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6-DOF simulation and the vulnerable area of the Air-to-Air missile to develop an End-game simulator

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Abstract

The vulnerability of a particular target to a weapon will be of interest to a number of analysts, each with their own perspective on the requirements for data and measures of damage. The one of the most important tasks in the end-game simulation is to determine the probability of kill ($P_{k/h}$). The probability of kill is the key element for End-game simulation to measure air-to-air/air-to-ground combat missions and training accomplishments in process of disciplines. Models such as Air Combat Maneuver Instrument (ACMI), Weapon Simulator and War-game are possible to make use of these models as a core input data. In order to obtain $P_{k/h}$ value, however, It is required for the combat aircraft of radar detector, explode, trajectory modeling, vulnerability and survivability etc. Among them, it is found that the getting aircraft vulnerable areas for each components plays a very important role in assuring the probability of kill. Nevertheless, the existing vulnerability computation methods cannot meet engineering application currently. With this in mind, this paper presents the computation of vulnerable area method and verifies the result of the 6-DOF simulation for AIM-120B with non-dynamic seeker and dynamic seeker using MATLAB/SIMULINK.

Keyword : End-game, Vulnerability, Survivability, Probability of Kill, AIM-120B, Lethality, PNG, Missile DATCOM

1. Introduction

With the revolutionary development of Air-to-Air missile technology, the ability to attack the air battle has been significantly improved, and it must be necessary for pilots to improve the ability of air battles. In reality, however, it is hard to perform tasks of launching missiles to shoot aircraft, so missile simulator is required and needs to be developed. Hence, Endgame simulator is being developed at Konkuk University. The Endgame simulator is a model that computes $P_{k/h}$ for targets. According to Endgame that we are developing, there are two important factors to include; one is the survivability/vulnerability assessment, the other is trajectory tracking of the missile.

Aircraft combat survivability (ACS) is defined as the capability of an aircraft to avoid or withstand a man-made hostile environment and also the vulnerability of a particular target to a weapon is of interest to a number of analysts. [1] Currently, improving survivability has become one of the most important design elements of combat aircraft. In fact, for improving efficiency and accuracy of vulnerability assessment, a number of software and programs have been developed by American researchers, to name a few, vulnerability software BRL-CAD, shot-line generation program FASTGEN, vulnerable area computation program VAREA, vulnerable area and repair time computation program COVART, missile endgame computation programs ESAMS, JSEM, AJEM, etc. [4] They have high-fidelity performances that produce more accurate prediction but take more time and other resources to develop. In this paper, therefore, we present the cost and time effective vulnerability assessment methodology to get projected area for computing $P_{k/h}$ and the autopilot algorithm using the feedback normal and directional acceleration for AIM-120B missile, guidance algorithm based on compensated PNG (Proportional Navigation Guidance) command and the dynamic model with seeker considering time-delay and error are presented.

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2. Technical Description for Mathematical Model of AIM-120B

2.1 AIM-120B dimension and modeling

For this study, the configuration and the dimension of AIM-120B such as Fig.1 and Table.1 are selected, and Aero DB of the target system can be obtained using Missile DATCOM.

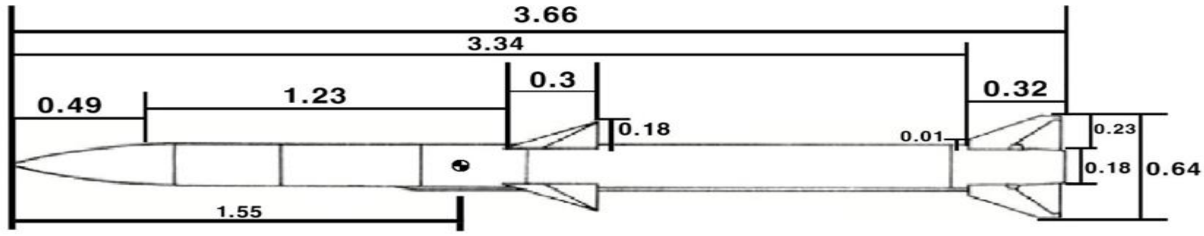

Fig. 1 The drawing of AIM 120B (Unit: m)

Table. 1 The performance and properties of AIM-120B

Type	Property
Fuse	Proximity
Guidance system	Active radar
Deflection of Control surface	$\pm 15°$
Maximum velocity (Mach No.)	4.0
Mobility (g)	35
Effective range (km)	64

2.2 Aero DB computation

In this study, an aerodynamic database for AIM-120B are derived by using Missile DATACOM, which is the reliable program to compute stability and control derivatives.

