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MODELLING AND SIMULATION OF THE PROTECTION SYSTEM FOR HELICOPTERS SELF-DEFENCE AGAINST GUIDED MISSILE WEAPONS WITH IR SEEKERS

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Abstract

This article concerns project of developing helicopter self-defence system model in infrared (IR) region of electromagnetic spectrum, to allow simulation of different scenarios. To these end mathematical tools describing relations between dynamic and energetic parameters of helicopter, flare and missile were developed. Models developed allow for analysis of self-defence system reliability, accounting influence of different parameters: energetic, dynamic, time-dependencies, system configuration and different scenarios. Pyrotechnic flares have developed in very effective countermeasures system used against IR missiles seekers. Some of these seekers are equipped in devices and algorithms that allow detecting a presence of decoy in the field of view (FOV) of the seeker, and discriminating it. The IR spectral signature of flare is distinctively different from real target (helicopter). One of counter-countermeasures solution is two-colour seeker, which detects and measures infrared radiation in two bands of infrared spectrum simultaneously. To discriminate false signal we have used signal spectral analysis. Because two-colour seekers, to recognize real signal uses differences in IR energy spectral distribution, it was necessary to provide models of spectral signatures of target and flare. To this end, we have used experimental data of IR measurements of helicopter and flare countermeasures. Results of this measurements reveals, that spectral characteristics of helicopter and flare are distinctively different. Changes of the ratio of helicopter and flare IR energy in different spectral bands can be used as a way to attenuate signal of false target from detector output. We have used two-detector solution. One detector works in 2.5-3 micrometres band and the other in 3-5 micrometres band. Flares are usually dispensed from helicopter in such a way, to disrupt tracking in IR guided missile. The angular separation of flare from helicopter should be as high as possible, but it should not be higher than seeker tracking capabilities. While in FOV of seeker, the flare should reach radiation level higher than real target. Most flares ignite in period shorter than 1 s, and burn longer than 5 sec. Flare has smaller dimensions and higher intenssivity than helicopter. Because of it flares are brighter a short waves, and darker at longer waves than real targets. When seeker collects data from two spectral bands, it can easy discriminate flare signal.

Keywords: *simulation, missile and helicopter dynamics, IF signatures*

1. Introduction

All objects are radiating energy in infrared region of electromagnetic spectrum. This energy depends on absorption, reflection, and transmission of radiation.

To assess infrared signature of a target, one has to take into account such factors as object temperature, object emissivity and reflection factors, atmospheric attenuation etc. Knowledge on IR signatures is necessary to model IR guided missiles, countermeasures (IR flares) and targets (helicopter – in our case).

To obtain a realistic model one has to take into account IR signatures of object present in the IR scene, atmospheric attenuation and optical parameters, such as the Total Power reaching the detector [1]. The primary sources helicopter IR radiation is hot engine exhaust, exhaust gases and helicopter skin. In case of helicopter, because of narrow range of its speeds, there is no need to take into account aerodynamic heating of skin (see Fig. 1).

The main sources of radiation in jet engine are exhaust pipe and exhaust gaseous plume. The pipe can be treated as grey body with 0.9 emissivity. The exhaust plume has temperature up to 1173 K. It is assessed, that radiation of exhaust pipe is 25 times higher than radiation of the exhaust plume.

This result is very significant when we take into consideration that it has been achieved only due to a better regulation of the engine cylinders filling by means of a variable timed valve gear, without any change of the engine dimensions, compression ratio or maximum value of rotational speed.

In the framework of our work, the IR parameters of multipurpose helicopter were measured, i.e. temperature pattern of helicopter and background. The characteristics of IR power and radiance were obtained experimentally. We have used two scanner AGEMA 900 System with thermal sensivity of 0.1 K, working in 2.5-5 µm and 8-12 µm regions of electromagnetic spectrum, and 25° FOV lenses for both scanners. Samples of results are presented on Fig. 2a and 2b (ACCORDING TO REFERENCE [6].

