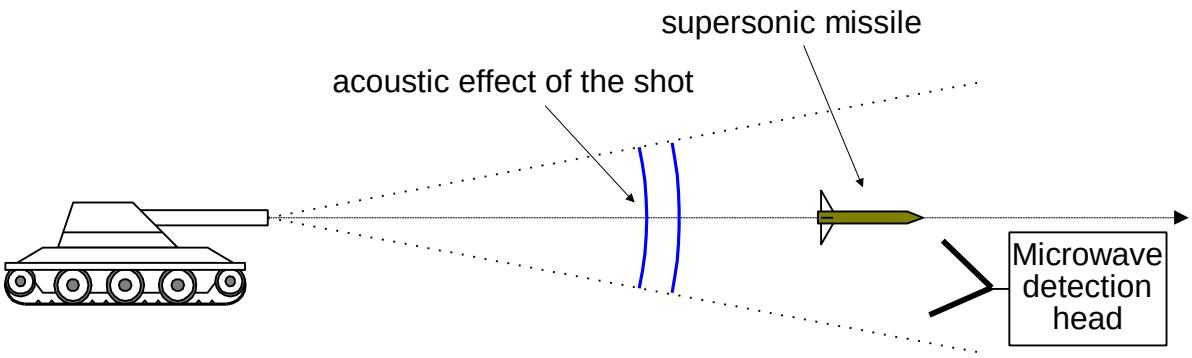

Fig. 5. An example scenario of tests for the detection of a supersonic missile using a microwave detection head with the antenna placed parallel to the missile trajectory

Rys. 5. Przykładowy widok stanowiska do badań wykrywania pocisków naddźwiękowych przy użyciu mikrofalowej głowicy detekcyjnej z anteną umieszczoną równolegle do trajektorii lotu pocisku

The supersonic missile was fired using especial cannon. The microwave detection head was placed very close to the trajectory of the missile, similar to the tests of subsonic missiles. Two cases of experiments were tested. In the first one, the antenna of the detection head was aimed parallel to the missile trajectory. This variant of experiment is shown in Fig. 5. In the latter case, the antenna of the detection head was directed perpendicular to the missile trajectory. This variant of experiment is shown in Fig. 7. The main goal of performing these two variants of experiments was to observe the phenomena occurring during missile flights along the main lobe (beam axis) of the microwave antenna pattern (Fig. 5) and when the missile trajectory is normal to the boresight axis of the microwave antenna main lobe (Fig. 7).

The signal u_d from the microwave detection head was recorded with a high-speed recording device. The acquisition process was synchronized with the shot.

The results of the test with the antenna of detection head directed parallel to the missile trajectory are shown in Fig. 6. Three characteristic segments can be distinguished in the graph presented in this figure.

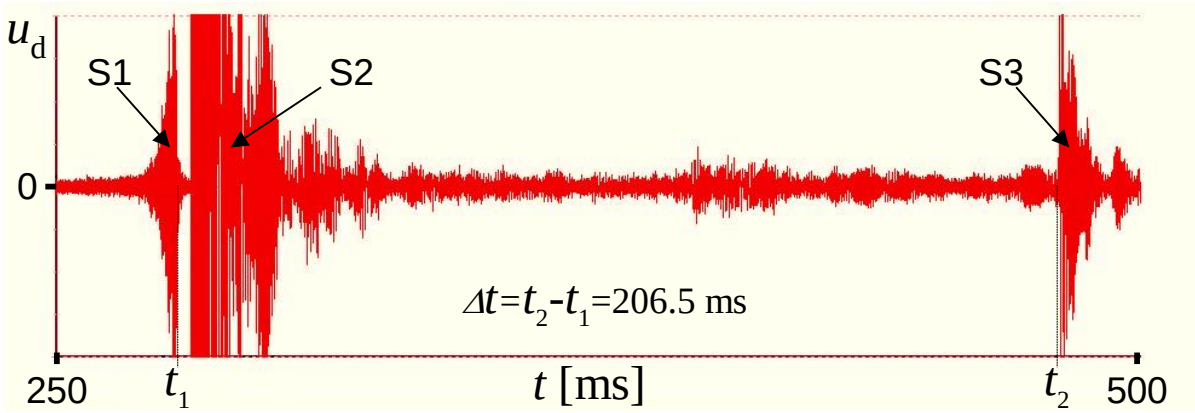

Fig. 6. Microwave detection head output signal u_d versus time recorded while observing a supersonic missile – test ND05R, antenna placed parallel to the missile trajectory
(t_1 – the moment when the flying missile passes the microwave detection head,
t_2 – the moment when the acoustic effect of the shot reaches the microwave detection head)

Rys. 6. Sygnał wyjściowy u_d mikrofalowej głowicy detekcyjnej w funkcji czasu, w warunkach obserwacji pocisku naddźwiękowego – próba ND05R, antena umieszczona równolegle do trajektorii lotu pocisku
(t_1 – chwila, gdy lecący pocisk mija mikrofalową głowicę detekcyjną,
t_2 – chwila, gdy akustyczny efekt wystrzału dociera do mikrofalowej głowicy detekcyjnej)