(1) Components of Aero DB

Variables for Aero DB involve the five of the Mach numbers (M = 0.7, 0.9, 1.1, 2.0, 3.0), the angle of attack (-40deg$\leq \alpha \leq 40$deg) and sideslip angle (-40deg$\leq \alpha \leq 40$deg) variables etc. The Aero DB process is shown in Fig.2

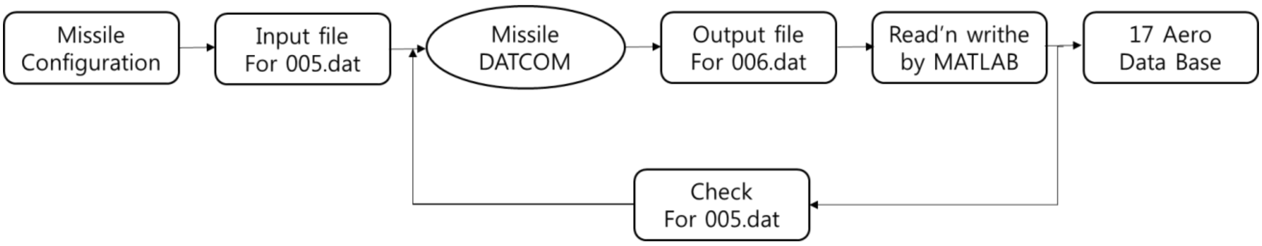

Fig. 2 The block diagram of Aero DB process

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2.3 Autopilot

Fig. 3 shows the simplified structure of normal acceleration autopilot for AIM-120B. The autopilot algorithm of the target system was constructed using PI control and was designed with the normal/directional acceleration controller. The main points of applied autopilot are as follows.

(1) Normal acceleration autopilot

The eigenvalue of this equation leads to the on-line calculation of the gains $\bar{c}$, G_I, G_p given the desired closed-loop poles p_i. These control techniques are commonly used and can be confirmed in the reference [3], so a detailed description will be omitted in this paper.

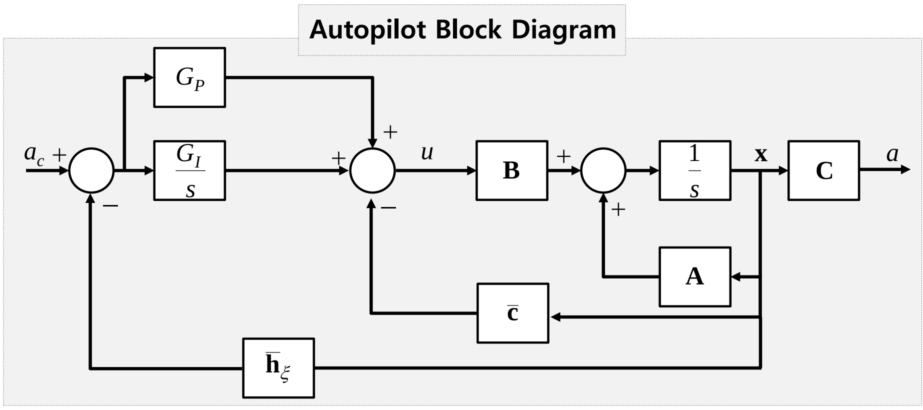

Fig. 3 Block Diagram for Acceleration Autopilot

From the reference [3], the state equation of the linear model for the normal acceleration can be expressed as

$$\begin{bmatrix} \dot{q} \\ \dot{a}_z \end{bmatrix} = \begin{bmatrix} M_q & \frac{M_\alpha}{Z_\alpha} \\ Z_\alpha & -\frac{Z_\alpha}{V} \end{bmatrix} \begin{bmatrix} q \\ a_z \end{bmatrix} + \begin{bmatrix} M_{\delta_e} \\ 0 \end{bmatrix} \delta_e \tag{1}$$

$$\mathbf{x} = \begin{bmatrix} q \\ a_z \end{bmatrix}, \mathbf{A} = \begin{bmatrix} M_q & \frac{M_\alpha}{Z_\alpha} \\ Z_\alpha & -\frac{Z_\alpha}{V} \end{bmatrix}, \mathbf{B} = \begin{bmatrix} M_{\delta_e} \\ 0 \end{bmatrix}, \mathrm{u} = \delta_e,\ \bar{\boldsymbol{h}}_\xi = [0 \quad 1], \bar{\boldsymbol{c}} = [k_2 \quad k_1] \tag{2}$$

