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SURVIVABILITY ANALYSIS OF AIRCRAFT UNDER FRAGMENTATION WARHEAD THREAT

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ABSTRACT

Aircraft survivability consideration became a crucial issue for especially military aircraft since about last quarter of the last century. Vulnerability assessment is one of the main items for survivability analysis. Vulnerability assessment consists of the determination of the kill probability of the aircraft against military threats such as anti-aircraft artillery, missiles, etc. In this paper survivability analysis is demonstrated by vulnerability calculations of the aircraft against a fragmentation warhead threat. The vulnerability models and fault trees are generated for two aircraft one with single engine and the other with two engines. In this study, the effect of using two engines and one engine configuration for a military aircraft is evaluated in terms of their overall probability of kill calculated against fragmentation warhead threat. For this purpose, survivability analysis of the twin and single engine configurations are performed by implementing warhead aircraft interaction calculations based on a fault tree established for the sample aircraft configurations studied. It is determined that using two engines decreases the overall probability of kill of the aircraft about %30, compared to single engine aircraft, for the tail-chase engagements of the air-to-air missile with target aircraft.

INTRODUCTION

Combat aircraft conceptual design did not include survivability enhancement in the past (before 1970s), because survivability features were not included in previous aircraft [Gilman, 1986]. Application of survivable design concepts during conceptual design may financially cost little, while significantly increase the combat effectiveness.The design of aircraft (both fixed wing and rotary wing) considering survivability is very important considering that tens of million dollar aircraft being killed by a 200 $ small arms weapon, is just not acceptable. Furthermore, counter threats develop faster than aircraft so, more survivable aircraft design is even more important today. Hence, new generation combat aircraft such as A10, F-18, F-22, F-35 etc. have been designed considering combat survivability. Thereby, these aircraft are more effective to survive and to succeed in their missions because they are more survivable against the anti-aircraft threats by the virtue of their design enhancements in terms of survivability.

The main reference for the surviability concept is MIL-HDBK-336. This military handbook gives the keypoints for the survivability consideration of both fixed wing and rotary wing aircraft. The kill levels for the aircraft are given in this handbook. The main kill level is the attrition kill which has some categories such as K-kill (aircraft cannot keep on flying in 30 seconds after the engagement of the threat), A-kill (cannot keep on flying in 5 minutes), B-kill (cannot keep on flying in 30 minutes), etc.

Additionally the first and only book on the subject was provided by Ball [Ball, 2003]. The survivability is defined as the ability to remain mission capable after a single engagement [Ball, 2003]. It comprises three elements: 1) Susceptibility (the inability to avoid being hit (by a weapon)). 2) Vulnerability (the ability to withstand the hit). 3) Recoverability (longer term post hit effects, damage control and firefighting, *capability restoration* or (in extremis) escape and evacuation).

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First two items above are most related to the combat survivability of aircraft. Furthermore,for the survivability design of an aircraft, the following items should be considered [Gilman, 1986]:

1) Delay detection as long as possible
2) If detected, avoid being fired   Susceptibility reduction
3) If fired at, avoid being hit
4) If hit, avoid aircraft kill   } Vulnerability reduction

The first three of these items are related to the design of the aircraft according to susceptibility reduction. The last but not the least item is related to the vulnerability reduction. For vulnerability reduction, the fundamental applications are said to be as:

1) Component redundancy (with seperation)
2) Component location
3) Passive damage suppression
4) Active damage suppression
5) Component shielding
6) Component elimination

The vulnerability assessment has an important place in the combat survivability analysis of the aircraft. Vulnerability comprises the interaction of the threat with target aircraft to determine the kill probability of the aircraft against that threat. Besides anti-aircraft artillery projectiles, today, modern threats such as proximity fuzed anti-aircraft missiles (surface-to-air or air-to-air) are the primary threats for combat aircraft. These missiles generally consist of fragmentation warhead as lethal payload.These guided missiles generally cannot hit the target aircraft but they pass near it with a miss distance. This path is called intercept path and the miss distance is defined as the distance of the intercept path to the center of the target [Ball, 2003]. By means of the proximity fuze (target detector), warhead is initiated while missile is passing near the target. Air to air missiles are this type of threat for military aircraft. A fragmentaion warhead includes high explosive inside the body and after detonation of the explosive, high velocity fragments are dispersed from the warhead which may damage the target once they hit the target. Hence, determining vulnerability and the evaluation of the survivability of aircraft against this type of threat is a necessary issue for survivability analysis.

