Flight Trial against Low Speed Ballistic Target Emulating High Speed Target Interception

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Abstract—**Defending the territory against the incoming threats like high speed Intercontinental Ballistic Missiles (ICBMs), Theatre Ballistic Missiles (TBMs), multiple Re-entry Vehicles (RVs), Quassi-Ballistic Missiles (QBMs) and simultaneous or coordinated attack of one such class or combination of all, still poses a daunting challenge to the missile defence designers. Although missile and other supporting systems are designed (or selected) using extensive modeling & simulations and each of them undergo various stages of qualification and checks, it is imperative to carry out the actual flight trials to assess the performances of each of these along with the overall mission. Many times, flight trial with actual target is not possible due to unavailability of high speed (or higher range) targets and test range constraint. In this paper, a method has been proposed where the flight trial can be conducted with a low speed target which can simulate all the problems of hight speed target and hence eliminate the requirement of testing high speed real target.**

Index Terms—**Ballistic Missile Defence, High Speed Target, Hardware Limitation, Flight Simulation.**

On March 23, 1983, Ronald Reagan announced the Strategic Defense Initiative (SDI), popularly known as Star Wars. Subsequently several other countries also pursued for Ballistic Missile Defence (BMD) for their own countries security. Ironically each of those countries also gave great importance to developing very intelligent and highly effective offensive missiles capable of delivering nuclear warhead, which will eventually cause enormous destruction to the enemy landmass. The technologies required to engage these targets, also developed in later times and thus the battle for supremacy between offensive and defensive capabilities continued forever [et. al [2]].

To reliably destroy even a simple, non-manoeuvering target traveling at great speeds (upto 8-10 km/s) and probably possessing decoys to create last moment countermeasures is very difficult. To do so, for many such objects approaching simultaneously has simply been infeasible. The margin of error in BMD operation comes down dramatically if target accompanies nuclear warheads. Nuclear weapons enormously compounded the technological challenge of BMD, because they set the standard for system performance so high. In essence, when the target payloads are nuclear warheads, only perfect or near-perfect BMD performance is of any real interest [[3]].

The missile defence has seen many successes worldwide and still remain one of the major area of technological marvel. Introduction of new technologies has pushed the interceptor design, as well as the associated weapon systems to perform as a full proof missile shield, but none of the systems worldwide has provided the guarantee of 100% protection against the enemy targets.

Although missile and other supporting systems are designed (or selected) using extensive modeling & simulations et. al. [4] and each of them undergo various stages of qualification and checks, it is imperative to carry out number of flight trials to assess the performances of each of these along with the overall mission. The development phase of Missile defence system can only be finished if validation in terms of sufficient number of flight trials are done and the performance is demonstrated.

The purpose of flight trials is to prove the concept and all the subsystems. This can be done even with electronic target and low speed targets.The other objective is to show the capability in real scenarios. But validation at entirety usually is not possible due to following type of problems:

1) Flight trials may not be cost effective,
2) Targets of all class may not be available
3) Test range may not be adequate to accommodate the engagement geometry
4) Enemy target information not known precisely and hence the target that is to be used in flight trial, can not guarantee exact target behavior
5) Full scale war, where the actual enemy target may be fired is not an obvious option
6) International pressure, etc

In such scenarios, the most appropriate methodology that can be followed is to use the modeling and simulation for the entire operating envelope to assess the performance of the missile under all possible cases. Subsequently the validation procedure has to be established. The validation process can follow a two step approach:

1) Feasible engagements: Number of flight trials can be conducted and the flight trial data need to match with the pre-flight performance predictions.
2) Infeasible engagements: Every complex system contains several smaller subsystems. In the BMD scenario there are several elements that participate in the overall mis-

sion of neutralizing the target. The designer need to find out the infeasible elements (or unrealistic conditions) that hinder the actual validation process or conducting the flight trial. These elements (flight conditions) can be replaced with their corresponding models (or equivalent simulated conditions) to conduct a scaled flight trial where a logical conclusion can be ascertained about the overall system performance.

This paper explains the innovative method where a low speed target can be used in the flight trial, but inducing all these problems into the BMD performance. The higher seeker gimbal angle requirement can be demanded by selecting the target with higher re-entry angle. This in turn as higher gimbal to track the target. Higher miss can be achieved by intentionally delaying the seeker pointing, thus reducing seeker homing time and by making the handing over error to build up for some more time. Warhead firing time error can be introducing additional noise and bias into the RPF measurements. The lower reaction time can be simulated by skirting off the early warning radars beam in such a way that delayed detection will occur. All these concepts can be combined, to obtain the desired flight trial performance against a high speed target by using a more realistic low speed counterpart.