(2) Directional acceleration autopilot

The directional acceleration autopilot has the same structure with normal acceleration autopilot. It is similar to the rate equation, except for the angle of attack, which is replaced by the side acceleration $a_y = \dot{v}$

$$\begin{bmatrix} \dot{q} \\ \dot{a}_y \end{bmatrix} = \begin{bmatrix} N_r & \frac{N_\beta}{Y_\beta} \\ -Y_\beta & \frac{Y_\beta}{V} \end{bmatrix} \begin{bmatrix} r \\ a_y \end{bmatrix} + \begin{bmatrix} N_{\delta_r} \\ 0 \end{bmatrix} \delta_r \tag{3}$$

$$\mathbf{x} = \begin{bmatrix} r \\ a_y \end{bmatrix}, \mathbf{A} = \begin{bmatrix} N_r & \frac{N_\beta}{Y_\beta} \\ -Y_\beta & \frac{Y_\beta}{V} \end{bmatrix}, \mathbf{B} = \begin{bmatrix} N_{\delta_r} \\ 0 \end{bmatrix}, \mathrm{u} = \delta_r,\ \bar{\boldsymbol{h}}_\xi = [0 \quad 1], \bar{\boldsymbol{c}} = [k_2 \quad k_1] \tag{4}$$

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2.4 IR Seeker

The main components of IR seeker are described in Fig. 4. In case of AIM-120B model, As IR seeker is used and applied to the coordinate system and the transformation. In order to configure the practical seeker, it is required to add error term to ideal seeker. Details of the error factors will be briefly described in this section.

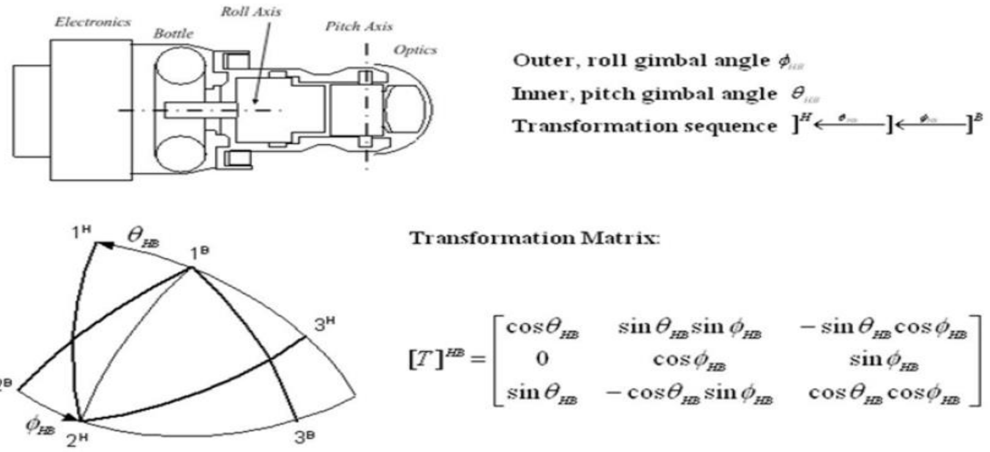

Fig. 4 IR seeker of the transformation matrix

2.5 Compensated proportional navigation

In this study, the Missile guidance is based on the method of PNG (Proportional navigation guidance). However, the rapid maneuvering is required to intercept the target due to the evasion flight of the target, and therefore the compensation for acceleration / deceleration of the missile is required in the actual guidance process.