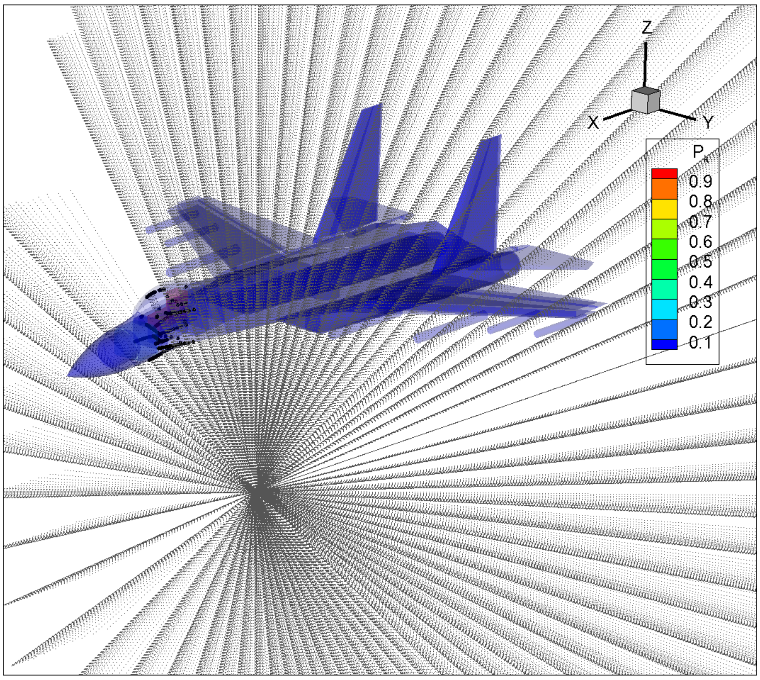


Figure 1: *Aircraft vulnerability analysis performed using HATa software against a single engagement of a fragmentation warhead*

In the nature of engineering, finding the best way for the design is very important to obtain the most effective final result. To find the best way for survivability in terms of vulnerability reduction, a mathematical tool is needed. This tool should give numerical values to assess the vulnerability of an aircraft configuration against different threats. It should give component level, (sub)system level and aircraft level kill probability and/or vulnerable area as the numerical result.For this purpose, an aircraft vulnerability assessment software has been developed called HATa (in Turkish "*H*ava *A*raçları*Ta*hribi Hesaplama Yazılımı"). This software is a tool which can be used not only for the assessment of vulnerability of aerial vehicles but also for the design and analysis of anti-aircraft warheads. Figure 1 shows a generic calculation performed using HATa software. In Figure 1, shotlines originating from the detonation location of a missile warhead are shown. Shotlines represent warhead fragments which travel with very high speed and some of them may hit the target aircraft in critical locations. In this study, using the HATa software, vulnerabilities are analysed for two generic aircraft to compare the effect of two engine and single engine configurations for the tail-chase engagements of the air-to-air missile with target aircrafts.

METHOD

Survivability and Vulnerability Relation

Survivability is the ability to remain mission capable after a single engagement. In other words, survivability is capability of an aircraft not to be killed by the threats such as anti-aircraft munitions. Hence, starting with this expression, survivability can be described mathematically as given by equation (1) [Ball, 2003]:

Probability of survivability = 1 – Probability of killability :

$$P_S = 1 - P_K \tag{1}$$

where

Probability of killability = Probability of susceptibility x Probability of vulnerability

Therefore,

$$P_S = 1 - P_H P_{K/H} \tag{2}$$

If the aircraft could have zero susceptibility, aircraft would be completely survivable during combat since it would not be hit by the threats. However, designing an aircraft with zero susceptibility is not possible and hit of the aircraft by threats during combat is not a case which can be underestimated. Therefore, vulnerability issue has a very important place in the survivability of an aircraft.

Vulnerability Calculation

Vulnerability calculation of an aircraft consists of the interaction of the threat with the aircraft. For example, for a missile with fragmentation warhead detonated at a distance away (miss distance) from aircraft (see Figure 2), calculation starts with the determination of the spatial distribution of the fragments and the initial velocities of these fragments just after the detonation. Then, fragment trajectories and the velocity decays due to air drag are determined. Additionally, the engagements and hits of the fragments to the aircraft should be determined. Where the fragments hit on the aircraft and which components can be hit are determined using shotline algorithm integrated in the developed code. The hit locations inside the aircraft are determined by tracing the fragments through the aircraft provided that the hit has enough energy to penetrate into the aircraft through its exterior. After the traces of the fragments through the aircraft are determined, hit locations, components which are hit by the fragments, mass and the velocity of the impacting fragments are determined using penetration equations. Then, probabilities of kill of the hit components are calculated and lastly probability of kill of the aircraft is determined cumulatively.

Shotline algorithm is important part of the vulnerability analysis tool. It should not require too much time to give the traces of the fragments not to result in too much CPU time for whole process. Because, during the calculations many shotline calculations are needed for the hundreds of the fragments hitting the aircraft. For this purpose, a fast shotline algorithm is integrated in the developed code.

For each trace of the fragment along the target aircraft, penetration calculations are performed and which components are being hit with which velocity and mass of the fragments are determined. Then damage and probability of kill of the components are determined according to the characteristics of the hitting fragments.