This paper is organized as follows: The operating principle of BMD systems and different challenges posed for the successful neutralization of an incoming target are explained in chapter-2 and 3 respectively. Gimbal angle requirement due to higher target speed is discussed in chapter-4 along with the technique to simulate the same using the low speed target in the flight trial. Subsequently, chapter-5 & 6 provides insight into the problems of higher miss distance and increase of firing time error and its associated simulation conditions. The reaction time problem is deliberated in the next section followed by the concluding remarks.

I. Problems Posed to the Ballistic Missile Defence System

Ballistic missile defence programs around the world has faced constant deliberation in terms of financial implications w.r.t offence vs defence policy. Attack is always found have an upper hand and this lead to the design and production of intelligent and very lethal offensive missiles. Intelligence provided to the Ballistic missiles tend to defeat the defence capability and hence BMD remains as second fiddle in terms design and development. Technology limitations at various subsystem design phase has compounded the problem to higher scale. Although several advances have been made and several countries could show the target neutralization, the full scale validation and target neutralization in the entire gamete of operation remains as a challenge.

The major problems posed by the high speed targets on the BMD performance are:

1) Demand larger seeker gimbal angles for target tracking.
2) Miss distance increases as the time available handing over correction reduces due to lower seeker homing time.
3) Error in the computation of warhead firing time, escalates to a level, where the missile exhibits the tendency to miss the target.
4) Reaction time of the BMD system as a whole, reduces as the target speed increases. The time available from the time the target is detected (by the early warning radars) to the actual launch of the missile fall drastically with target speed.

Extensive flight simulation are done to validate the missile performance prior to the flight trial. The aim is to reduce the number of required amount of flight testing. In case of complex aerospace systems this provides well recognized benefit. Simulation usually identify the scenario and the different possible cases in respect of subsystems to predict the overall performance [[1]]. This paper backs the idea of combining the concept of simulation and conducting certain number of flight trials, so that many impractical missions can be avoided.

II. Simulating Gimbal Angle

A typical engagement geometry for ballistic missile interception appears as shown in fig-[1 & 2]. Here it is assumed that missile longitudinal axis is along its instantaneous velocity vector (i.e. angle of attack at the end are assumed zero). This is a safe assumption as missile guidance does not keep much correction at the end. The target usually diffused in its decent phase, which means missile will look at the target always in the upper horizon. Hence seeker needs a higher pointing freedom towards the upper direction, RPF beam should be pointed upward and if a directional warhead is employed it also need to be canted towards body up direction.

The engagement cannot happen in a tail-chase mode because of the high velocity disadvantage of the interceptor with respect to the target [et. al. [6]]. Hence the flight path angle of the missile cannot become negative at the end. The minimum possible value of terminal flight path angle of missile can be 0^0.

Thus the guidance law used in the missile has to have the following objectives:
(i) Non-negative flight path angle at interception.
(ii) Range of interceptor is enhanced with low velocity loss.
(iii) Meet the seeker look angle constraint during terminal phase.

From the Fig-[1,2] the relationship between the gimbal angle and flight path angle can be found in both the planes (Azimuth plane & Elevation plane), and this relationship is given by Eqn-1.

$$\begin{aligned} \tan\left(\phi_{e_f}+\gamma_{e_f}\right) &= \frac{-V_{T_X}+V_{M_f}\sin\gamma_{e_f}}{V_{T_H}+V_{M_f}\cos\gamma_{e_f}} \\ \tan\left(\phi_{a_f}\right) &= \frac{V_{T_H}\sin\left(\psi_T-\gamma_{a_f}\right)}{V_{T_H}\cos\left(\psi_T-\gamma_{a_f}\right)+V_{M_f}\cos\gamma_{e_f}} \end{aligned} \tag{1}$$

The elevation plane equation can be solved independently as:

$$V_{T_H}\sin\left(\phi_{e_f}+\gamma_{e_f}\right)+V_{T_X}\cos\left(\phi_{e_f}+\gamma_{e_f}\right)= \\ V_{M_f}\left[\sin\gamma_{e_f}\cos\left(\phi_{e_f}+\gamma_{e_f}\right)-\cos\gamma_{e_f}\sin\left(\phi_{e_f}+\gamma_{e_f}\right)\right]$$

