THE APPLICATION OF OPTIMAL FLIGHT PATHS IN COMPLEX AERIAL COMBAT SIMULATIONS

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Abstract

In order to analyse the effectiveness of weapon systems in aerial combat, complex digital simulation programs are used. Tactics and manoeuvres in such engagements are very complex due to the large number and complexity of interactions. This complexity makes the formulation of current optimisation techniques for the engagement unrealistic.

In this paper, elements of the combat have been identified and optimal controls for a particular manoeuvre are derived. These are then developed into tactical rules for use in combat modelling. The objective is to develop readily usable techniques for use in highly dynamic and complex air combat simulations.

The purpose of the paper is to develop a methodology whereby the optimal controls developed above can be applied to a complex air combat simulation. The benefits of using optimised manoeuvres can then be assessed using combat effectiveness measures. Such a methodology will ensure that weapon systems are being used to their full potential in the simulations, giving a more realistic assessment than considering optimal control or aircraft performance and capabilities in isolation.

1. Introduction

Air to air combat as represented by combat models can be very complex, sometimes involving many aircraft and sophisticated weapon systems. Both beyond visual range (BVR) and close in combat (CIC) engagements may occur. It is currently impossible to optimise the behaviour of the combatants in such a complex scenario. However, analysis of the air combat problem has shown elements within the combat which can be optimised in isolation.

In representing the tactical logic for scenarios such as this, combat simulations must use simplified rules for the aircraft tactics and manoeuvring. Currently, these rules are not optimised, and in some situations may actually degrade the combat performance of the weapon system.

An example of this is the climb profile used by a fighter during an attack. A simple general assumption may be to use an approximation to the 'optimal' energy-time profile. This does not take into consideration other important factors such as distance covered or range to target. It may not even be optimal for maximising the final energy. References 1 and 2 address optimal climb profiles using different criteria. Considerable differences are shown depending on the criteria used.

Other examples include the full exploitation of the capabilities of the aircraft and weapon system in turning performance, as discussed in references 3 and 4, although this is of more interest with regard to CIC.

Good controls for a particular manoeuvre are developed from optimal solutions in an extension to the techniques in references 1 and 2. This seems more feasible than using the optimal feedback control techniques in reference 5. The latter techniques would be more complicated and difficult to apply to the complex air combat problem. A special three dimensional case, turning to evade a missile, will also be addressed in this paper. The objective is to develop a tactical manoeuvre logic for use in highly dynamic and complex air combat simulations. The rules that are developed must also be robust in order to remain viable in all situations, taking account of the complex interactions inherent in such simulations. For future studies, the use of neural networks as control law generators may be considered, in order to cope better with these problems (see reference 6).

The purpose of the study described in this paper is to apply optimal, or close to optimal, controls to a complex air combat simulation. The study so far considers elements of BVR combat. The tactical logic of the combat modél will decide when a particular optimal strategy should be used. The benefits of using optimised trajectories can then be assessed using combat effectiveness measures. Such a methodology will ensure that weapon systems are being used to their full potential in simulations, giving a more realistic assessment than considering optimal control or aircraft capabilities in isolation.

2. Models Used

Aircraft Models

Two different standards of fighter are considered. The Current Fighter (CF) is a supersonic fighter with performance typical of aircraft in service in the 1970s and 1980s. The Future Fighter (FF) is an agile, high performance supersonic fighter of performance typical of aircraft entering service in the 1990s. Both aircraft are armed with the same missiles. All aircraft begin with 100% internal fuel, carrying 4 medium range and 2 short range missiles. This gives a starting mass of 20870 kg for CF and 15370 kg for FF. Both aircraft have a 50

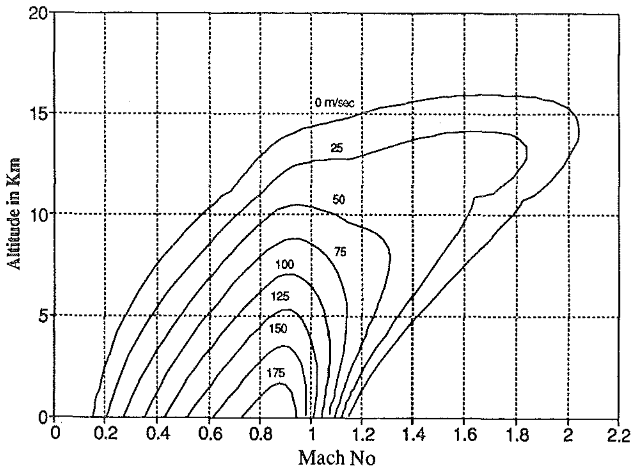

FIGURE 1. Current Fighter Specific Excess Power

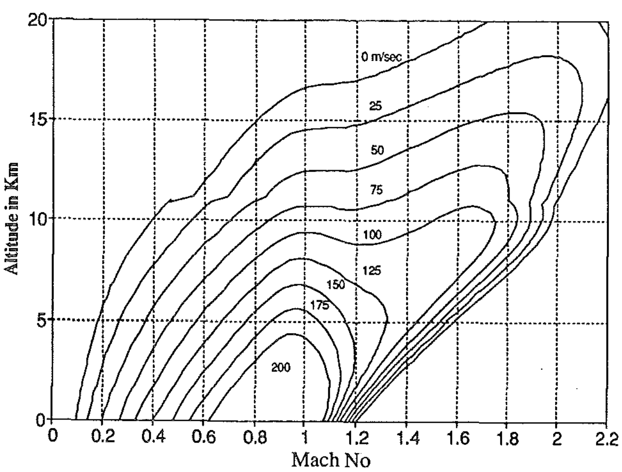

FIGURE 2. Future Fighter Specific Excess Power

m^2 wing area.