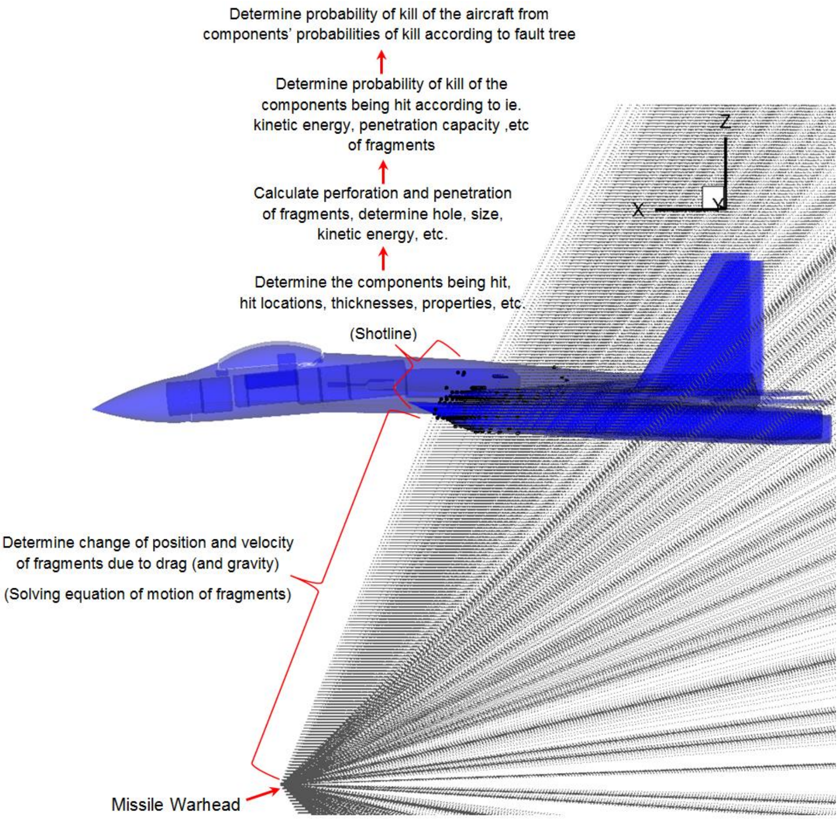


Figure 2: *Fundamental steps of aircraft vulnerability assessment*

An aircraft consists of many components which are crucial for flying. These components are considered as critical components for the aircraft. They can be single meaning non-redundant or more than one item may do the same function which implies redundancy.

Kill of each non-redundant critical component due to hits by threats results in the kill of the aircraft. Hence, probability of survivability and probability of kill of an aircraft whose non-redundant critical components are hit can be calculated as follows:

$$P_S = \prod \left(1 - P_k\big|_i\right) \tag{3}$$

$$P_K = 1 - \prod \left(1 - P_k\big|_i\right) \tag{4}$$

where P_S is the probability of survivability of aircraft, P_K is the probability of kill of aircraft and $P_k|_i$ are non-redundant critical components' kill probabilities. By this equation, it can be interpreted mathematically that individual kill of just one of the non-redundant critical components does result in the kill of the aircraft. For instance, kill of the pilot of one seated aircraft results in attrition kill of aircraft due to loss of control.

When the aircraft has redundant critical components, such as in two engine aircraft, aircraft can fly with one of two engines working, probability of survivability and probability of kill of the aircraft whose redundant critical components are hit can be calculated as follows:

$$P_S = 1 - \prod_{i=1}^{nr} P_k\big|_i \tag{5}$$

$$P_K = 1 - \left(1 - \prod_{i=1}^{nr} P_k\big|_i\right) = \prod_{i=1}^{nr} P_k\big|_i \tag{6}$$

where $P_k|_i$ are redundant critical components' kill probabilities and nr is the number of redundant critical components. By this equation, it can be interpreted mathematically that individual kill of just one of the redundant critical components does not result in the kill of the aircraft. Kill of the aircraft due to redundant components occurs when all the redundant components are hit and fail to work.

Therefore, using equations (4) and (6), the probability of kill of the aircraft due to all of the critical components can be calculated as follows:

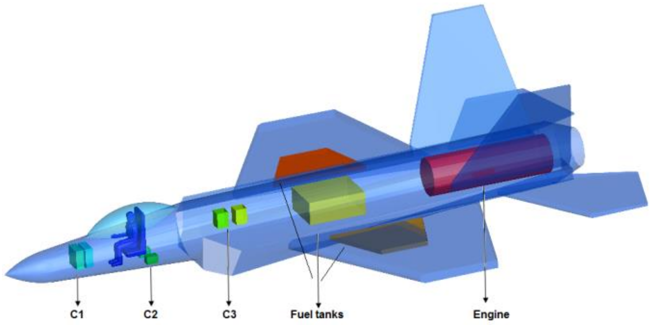
$$P_K = 1 - \prod_{i=1}^{nnr} \left(1 - P_k\big|_i\right) \cdot \prod_{j=1}^{nrs} \left(1 - \prod_{i=1}^{nr_j} P_k\big|_{i,j}\right) \tag{7}$$

Where nnr is the number of non-redundant critical components, nrs is the number of sets (systems) with redundant critical components and nr_j is the number of redundant critical components of j^{th} redundant set.