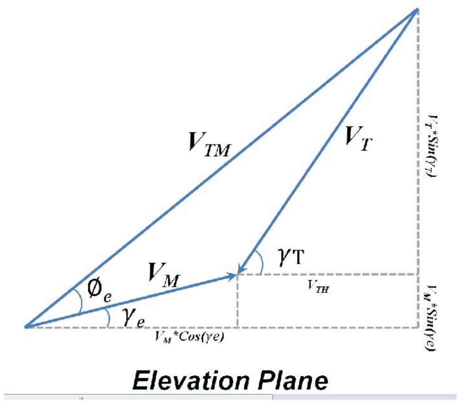

Fig. 1. Elevation Plane of the Engagement

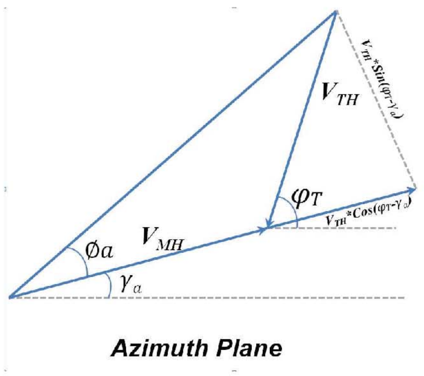

Fig. 2. Azimuth Plane of the Engagement

Further simplification lead to

$$\left(V_{T_H}\sin\gamma_{e_f}+V_{T_X}\cos\gamma_{e_f}\right)\cos\phi_{e_f}=\\ \left(V_{T_X}\sin\gamma_{e_f}-V_{T_H}\cos\gamma_{e_f}-V_{M_f}\right)\sin\phi_{e_f}$$

The solution in the elevation plane appear in the following form as:

$$\phi_{e_f}=\tan^{-1}\frac{V_{T_H}\sin\gamma_{e_f}+V_{T_X}\cos\gamma_{e_f}}{V_{T_X}\sin\gamma_{e_f}-V_{T_H}\cos\gamma_{e_f}-V_{M_f}} \quad (2)$$

where

$V_{T_X}=V_T\sin\gamma_T$: Target Vertical Velocity
$V_{T_H}=V_T\cos\gamma_T$: Target Horizontal Velocity
$V_{M_f}=$ Missile terminal Velocity

Priori information about V_T and γ_T are required to be known which are target parameters at the time of interception. These can be obtained by extrapolating the current target states, till the desired altitude of kill using a realistic ballistic model. The calculation will give better result if there is no target maneuver.

The solution in the azimuth plane can be obtained in a similar way as:

$$\phi_{a_f}=tan^{-1}\left[\frac{V_{T_H}\sin\left(\psi_T-\gamma_{a_f}\right)}{V_{T_H}\cos\left(\psi_T-\gamma_{a_f}\right)+V_{M_f}\cos\gamma_{e_f}}\right]$$

where ψ_T can be assumed to be constant, if target does not perform any maneuver. γ_{a_f} is the terminal heading angle of the interceptor. This can be available by joining the line between the predicted target point and the missile launch location. Missile usually engage the target by traveling in this fictitious line and hence this angle can also be assumed constant.

Using this algorithm, for the given terminal flight path angles $\left(\gamma_{a_f},\gamma_{e_f}\right)$ terminal desired gimbal angles $\left(\phi_{a_f},\phi_{e_f}\right)$ can be calculated using eqn-[2 & 3].

Seeker Gimbal angle Requirement

Case No	Target Speed (m/s)	Target Re-entry Angle (deg)	Elevation Gimbal Angle (deg)	Azimuth Gimbal Angle (deg)
1	1000	50	25	0
2	1000	60	30	0
3	1000	70	35	0
4	2000	50	33	0
5	2000	60	40	0
6	2000	70	48	0
7	3000	50	38	0
8	3000	60	46	0
9	3000	70	54	0
10	4000	50	40	0
11	4000	60	49	0
12	4000	70	57	0
13	5000	50	42	0
14	5000	60	51	0
15	5000	70	60	0

Fig. 3. Seeker Gimbal angle Requirement

Different engagement scenarios are explored to explore the problems encountered by the interceptor against different types of targets. The Missile velocity is assumed to be 1000m/s. Whereas the target velocity is considered as 1000m/s 2000m/s, 3000m/s, 4000m/s and 5000m/s for different runs. The target flight path angle in elevation plane is varied over the range [50-70] deg. Using the eqn-[2 & 3] the terminal gimbal are calculated and tabulated. Results are validated using full missile 6DOF model and realistic target model[[5]] for each of the given engagement scenarios.