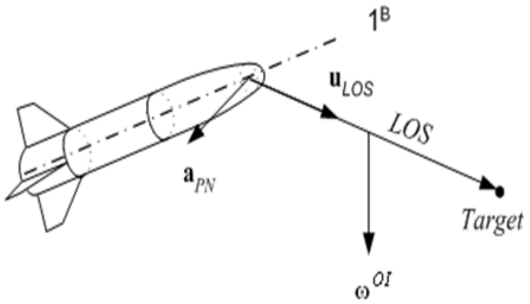

Fig. 6 Classical proportional navigation [3]

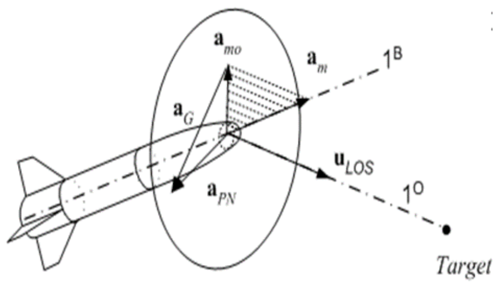

Fig. 7 Compensated proportional navigation [3]

PNG is summarized under the assumption that the relative speed is constant as shown in Eq(5), and Fig.6 shows the physical meaning of each variable.

$$\bar{a} = \mathrm{NV}\bar{\Omega}^{OI} u_{LOS} - \bar{g} \tag{5}$$

Where N is the navigation gain, V the closing speed, $\bar{\Omega}^{OI}$ the inertial angular velocity and $\bar{g}$ the gravity term. Compensated PNG can be calculated by the modified acceleration command as shown in Eq(6) taking into account the target and acceleration changes when encountering the target. The physical meaning of each variable can be confirmed in Fig.7. The missile's longitudinal acceleration a_m^B is projected into the LOS plane with the projection tensor P_{LOS} and subtracted from the PN command a_{PN}^L to obtain the augmented command [3].

$$a_{mo} = P_{LOS} a_m \tag{6}$$

$$\bar{a} = \mathrm{NV}\bar{\Omega}^{OI} u_{LOS} - \bar{a}_{mo} - \bar{g} \tag{7}$$

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Where a_m is the missile's longitudinal acceleration and P_{LOS} the projection tensor. The details of the guidance command can be confirmed through reference [3], so the detailed description will be omitted.

2.6 Results of simulation

The simulations are performed for each of the Mach numbers 0.7, 0.9, 1.1, 2.0 and 3.0, and only the representative results will be included in this paper. From the simulation results, there are differences when the Mach number was 9 or more. However, since there are many parameters of Mach number, we will only show the experimental results at Mach number 0.9.

Table 2 Missile and target initial condition

Variable (unit)	Missile	Target	Reference axis
Velocity (m)	[306 0 0]	[200 0 0]	Body
Position (km)	[0 0 5]	[0 0 4]	Inertial
Attitude angle (deg)	[0 0 0]	[0 0 0]	Body