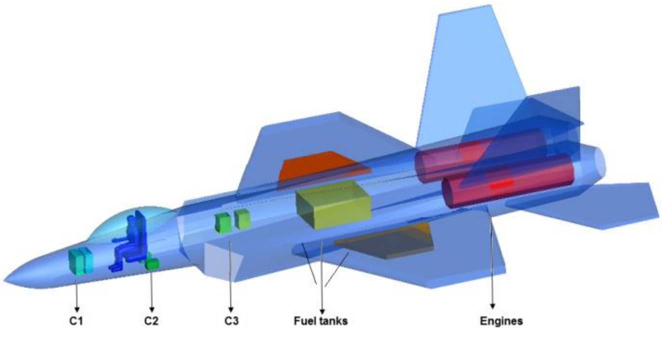
According to a kill level, fault tree of the aircraft is determined and this tree is used to determine the redundant and the non-redundant critical components [Pei, Guo, Dong, Song, 2013; Pei, Guo, Dong, Song, 2011]. In the fault tree, based on the distribution of the “and” and “or” gates, the total probability of kill of the aircraft given by equation (7) is determined.

CALCULATIONS

In order to evaluate the effect of using two engines in terms of the survivability of the aircraft, two generic aircraft vulnerability models are formed. First model includes one engine and the other one includes two engine as shown in Figure 3. The aircraft models have also pilot, main critical components such as flight computers, power supplies etc. and fuel tanks.



a) Single engine model



b) Twin engine model

Figure 3: *Aircraft Vulnerability Models*

Generic fault trees are constructed for the single engine aircraft and twin engine aircraft as shown in Figure 4 and Figure 5. In both models, three sets of critical components are defined which are flight computers (C1, C2) and power supplies (C3). These sets include redundant critical components. However, pilot and fuel tanks are defined as non-redundant components. Fuel tanks are treated such that when a fragment impacts the fuel tank, it may cause fire and eventually leads to explosion which ultimately causes attrition kill of the aircraft. For single engine aircraft, engine is non-redundant and for twin engine aircraft engines are redundant assuming the aircraft can continue to fly with one engine.