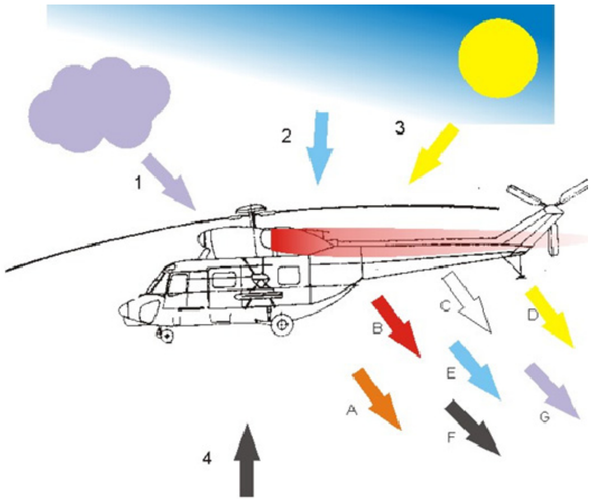


Fig. 1. Sources of helicopter IR radiation: 1. Clouds radiation, 2. Sky radiation, 3. Sun radiation, 4. Terrain radiation, A. Radiation of the engine hot parts, B. Engine exhaust plume, C. Helicopter skin radiation, D. Reflected Sun radiation, E. Reflected Sky radiation, F. Reflected earth radiation, G. Reflected Clouds radiation

According to our analysis, the factors shaping helicopter signatures in 2.5-5 micrometres band are hot parts of engine and exhaust plume. This is in agree with Wien law, according to which, with increase of temperature, the maximum of energy emission is shifting toward short waves. In 8-12 micrometre band, the contribution of helicopter skin dominates the signature. Because of large skin area, its energy is much higher than engine and plume energy

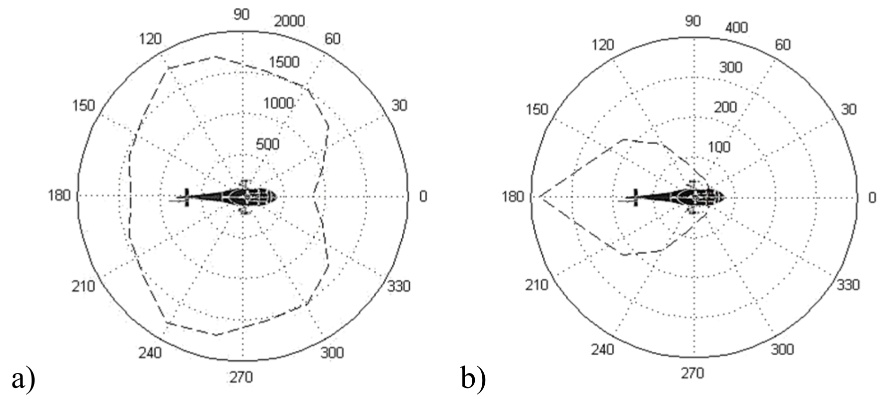


Fig. 2 a) Power of IR emission in 8-12 micrometre band [6], b) Power of IR emission in 2.5-5 micrometre band [6]

2. Mathematical model of self-defence system

2.1. Model of flare

It was assumed, that flare is a point mass, which is subject to lift, air drag, thrust and gravity. When flare is moving along two axis x and x, its dynamics can be described as:

$$\dot{V}_x = (T - D)\cos\gamma + L\sin\gamma\,, \tag{1}$$

$$\dot{V}_z = mg + (T - D)\sin\gamma - L\cos\gamma\,, \tag{2}$$

where: $\dot{V}_x$ – acceleration in x axis, $\dot{V}_z$ acceleration in z axis, γ – angle between x axis and flare speed vector, m – flare mass, g – earth acceleration, T – thrust, D – drag, L – lift.