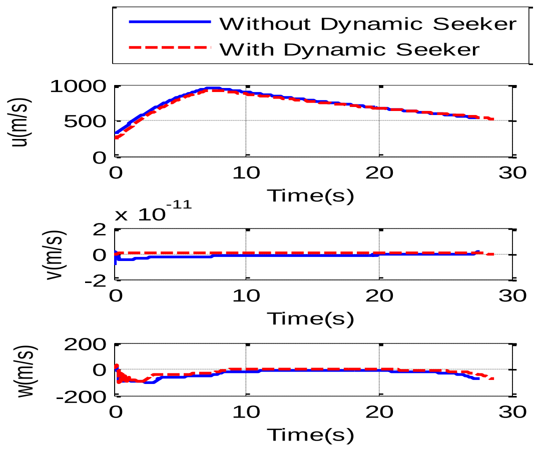

Fig. 8 Missile Velocity with respect to Body coordinate

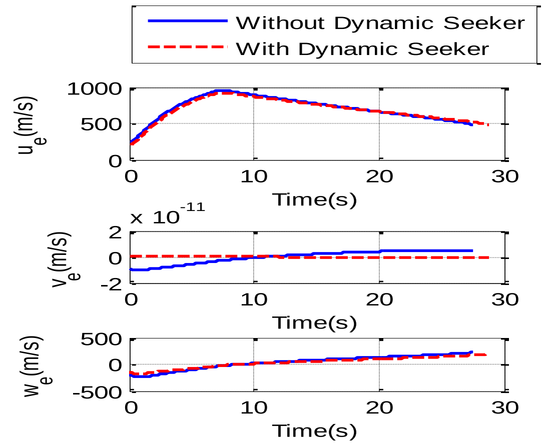

Fig. 9 Missile velocity with respect to inertial coordinate

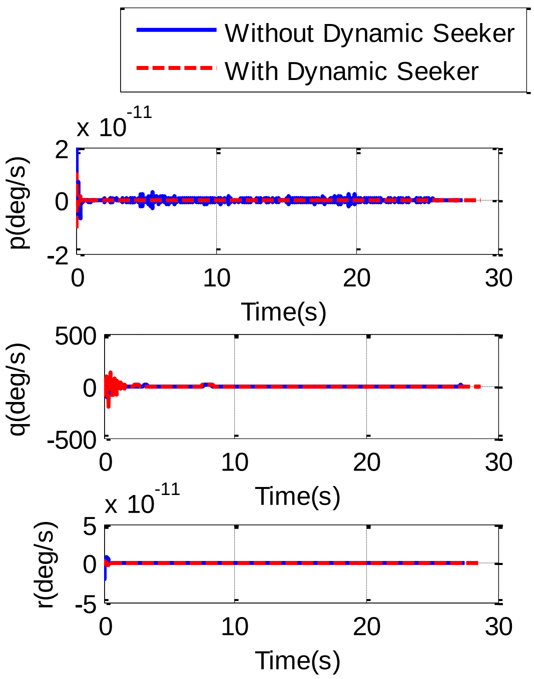

Fig. 10 Missile angular velocity

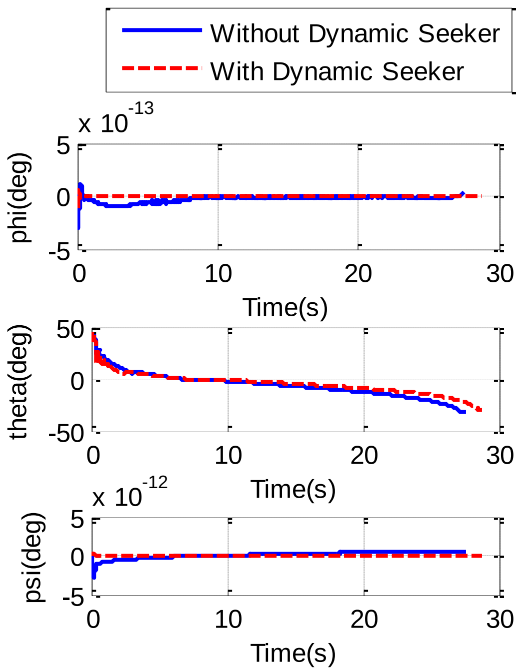

Fig. 11 Missile attitude angle

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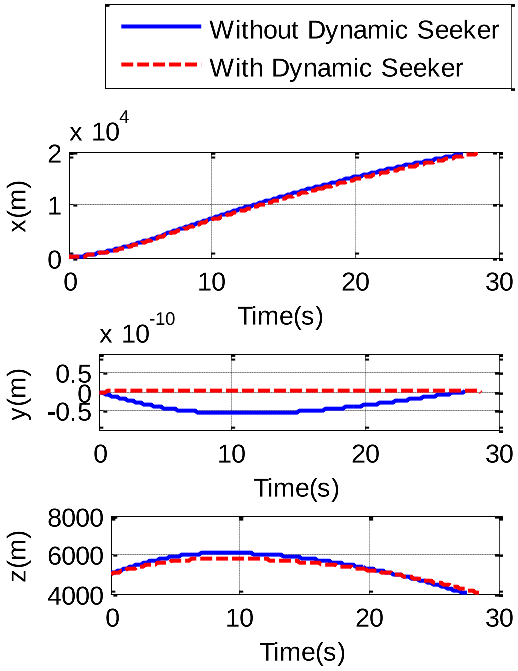