These segments are marked with the symbols S1, S2, S3. As shown in Fig. 5, when supersonic ammunition is used, the missile reaches the target earlier than the acoustic effect of the shot (missile launch). The plot segment S1 of the voltage u_d is caused by the microwave signal emitted by the detection head and then reflected from the flying missile. This segment lasts approximately 5.3 ms. This time depends on the sensitivity of the receiver channel of the detection head and on the radar cross-section of the flying missile. A time interval of 5.3 ms is sufficient to detect the received signal and estimate its basic parameters. One of these parameters is the frequency f_d. This frequency is used to evaluate the speed of the missile using formula (4). The amplitude of the signal u_d inside the segment S1 increases as the missile approaches the detection head. The time t_1 is the moment when the missile passes the plane of the antenna aperture. Right after the moment t_1 voltage u_d goes to zero, because the missile has just passed the aperture of antenna and the back lobe of the antenna pattern is very low. During the flight of the missile, high pressure forms in front of it, but a vacuum appears after the missile. The air surrounding the trajectory of the missile rapidly fills this vacuum. The filling of the vacuum is accompanied by a loud shock (blast). Such phenomenon can be noticed, for example, when the airplane crosses the sound barrier. Air distortions appearing after the missile cause vibrations of the microwave detection head. These vibrations result in appearing of high value of u_d signal at the output of the detection head. As the missile moves away, the amplitude of the vibrations and the signal u_d decrease. Segment S2 in the graph u_d

in Fig. 6 illustrates this phenomenon. The bandwidth of the signal u_d inside the segment S2 is greater than that in the segment S1. After the time dependent, i.a. on the speed of the missile, the sound effect of the shot reaches the microwave detection head. At this point of time the sound wave generates vibrations of the microwave heads and the high level of the voltage u_d appears again. The segment S3 of the signal u_d plot in Fig. 6 corresponds to this phenomenon. The moment at which the sound of the shot reaches the detection head is marked as t_2 in Fig. 6. The shape of the segment S3 of the signal u_d plot can suggest that the microwave head "sounds" like a knocked bell.

The flattening of the segment S3 of the graph in Fig. 6, as it was for Figs 3 and 4, is an effect of the saturation of the last chain of amplifiers in the receiver channel. This saturation was intended to allow better viewing of the weaker signals within the S1 and S3 segments.

In the plot shown in Fig. 6 (test ND05R), the difference Δt between the times t_2 and t_1 is approximately of 206.5 ms. Whereas the sound and missile velocities calculated from formulas (1) and (4) were, respectively, of 352.5 m/s and of 818 m/s. Thus, in these conditions, according to the relation (2), the evaluated distance to the cannon (missile shot point) was about of 128 meters.

The variant of the experiment in which the antenna of the detection head was directed perpendicular to the missile trajectory is shown in Fig. 7. In this case, the flying missile cuts perpendicularly the main lobe of the antenna pattern, that is, it flies parallel to the plane of the antenna aperture. The results of this variant of experiments are presented in Fig. 8.

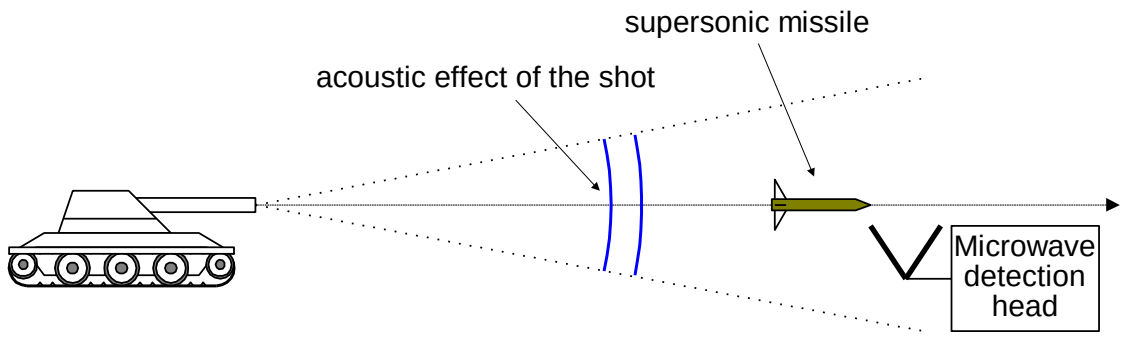

Fig. 7. An example scenario of tests for the detection of a supersonic missile using a microwave detection head with the antenna placed perpendicular to the missile trajectory

Rys. 7. Przykładowy widok stanowiska do badań wykrywania pocisków naddźwiękowych przy użyciu mikrofalowej głowicy detekcyjnej z anteną umieszczoną prostopadle do trajektorii lotu pocisku

Since the main lobe of the antenna used in the microwave detection head under test is symmetrical along its axis, the plot of u_d voltage versus time is also symmetrical when the missile passes near the antenna aperture. This interval of time is marked as segment S1 in

Fig. 8 and is approximately 3.4 ms. The shape of the segment S1 is different in this case than when the antenna of the detection head is positioned parallel to the missile trajectory. It should be emphasized that the frequency f_d of the signal u_d in the middle of the segment S1 is close to zero because the radial velocity of he missile relative to the antenna (phase center of the antenna) is zero when the missile flies directly in front of the antenna. Thus, estimating the missile velocity from the u_d signal segment S1, when the antenna of the detection head is placed perpendicular, is more complicated than when the antenna is aimed parallel to the missile trajectory.