Drag and lift forces depend on flare geometry, speed, and atmosphere density – ρ. Lift and drag can be described as:

$$D = \frac{K_D}{2m}\rho V^2\,, \tag{3}$$

$$L = \frac{K_L}{2m}\rho V^2\,, \tag{4}$$

where K_D and K_L are parameters dependent on drag coefficient and lift area. The thrust force depends on atmospheric pressure. Model calculates lift as difference of vacuum thrust force T_V and ratio of atmospheric pressure and exhaust pipe area A_n.

2.2 Mathematical model of human – helicopter system

Helicopter model used in our work allows simulation of steered flight helicopter, treated as 6 DOF dynamical system [7, 8, 10, 23, 26].

Model of simulation of steered flight of helicopter is presented in Fig. 4. It contains of following modules:
- Pilot,
- Pitch, yaw and roll steering devices,
- Engine (or engines),
- Helicopter aerodynamics,
- Helicopter dynamics (movement equations and cinematic relations),
- Environment (atmosphere model).

2.3. Missile guidance model

Many short-range IR guided missiles utilize proportional navigation (PN) guidance law. This law is simple in implementation and effective. There are no much target parameters needed, so seeker can be relatively simple. With PN guidance, one obtains acceleration command perpendicular to Line of Sight (LOS) and proportional to instantaneous rotation of LOS, and missile closing speed V_c (missile – target relative speed).

The rotation of missile speed vector is proportional to the rotation of LOS. When rotation of LOS is equal to zero, then missile is on collision course toward target.

The missile seeker is tracking target by measuring LOS angle, and estimating closing speed V_c. Using this data, autopilot generates guidance command [11]:

$$n_c = N' V_c\ \dot{\lambda}\,, \tag{5}$$

where: n_c is an acceleration command, N' is the navigation ratio (usually 3-5), Vc is a closing speed, and $\dot{\lambda}$ is LOS rotation.

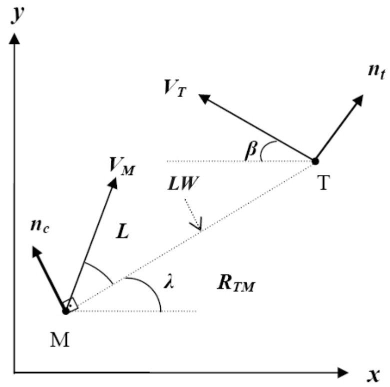


Fig. 3. Two-dimensional geometry of missile proportional navigation

Two-dimensional geometry of missile proportional navigation is presented on Fig. 3. *M* stands for missile, and *T* stands for target. Line between missile and target is the LOS line. The angle between LOS line and *x-axis* is described as λ. The length of LOS, i.e. distance between missile and target is described as R_{TM}. The angle between speed vector and LOS is *L* angle. V_t is the target speed. β is an angle between target speed vector and *x-axis*, n_c is an acceleration command generated by PN law.

2.4. Model of missile seeker

To obtain information of target location in relation to missile, seekers use modulation disks, which allow measuring the angle between missile speed vector and target location.

The pulse modulation disk can be described with three parameters: frequency as function of disk angle $f(\theta)$, radius *m(r)*, and phase $\rho(r)$. Transmission for any three parameters of $f(\theta)$, *m(r)* and $\rho(r)$ can be written as [18]:

$$T(r,\theta)=\frac{1}{2}+\frac{1}{2}\cos\left[m(r)\int_0^{\theta+\rho(r)} f(\alpha)d\alpha\right]. \tag{6}$$

To measure a location of target on polar coordinates one has to impose on modulation disk parameters of $f(\theta)$ and *m(r).* To correlate location of the target image on modulation disk with location of target in the background, one has to impose on modulation disk the function of the phase $\rho(r)$.