Fig. 12 Missile position

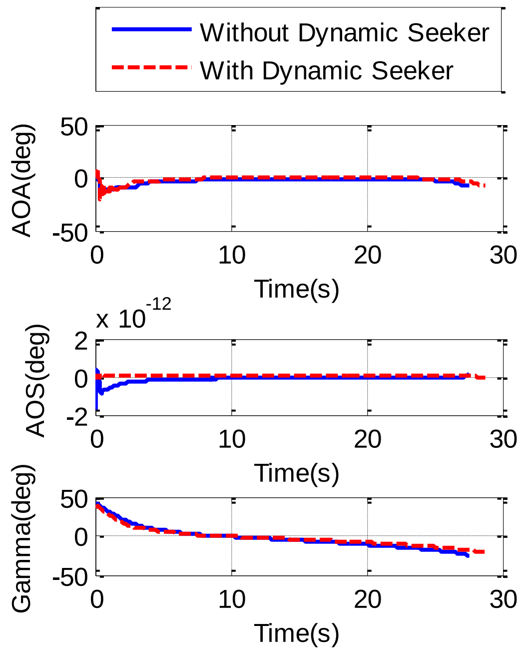

Fig .13 Missile sideslip, Climb, angle of attack

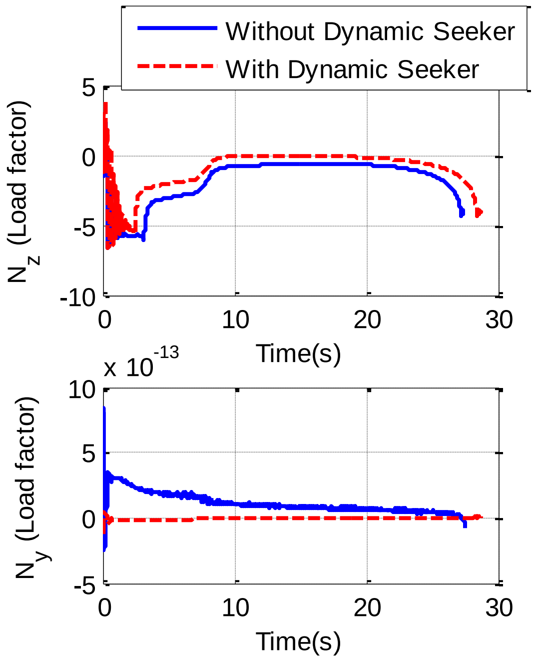

Fig. 14 Missile Load factor

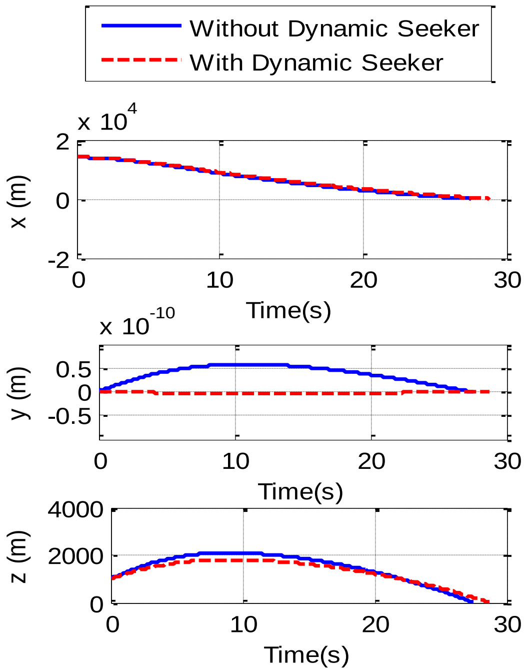

Fig. 15 Component of the LOS distance

3. Vulnerability assessment

Vulnerability is the probability that the aircraft will be killed if hit; and is a function of detailed aircraft configurations, including specific armament, system locations and redundancies [6]. Aircraft is composed of a lot of components, and each components has a level of vulnerability. In this section, The computation of the vulnerable area is described for calculating $P_{k/h}$. The vulnerable area of the ith component, A_{Vi} depends on the projected area of the component in the plane normal to the impact direction of the threat (A_{pi}) and the probability of kill of the *i*th component, given a hit on the components ($P_{ki/h}$) as following :

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$$A_{Vi} = A_{Pi}\, P_{ki/h} \tag{8}$$

3.1 Vulnerability attributes

The task in the study assumes that the system with redundancy is non-overlapping. The vulnerable area of the *i*th component is denoted by A_{Vi}, the projected area A_{Pi} and $P_{ki/h}$ probability of killing the *i*th component given a hit on the target. The $P_{k/h}$ is the summation of the $P_{ki/h}$ and may be expressed in the form

$$P_{k/h} = \sum_{i=1}^{N} P_{ki/h} = \frac{1}{A_P}\sum_{i=1}^{N} A_{Vi} \tag{9}$$

However, one of the difficulties in vulnerability assessment is estimation of $P_{ki/h}$, it needs experiment or great experience [6]. In this study, therefore, the $P_{k/h}$ are set up as the assumed value shown in Table.3.