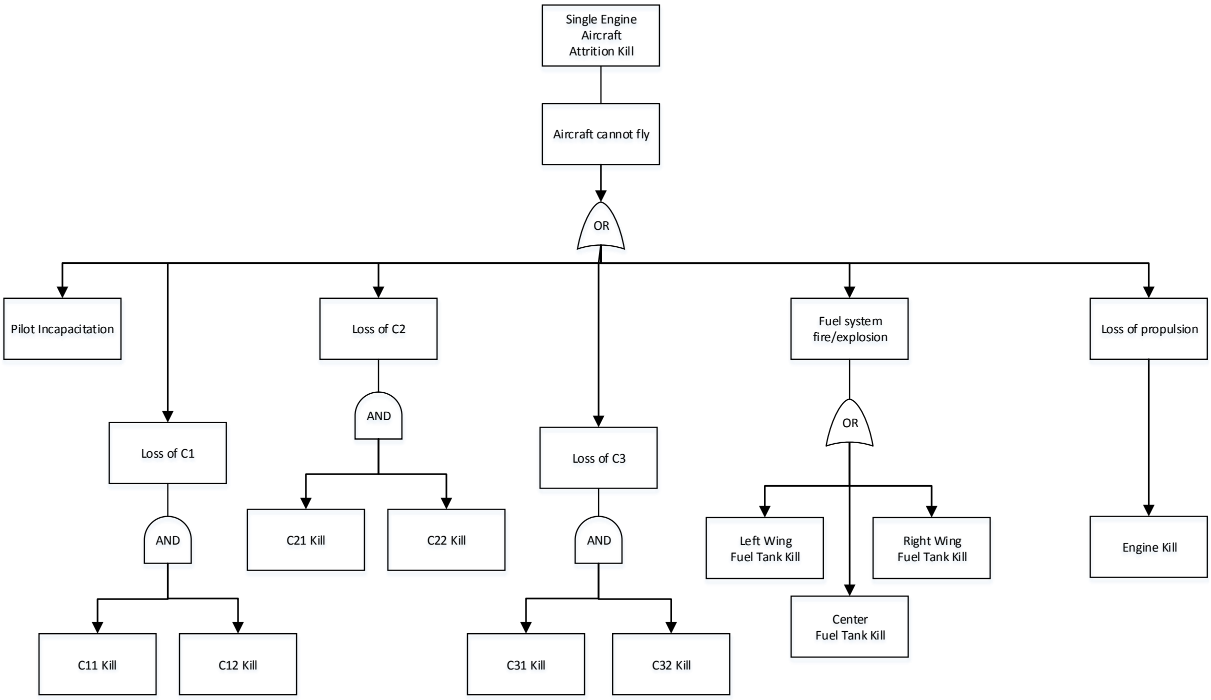


Figure 4: *Generic Single Engine Aircraft Fault Tree*

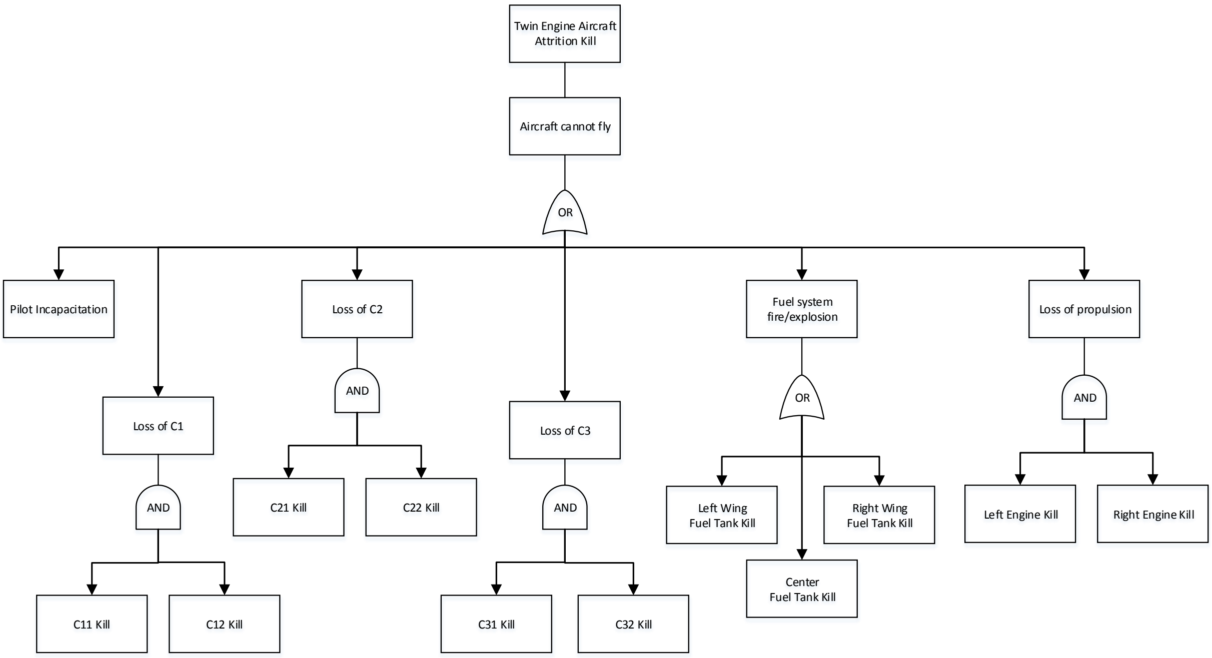


Figure 5: *Generic Twin Engine Aircraft Fault Tree*

The simulations are performed for tail-chase engagements of the air-to-air missile with target aircraft as shown in Figure 6. Tail-chase engagement condition is the case when guided missile approaches the aircraft from tail side, and for the simulations flight path of the missile is taken as parallel to the flight path of the aircraft. Intercept paths for the missile are generated at the elevation angles ranging from -90 to 90°. As shown in Figure 7, elevation angle is measured as the angle of the miss distance vector from the horizontal. Miss distances are taken in the range of 2 -12 m with 1 m intervals. The simulations are carried out at the points along each intercept path with 0.25 m intervals as shown in Figure 7. Only the effect of the fragments are calculated and the blast effect is not included in the calculations.

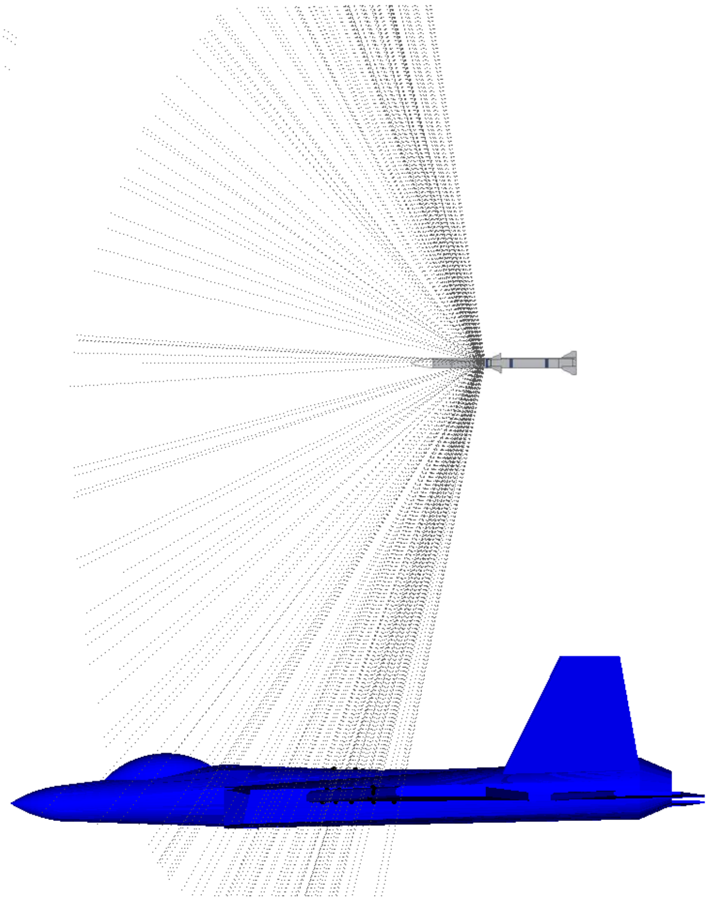


Figure 6: *A Simulation of the Detonation of the Warhead on a Location along the Intercept Path for the Tail-Chase Engagement of the Missile with the Aircraft*