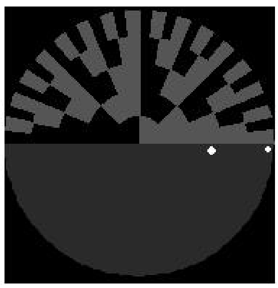
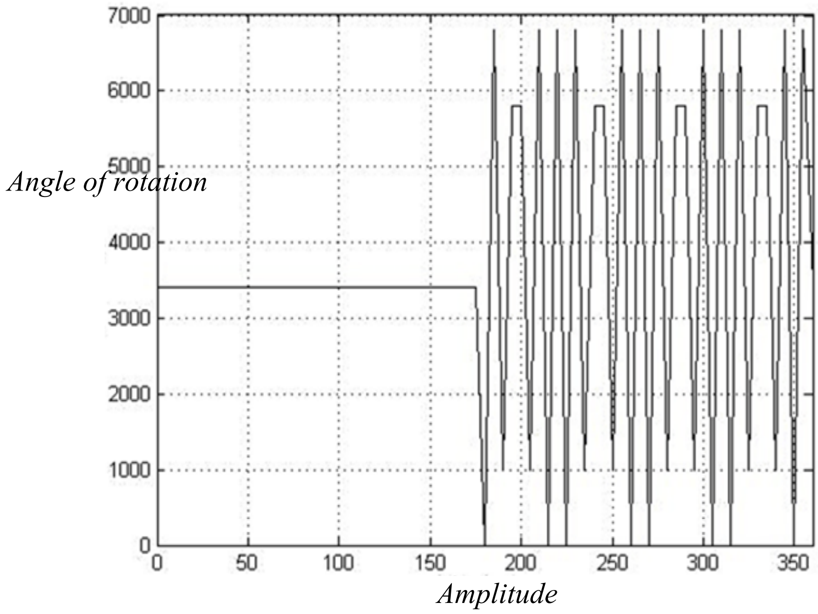
a)  b) 

Fig. 4 a) MATLAB® model of seeker modulation disk, b) Location of target and flare concerning modulation disk rings. White object are target (larger) and flare (smaller)

Modulation disk generates different number of pulses in dependence of location of the target in the seeker FOV. In classic solution of rotating raster, the carrier frequency equals of number of raster fields multiplied by frequency of raster rotation. Dependent on target location, output signal is modulated with different frequencies. To obtain information on target location (its radius) filters and demodulators are used. With such a system of signal processing, it is possible to find in which ring the target is located (Fig. 4).

In simple modulation disk used in our model, half of the disk is a grey sector with 50 percent optical transmission; this is needed to obtain phase information of demodulated signal in regard to reference signal [11, 17]. In this work, we have built a MATLAB model of modulation disk.

Model of disk was built wit use of graphic functions. The disk image was then animated, and rotated with constant step. For each step, the matrix of disk image was generated. This matrix was then transformed in transmission matrix, where opaque fields has transmission T=0, transparent fields has transmission T=1 and grey sector has transmission *T*=0.5.



Fig, 5. Detector signal is a linear combination of flare and target signal

Set of matrix was used to obtain output signal from detector. The modulation disk has dimensions of 240 x 240 pixels. The disk radius is 120 pixels.

Figure 4 and 5 show a situation when target and flare are in seeker FOV. Intensity of flare IR radiation is about 10 times higher than target. Target has radius of 3 pixels and flare 2 pixels.

3. Spectral analysis in seeker

Pyrotechnic flares has developed in very effective countermeasures system used against IR missiles seekers because of it, Some of this seekers are equipped in devices and algorithms, that allows to detect a presence of decoy in the field of view (FOV) of the seeker, and discriminate it [20]. The IR spectral signature of flare is distinctively different from real target (helicopter).

One of counter-countermeasures solution is two-colour seeker, which detects and measures infrared radiation in two bands of infrared spectrum simultaneously. To discriminate false signal we have used signal spectral analysis [3].

Because two-colour seekers, to recognize real signal uses differences in IR energy spectral distribution, it was necessary to provide models of spectral signatures of target and flare. To this end, we have used experimental data of IR measurements of helicopter and flare countermeasures. Results of this measurements reveals, that spectral characteristics of helicopter and flare are distinctively different. Changes of the ratio of helicopter and flare IR energy in different spectral bands can be used as a way to attenuate signal of false target from detector output.