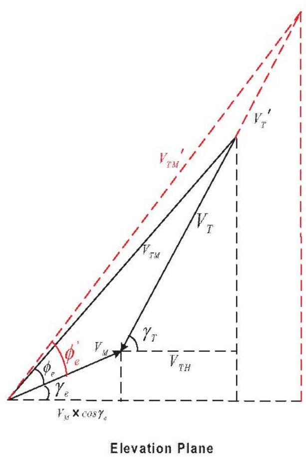

Fig. 4. Effect of High Speed Target

Figure-[3] & [4] suggests that as the target class increases or/and the target re-entry angle increases the seeker gimbal requirement also goes up. Similar effect can also be seen in the azimuth plane as well, where the crossing angle will dictate the azimuth gimbal angle requirement similar to re-entry angle in the elevation plane. However, every seeker comes with the gimbal limitations and hence the higher class targets tracking may not be as easy as compared with lower class. But, the effect of high speed target in gimbal angle requirement can be replicated using a low speed target but its trajectory can be configured so that higher re-entry/crossing angle can be achieved which in turn push the requirement for higher gimbals.

From the above analysis it is evident that, to simulate the case no-13 i.e. target velocity of 5km/s and reentry angle of 50^0, case no-5 can be chosen which is against a target moving with 2km/s velocity and having an re-entry angle of 70^0.

III. Simulating Higher Miss Distance

As the target speed increases, the achieved miss distance also grows. This is due to the fact that for a given seeker range, the homing time reduces as the target velocity increases (producing higher closing velocity). This in turn reduces time availability for correcting the handing over error. If handing over error between Radar to seeker is not corrected fully, miss will occur.

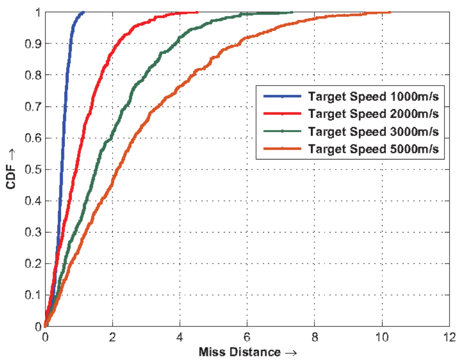

Fig. 5. Miss Distance vs Target Speed

From the above figure it is evident that the miss grow exponentially after a certain target speed. Hence it is Imperative to plan the flight trial against such target which gives higher miss. The scenario can be reconstructed using the low speed target in the flight trial while delaying the seeker lock on by reducing the seeker transmitted power and also increasing the handing over error at seeker handover time by introducing position bias in the radar measurements.

Thus with only a 1000m/s target and by modifying test conditions the scenario similar to a 5000m/s target could be exactly simulated. The miss profile became similar to the actual target case as shown in fig-[6]. Hence, it is concluded that the flight trial with lower speed target could reproduce similar result as the actual case.

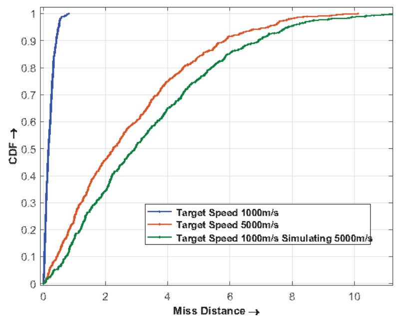

Fig. 6. Miss Distance vs Slow Target with Simulated Condition

IV. Simulating Warhead Firing Time Uncertainity

Radio Proximity Fuze gives very accurate target states measurements (Range and Range Rate) during the terminal phase of interception. Missile OBC uses them to compute warhead firing time and issues firing pulse to the detonation mechanism. Like other sensors, RPF also possess hardware limitations in terms of noise, bias and accuracy limits. Due to this, there may be error in the firing time computation. In simulation test bed, this error is calculated by comparing against the firing time obtained using the true target information.

Case No	Target Speed (m/s)	Tolerable firing time error (ms)	Maximum firing time error (ms)
1	1000	$\pm$ 2.50	0.4
2	2000	$\pm$ 1.25	0.5
3	3000	$\pm$ 0.83	0.6
4	4000	$\pm$ 0.62	0.7
5	5000	$\pm$ 0.50	0.8

TABLE I
Bounds of Firing Time Error

To illustrate the effect of the firing time error on the target neutralization, the table-[I] is constructed. Assuming a target of 3.0m in length and warhead fragment cloud diameter of 2.0m, the target residency time within the warhead beam can be found out which is summarized in the table. The result shows, the allowable limits on the firing time error, comes down drastically as the target speed increases.