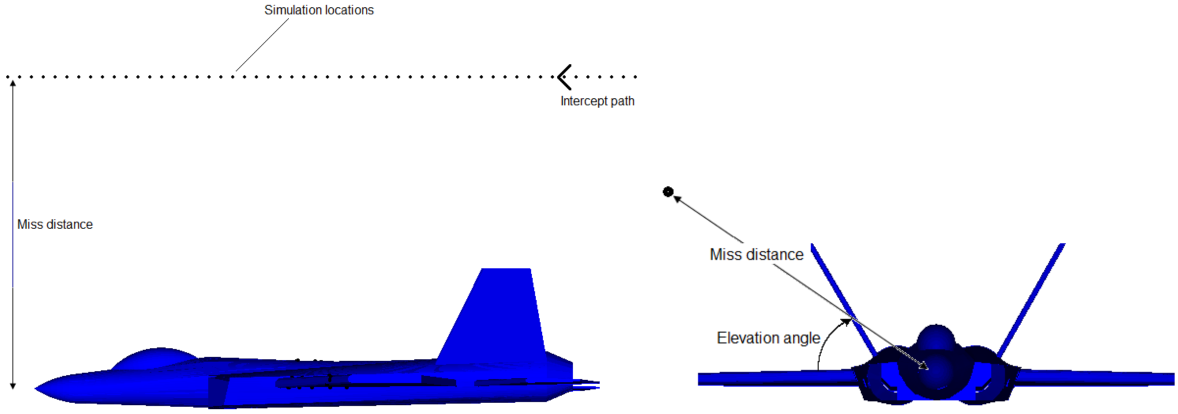
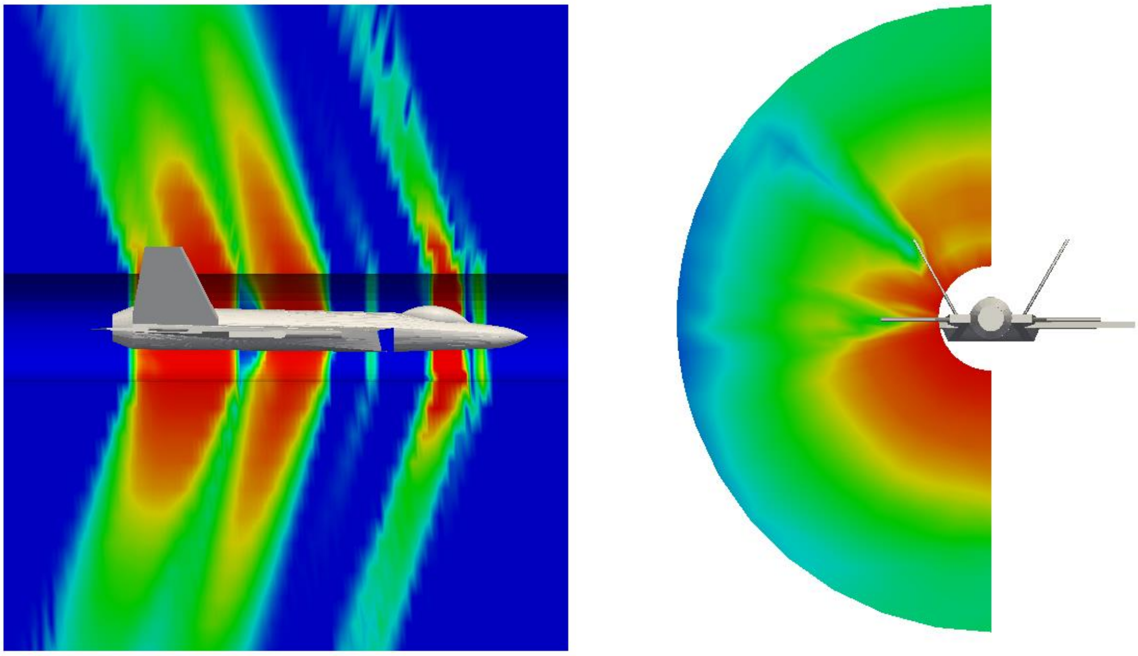
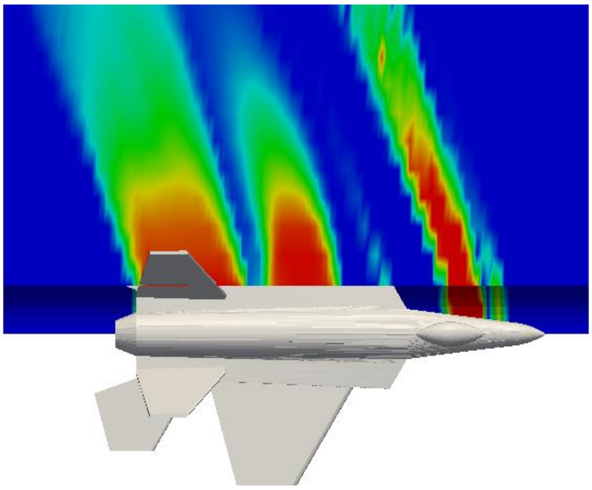