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4. Results of simulations

Using models described above the series of simulation scenarios were conducted. Intercepting of helicopter by IR missile was simulated.

In the scenarios different object speeds and different geometry of engagement was simulated. Dispensing of flare (or two flares) and its discrimination by missile equipped with spectral analysis system was also simulated.

It was assumed, that the target is hit, when missile reaches distance of less than 10 meters from the target. Results of simulations for 10 different scenario of missile attack and defense flares launching are shown in Fig. 6-15.

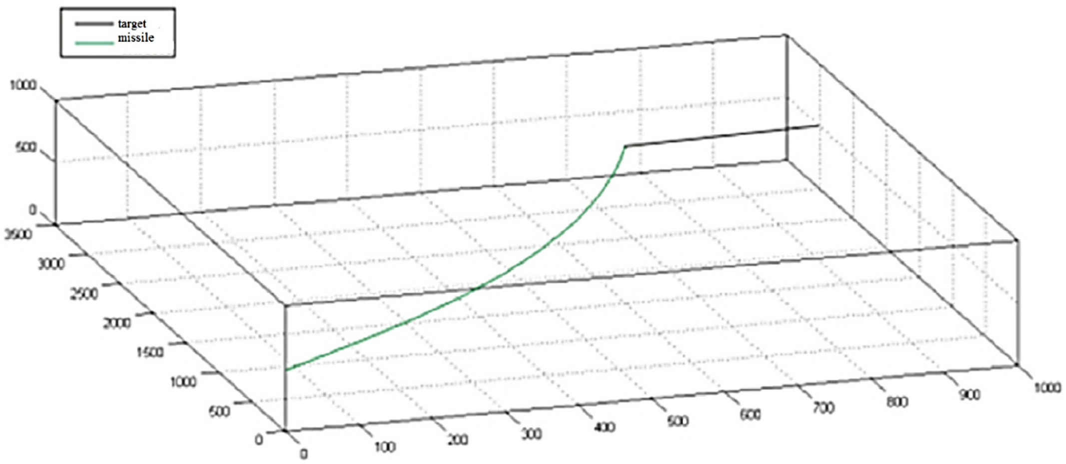

Fig. 6. Scenario no 1:V_c=100 m/s, Vp=600 m/s, t_T=4.31

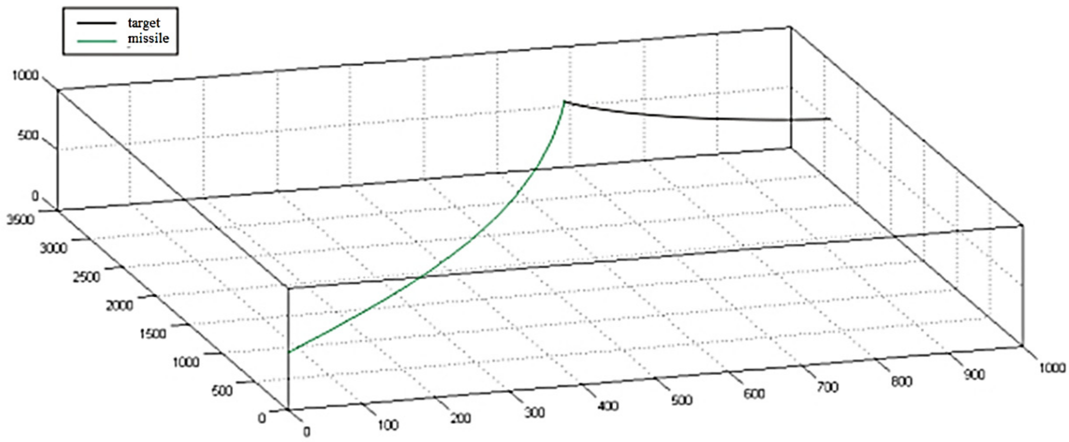

Fig. 7. Scenario no 2: Vc=100 m/s, target manoeuvre 1 g, Vp=600 m/s; t_T=4.53

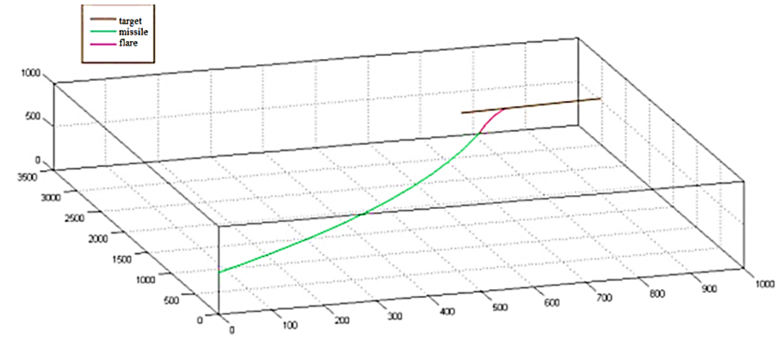

Fig. 8. Scenario no 3: Vc=100 m/s, flare after 2.5 s., Vp=600 m/s, t_T=4.11

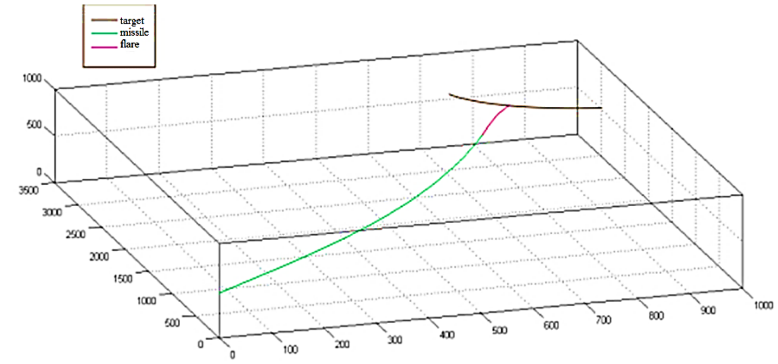

Fig. 9. Scenario no 4: Vc=100 m/s, target manoeuvre 1 g, flare after 2.5 s., Vp=600 m/s, t_T=4.13

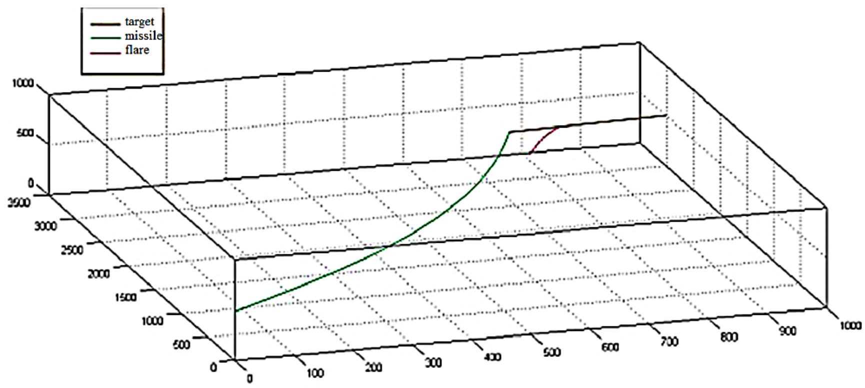

Fig. 10. Scenario no 5: Vc=100 m/s, flare after 2.5 s., Vp=600 m/s, t_T=4.12. Seeker with spectral analysis system