Montecarlo simulation is carried out with 500 runs for 3 such cases and the results are given in fig-([7]-[9])

The low speed targets produces lower miss as homing time is more. All the corrections must have finished before commencing the endgame guidance. The missile and target must be in the collision course that result in near miss and higher warhead effectiveness. The probability of target killing is very high in these cases. The target residency period (target inside warhead beam) extends to more than 1 msec on either side which gives extra margin for any error in the firing time computations.

As the target speed goes up, the error in firing time also increases and the residency time comes down. Both of these

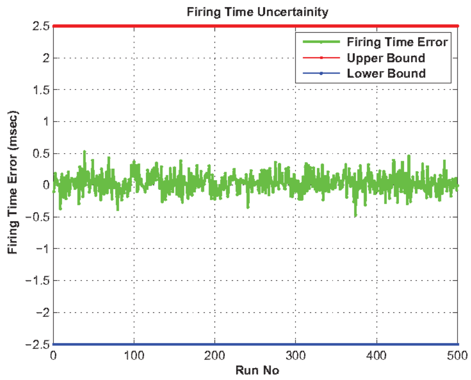

Fig. 7. Firing Time Error against Low Speed Target

factors severely affect the overall performance of interceptor against the target. Margins in terms of firing time error becomes non existent after certain target speed and this will dictate the interceptor capability.

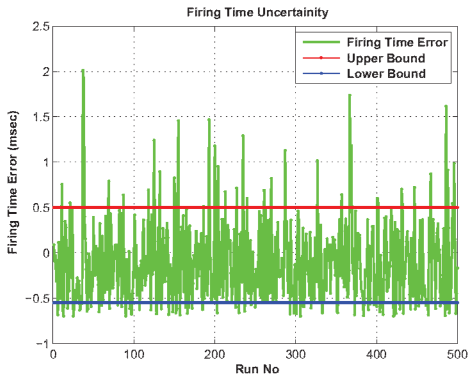

Fig. 8. Firing Time Error against Medium Speed Target

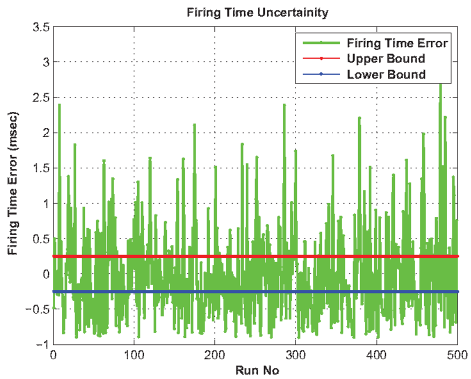

Fig. 9. Firing Time Error against High Speed Target

V. Simulating Lower Reaction Time

Subsequent to the Ballistic Target launched by the enemy country the first event of BMD system is the target detection by the network of early warning radars installed in the defending country. Now as the target speed increases, the time taken by the target to reach a particular location gets shorter and shorter. The BMD systems usually works in two modes: Hot start and cold start. In case of cold start launch, all the missile subsystems are switched ON only after the target is detected by the radars. The time taken by the interceptor missile from target detection to actual launch is called as reaction time. If the reaction time falls below the total preparation time required by the BMD system, the mission will fail to achieve the objective of neutralizing the target.

Low reaction time being caused by the target speed which is linked to the performance of the overall weapon system in BMD, need to be tested in flight trial. This scenario can be tested by: launching a low speed target against the BMD system and also delaying the target detection by radar either by intentionally positioning the radar beams at selective zone so that radar picks the target late or by ignoring all the measurements coming from the radars till a point where the time-to-launch becomes close to the missile preparation time.

VI. Conclusion

Effect of higher Target speed is studied in detail and a novel approach for alternate way of validating the interceptor performance is deliberated. The results are found to be very promising. The impact of the above said work is huge, as complete BMD performance validation is possible with less number of flight trials with low speed target. This can lead to massive saving of development time as well as cost. Cost will be going to be a major boost to the overall programme. Thus only a limited numbers of flight trials are necessary to check the interceptor effectiveness against some targets, while against the others, BMD performance can be demonstrated in a tailor made flight trial where the same low speed target can be used, while retaining all the problems posed by the high speed targets.

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