Figure 7: *Demonstration of Simulation Locations*

The simulations are performed at many intercept locations as shown in Figure 7 for both aircraft models. For different relative positions of the missile and the aircraft, probability of kill (P_k) distribution around the aircraft due to fragmenting warhead is determined. Figure 8 shows the P_k distribution constituted by the fragmenting warhead around the generic single engine aircraft and Figure 9 shows the P_k distribution around the generic twin engine aircraft.



a) Upper and lower side b) Around engine



c) Left side

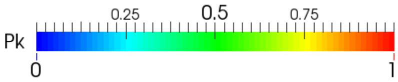
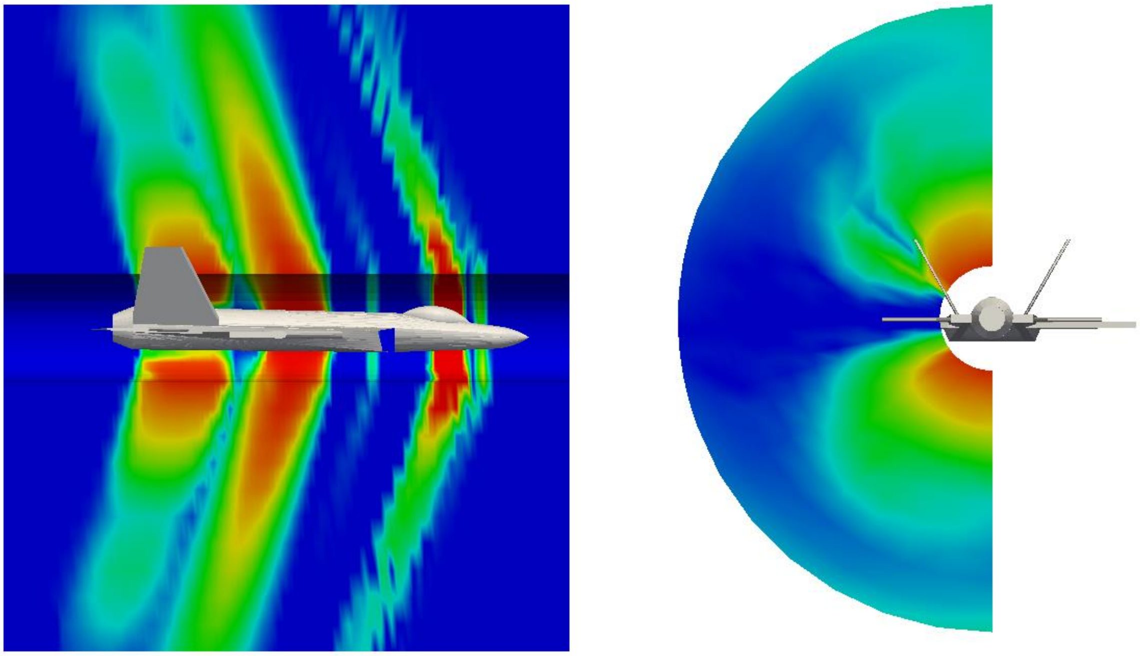


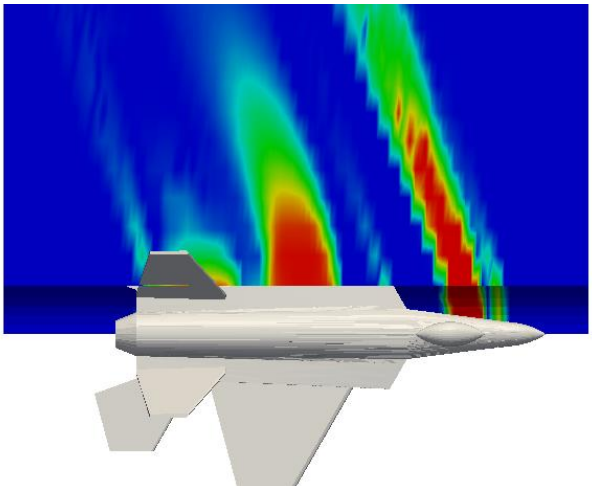
Figure 8: *Probability of Kill Contour of Fragmentation Warhead around Single Engine Aircraft*

When the P_k distributions for the two models are compared, it is observed that when detonation occurs, fragmentation warhead can be effective in a larger volume (at more locations) around the engine of the single engine aircraft compared to the twin engine aircraft (compare Figure 8 b-c and Figure 9 b-c). This is because of the redundancy of the engines for the propulsion of the aircraft. For the engagements of the missile at the side of the one engine for the twin engine aircraft, when one engine is killed, due to the shielding of the killed engine the other engine is not killed, hence the warhead cannot be effective for the detonation locations at side of one engine as shown in Figure 9 b.