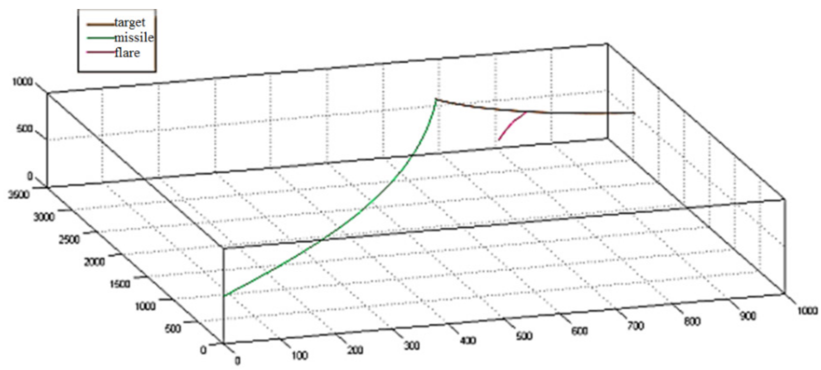

Fig. 11. Scenario no 6: Vc=100 m/s, target manoeuvre 1 g, flare after 2.5 s., Vp=600 m/s, t_T=4.21. Seeker with spectral analysis system

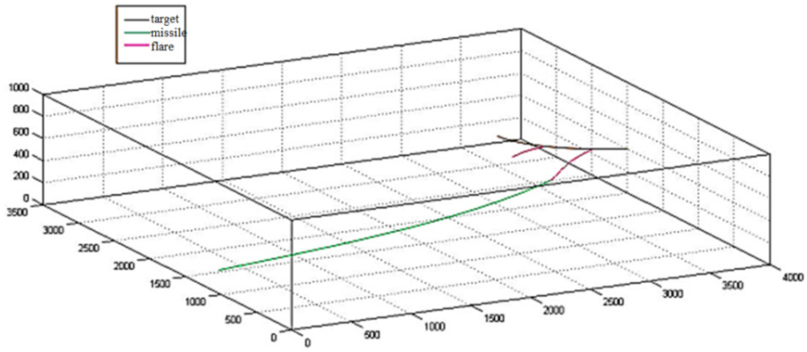

Fig. 12. Scenario no 7: Vc=100 m/s, target manoeuvre 1.5 g, Two flares, after 2.5 sec each, Vp=600 m/s, t_T=7.41

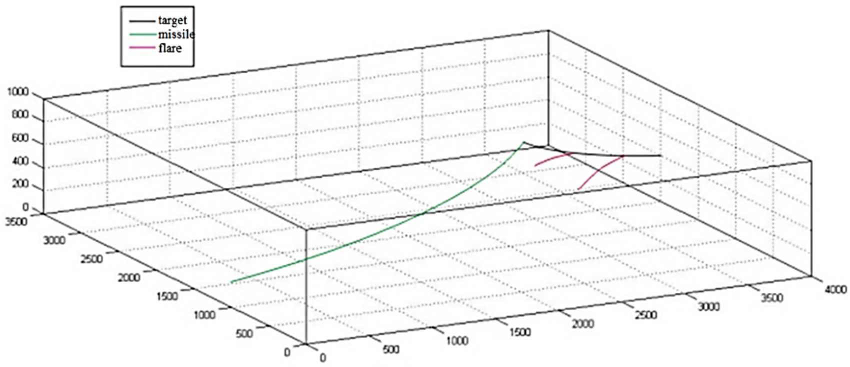

Fig. 13. Scenario no 8: Vc=100 m/s, target manoeuvre 1.5 g, Two flares, after 2.5 sec each., Vp=600 m/s, t=7.63 Seeker with spectral analysis system