Table 3 Assumed values for the critical component

Critical component	$P_{k/h}$
Cockpit	1.0
Fuel tank	0.3
Engine	0.6

3.2 The target of interest

In this section, the aircraft models applied to this study are introduced to use vulnerability computation. The MIG-23 and MIG-29 were selected in the simulation and each main components which are engine, fuel tank and cockpit is applied to this study. The aircraft consists of three critical components: an engine, one fuel tank, and one cockpit. None of the critical components overlap from this aspect.

3.2 Projected area computation methodology

This section presents the computation of the vulnerable area applied to the simulation based on the spherical coordinate system. The relative velocity vector between the approaching fragment and the aircraft at impact is

$$\vec{v}_{impact}(\mathrm{r,t}) = \vec{v}_{aircraft}(r,t) - \vec{v}_{fragment}(r,t) \tag{10}$$

A_p is the area of the aircraft as viewed from the perspective of the impacting fragment. More formally, the projected area is the aircraft area projected onto plane perpendicular to the impact velocity vector [6].

$$A_p = A_S\hat{v}_{impact}(r,t)\hat{n}_S + A_F\hat{v}_{impact}\hat{n}_F + A_T\hat{v}_{impact}\hat{n}_T \tag{11}$$

Where A_S is the side area of aircraft, A_F is the front area of aircraft and A_T is the top of aircraft, and $\hat{n}_S$, $\hat{n}_F$ $\hat{n}_T$ are unit vectors.

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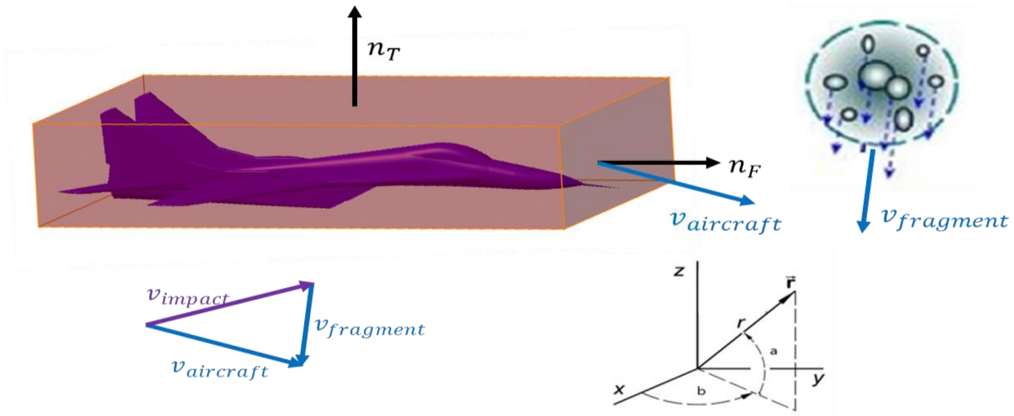

Fig. 16 aircraft areas and vector of aircraft relative to spraying fragment based on spherical coordinate system

4. Conclusion

The purpose of this paper is to recognize the importance of the aerial combat using air-to-air missiles and to develop the Endgame simulation applying the $P_{k/h}$ to help improve the domestic condition without proper training system. Although a large number of tests and data should be accumulated, it is almost impossible to obtain such data, and it is difficult to carry out such tests in domestic circumstances. In addition, the 6DOF nonlinear model of the target system is implemented using Missile DATCOM, and the Aero DB is supplemented with reference data and performance comparison. The difference between with dynamic seeker and non-dynamic seeker when Mach number was 9 or more showed the necessity of seeker mounted. In this study, the launching simulation of AIM-120B missile was constructed, and if it is designed to be mounted on the flight control computer after verifying and supplementing the results of this study, it will be done in the development of the simulator that can be operated in actual flight training.

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