a) Upper and lower side

b) Around engines



c) Left side

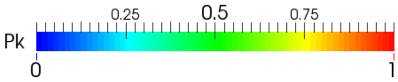


Figure 9: *Probability of Kill Contour of Fragmentation Warhead around Twin Engine Aircraft*

Additionally, it can be observed from Figures 8 and 9 that fragmentation warhead can cause attrition kill if detonates around the pilot and around fuel tanks. Other critical components may also be killed by the fragmentation warhead to cause attrition kill, however the probability of kill around those components is much less compared to the probability of kill of non-redundant components such as the pilot and the fuel tanks. It should be noted that for the demonstration problems, critical components C1, C2 and C3 in the fault tree are redundant and their presented areas are small. For detonations occurring near the pilot, fragmentation warhead can be more effective at larger miss distances when detonation occurs at the side of the aircraft compared to detonations occurring in locations at the upper and lower side of the aircraft. Comparison of Figures 8a and 8c for the single engine aircraft and Figures 9a and 9b for the twin engine aircraft reveals this fact clearly. Since the presented area of the pilot is larger when viewed from the left and the right sides of the aircraft compared to the presented area when viewed from the lower and the upper side of the aircraft, probability of hit of the pilot by the fragments are higher when the detonation occurs on the left and right sides of the aircraft.

Furthermore, in order to evaluate the survivability of the aircraft against the fragmentation warhead threat, a numerical value called “the mean volume of effectiveness” (MVE) of the warhead is defined. This value is the volume integral of the P_k distribution around the aircraft as given in Equation (8).

$$MVE = \iiint P_k \cdot dV \tag{8}$$

This volume integral gives the mean volume around the aircraft where the warhead can be lethal. Survivability enhancement of the aircraft should decrease MVE caused by the fragmentation warhead. From the vulnerability calculations given above, MVE of the fragmentation warhead for both aircraft models are determined and they are given in Table 1. It is determined that for the tail-chase fragmenting warhead threat, two engine configuration has a MVE which is about %30 less compared to the MVE of the single engine. This result shows that the probability of survivability of the twin engine configuration aircraft is higher than the probability of survivability of single engine configuration against tail chase missiles with fragmentation warhead.

Table 1: *Comparison of Mean volume of Effectiveness Single and Twin Engine Configurations*

	MVE of the Fragmentation Warhead [m^3]
Single Engine AC	1029
Twin Engine AC	731

CONCLUSION

In this paper, effect of using two engines instead single engine in terms of the survivability of the military aircraft against fragmentation warhead threat is determined by the simulation performed using survivability/vulnerability software HATa which is developed. For this purpose, two generic aircraft vulnerability models are formed which have the same critical components except that one aircraft has single engine and the other aircraft has twin engines. The survivability of the both aircraft against a fragmentation warhead is evaluated by vulnerability calculations. An air-to-air missile fragmentation warhead interaction around both aircraft are calculated on many points on many intercept paths for parallel tail chase engagements. At each point the probability of kill is determined to obtain the P_k distribution around the aircraft due to the fragmentation warhead. It is shown that for side engagements of the missile near the engine, twin engine aircraft can survive because of the redundant engines, however single engine aircraft most probably cannot survive for the same case. For the comparison of the overall survivability of the single and twin engine aircraft configurations, the mean volume of effectiveness (MVE) of the fragmentation warhead is defined. For the demonstrative fault trees established for the single and the twin engine configurations and for the tail-chase engagements of the missile, MVE of the warhead is determined to be %30 less for the twin engine aircraft compared to the single engine configuration. This value shows the survivability enhancement of using two engines compared to single engine case.

It should be noted that there are a lot of parameters to determine for the single or twin engine configurations during the design phase of an aircraft. For military aircraft, survivability is crucial for the permanence during military operations at hostile environments. This paper shows that using two engines for a military aircraft improves the survivability of the military aircraft in terms of vulnerability.

Additionally, it can be observed from the P_k distributions around the pilot cabins that this part of the aircraft is very critical for the vulnerability of the aircraft. It should be noted that pilot is more vulnerable than other material components because pilot can be incapacitated by fragments with less kinetic energy compared to other components and the presented area of the pilot is higher compared to the presented areas of most of the critical components. Therefore, if possible, installing the most critical components especially non-redundant ones near the pilot rather than putting them in a place away from the pilot in the aircraft is better for the survivability of the aircraft because pilot is already too vulnerable. Moreover, protecting the pilot by properly arranged armors can increase the survivability of the pilot and the aircraft.

HATa is the first aircraft vulnerability/survivability calculation software developed in Turkey. This tool can be used not only for the vulnerability/survivability analysis but also for the blast/fragmentation warhead lethality calculations. It can be used for any moving or static target against the fragmentation warhead threat by defining proper kill definitions and the fault tree. Survivability consideration is crucial for the design of the military aircraft and HATa software is a tool for the evaluation of the survivability of the aircraft.

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