In the graph in Fig. 8, apart from the segment S1, it can be also seen segments S2 and S3. As it was in Fig. 6, the segment S2 of the signal u_d is caused by high pressure before the flying missile and a vacuum after it. Air distortions appearing after the missile cause vibrations of the microwave detection head. These vibrations result in appearing of a non-zero signal at the output of the detection head. In Fig. 8, the signal u_d amplitude in the segment S3 resulting from the sound wave of the shot reaching the detection head, is smaller than in Fig. 6. It was probably caused by a different way of fixing the detection head.

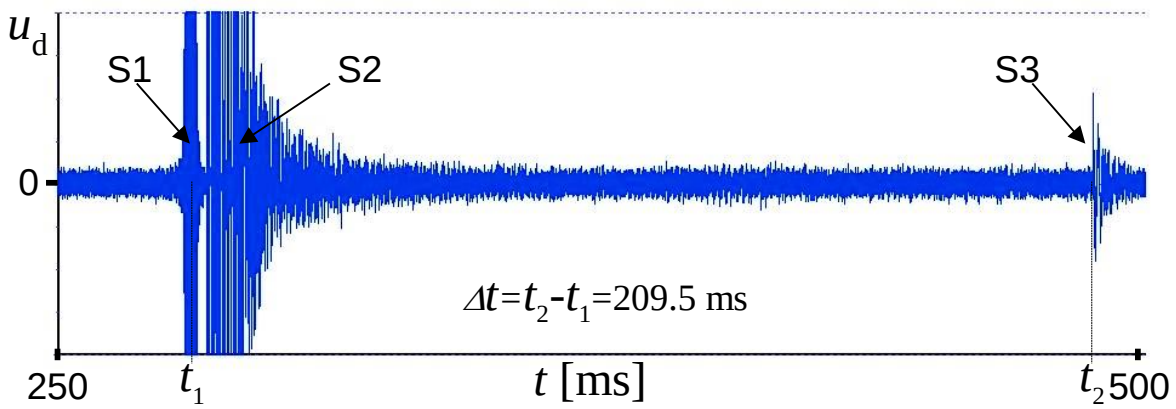

Fig. 8. Microwave detection head output signal u_d versus time recorded while observing a supersonic missile – test ND05P, antenna placed perpendicular to the missile trajectory
(t_1 – the moment when the flying missile passes the microwave detection head,
t_2 – the moment when the acoustic effect of the shot reaches the microwave detection head)

Rys. 8. Sygnał wyjściowy u_d mikrofalowej głowicy detekcyjnej w funkcji czasu, w warunkach obserwacji pocisku naddźwiękowego – próba ND05P, antena umieszczona prostopadle do trajektorii lotu pocisku
(t_1 – chwila, gdy lecący pocisk mija mikrofalową głowicę detekcyjną,
t_2 – chwila, gdy akustyczny efekt wystrzału dociera do mikrofalowej głowicy detekcyjnej)

In the plot shown in Fig. 8 (test ND05P), the difference Δt between the times t_2 and t_1 is approximately of 209.5 ms. The sound and missile velocities calculated from formulas (1) and (4) were, respectively, of 352.5 m/s and of 818 m/s. Thus, in these conditions, according to

the relation (2), the evaluated distance to the missile cannon was about of 130 meters. The difference in the values of the distance *d* calculated in tests ND05R (Fig. 6) and ND05P (Fig. 8) results from that the detection head with the antenna directed perpendicular to the missile trajectory was moved away from the cannon by 2 meters.

16.5. Conclusions

The microwave detection head working with the CW signal and with single common transmit-receive antenna can effectively detect both subsonic and supersonic missiles. During investigations, it was found that microwave detection heads are also able to effectively detect acoustic signals propagating in the surrounding space. They can also work as microwave-acoustic sensors. Such detection heads must cooperate with fast processors capable of quickly analyzing the received signals. These processor units have to indicate which portions of the signal from the output of the detection head are the results of the radiolocation phenomena and which have an acoustic basis. In the work such parts of the registered signals were pointed out. Explanations of the perceived phenomena were also presented.

The main purpose of the current stage of the research was to verify the main hypotheses, and not to obtain high accuracy in measuring the distance from the point of fire or the speed of sound and missiles. These problems will be the subject of further works in the future. It is planned to work on multi-channel microwave heads supported by typical acoustic sensors [6] and optoelectronic sensors. Such multi-channel systems will be able to estimate not only the distance to the shooting object, but also its direction.

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