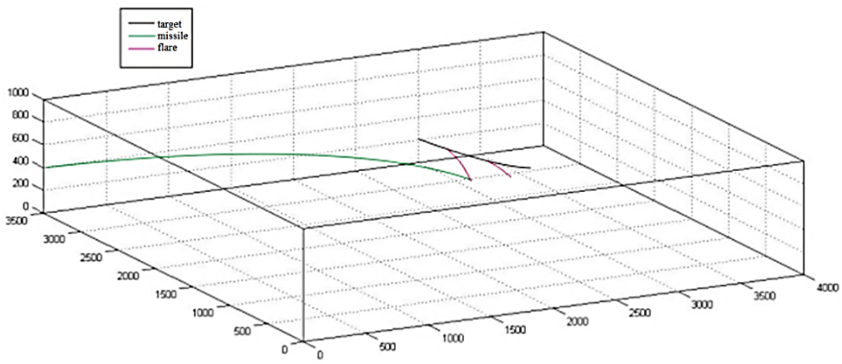

Fig. 14. Scenario no 9: Vc=100 m/s, target manoeuvre 1 g, Two flares, after 2.5 sec each., Vp=600 m/s, t_T=5.64

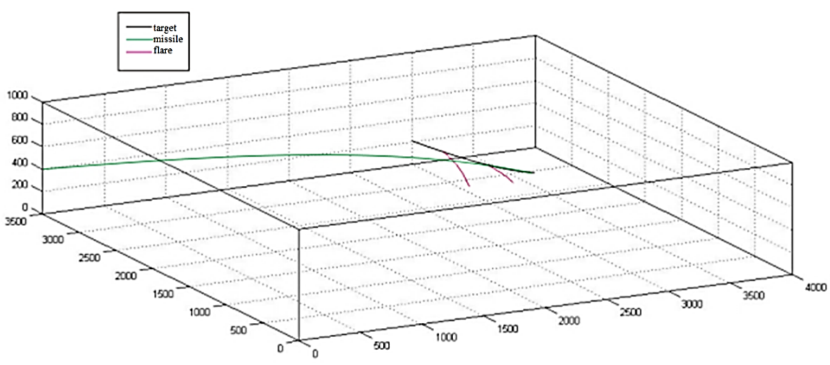

Fig. 15. Scenario no 10: Vc=100 m/s, target manoeuvre 1 g, Two flares, after 2.5 sec each., Vp=600 m/s, t_T=6.16. Seeker with spectral analysis system

5. Summary and concluding remarks

In our scenarios, we have verified our assumptions, models functioning and output correctness. Limitations of the models were not verified.

When assessing results, one hast to remember about many simplification of the models. We have assumed uniform thermal background. The atmospheric attenuation in target IR signature, flare IR signature, and optical channel of missile seeker was taken into account, but solar reflection were not simulated.

Tab. 1. Scenarios summary

Scenario no	Target speed [m/s]	Missile speed [m/s]	Target manoeuvre [g]	Time to hit [s]	Flare launch time [s]	Spectral analysis system usage	Target hit
1	100	600	0	4.31	NO	NO	YES
2	100	600	1	4.53	NO	NO	YES
3	100	600	0	4.11	2.5	NO	NO
4	100	600	1	4.13	2.5	NO	NO
5	100	600	0	4.12	2.5	YES	YES
6	100	600	1	4.21	2.5	YES	YES
7	100	600	1.5	7.41	2.5, and 5	NO	NO
8	100	600	1.5	7.63	2.5; 5	YES	YES
9	100	600	1	5.64	2.5, and 5	NO	NO
10	100	600	1	6.16	2.5, and 5	YES	YES

We have use a simple, linear pilot model. During launch, seeker starts to track target with error of 0.25 degree. Flares are launched in fixed moments. Modelling target signature, we have used results of helicopter IR radiation measurements. The seeker modulation disk rotates with frequency of 100 Hz. Results shows that our models work properly. IR missile intercepts helicopter flying with constant speed or manoeuvring. (scenarios 1 and 2). If there is no discrimination system on missile, then flare launch disrupts missile tracking, and missile follows flare (scenarios 3, 4, 7, 9). When the missile FOV enters second flare, with higher energy, then missile is following stronger signal source and intercepts second flare (scenarios 7 and 9). If false target discrimination system is used, missile can recognize real target and intercepts helicopter (scenarios 5, 6, 8, 10).

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