Figures 1 and 2 show the 1 g Specific Excess Power (SEP) for CF and FF.

Missiles

The medium range missile model used for this study has range characteristics as shown in figure 3. This shows the launch range against a typical moderate target manoeuvre. The missile benefits from a lofted trajectory as a result of the launch aircraft climb angle. It does not have a specific lofting control law.

Missile guidance is assumed to be command/inertial during the flight with active radar homing in the last 10 km. Although the missile is capable of fully autonomous operation, the probability of seeker acquisition at switch on would be degraded if no command updates are received. Therefore, the fighter will attempt to retain radar track of the target in order to provide updates to the missile. However, the seeker acquisition process is not modelled for this study.

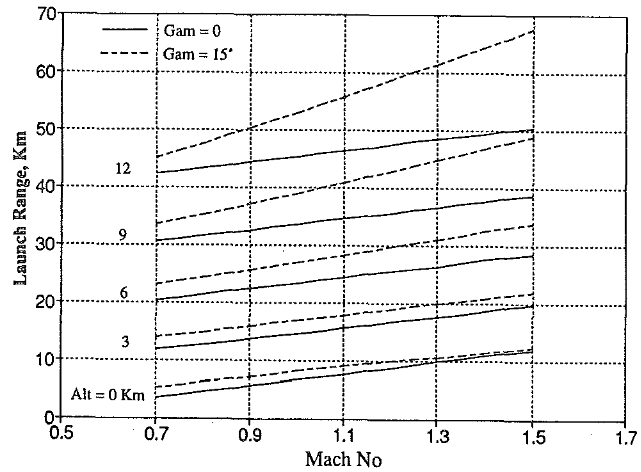

FIGURE 3. Medium Range Missile Performance

3. The AWSEM Combat Model

General Description

The Airborne Weapon System Engagement Model (AWSEM) has been developed at British Aerospace in order to study all aspects of air combat at the tactical (engagement) level. The model allows the representation of systems at different levels of detail depending on the problem under investigation, or the system under evaluation.

For the purposes of this study, systems are represented at the simplest level that is required for realistic representation. Aircraft are represented by 3 degree of freedom (DOF) kinematics using data derived from the aerodynamic and engine models used in the optimisation program. Missiles are also represented by 3 DOF kinematics, using a simplified velocity profile function.

Simple sensor representations are used. These give perfect information within typical geometric limits for radar, visual and radar warning receiver / missile approach warner.

Fighter Tactical Logic

Fighter aircraft begin on a default manoeuvre, such as a Combat Air Patrol, until such time as a target is detected. The fighter then begins the attack, following a defined steering logic for azimuth and elevation steering. In azimuth, collision steering is used, and in elevation, the control is to fly to and follow a defined profile. The predicted (approximate) launch range is continuously calculated, and at a predetermined time before predicted launch, the aircraft performs a pointing manoeuvre. This points the aircraft close to a missile collision course in azimuth, and commands a defined elevation pointing. The missile is launched, and the fighter begins a post launch manoeuvre. The purpose of this manoeuvre is to continue to attack the target, maintaining radar track for missile command update, at the same time reducing the effective missile range of the opponent for counterfire. This is done by turning to the radar limit (reducing closing speed, but maintaining radar contact), and diving to thicker air to slow the opposing missile. Speed is maintained or increased in this dive to a) maintain energy and b) maintain a good speed to outrun the opponents missile. Once the missile is finished, the fighter is free to begin another attack. If contact is lost, the aircraft turns towards the last known target position until the target is re-acquired. If the combatants come within 7.5 km range, they enter close combat, decelerating to the best speed for a turning engagement[3,4], and turning to point at the target. At any time during the combat the fighter may come under threat from an incoming missile. Threat warning will be via Radar Warning Receiver indication of an active radar missile in terminal homing or visual detection of launch for short range missiles. The evasive action overrides all other tactical considerations. The fighter will turn to put the missile on its tail, dive and accelerate in an attempt to outrun the missile.

4. Optimised Elements

The tactics and manoeuvres called on by the decision logic within combat simulation models are usually based on very subjective judgements as to what is likely to be tactically sound in most situations. In situations where the aim is more clear, it has been possible to identify isolated elements for further investigation and optimisation. Those elements specifically addressed in this study are missile launch range during the attack[1], and 3-D optimal turn away from a missile.

The optimisation is achieved by a modified differential dynamic programming (DDP) technique as in reference 1. The benefit from these optimal elements is ultimately dependent upon a good tactical decision logic.

Optimisation Cases

It is very important to select suitable success criteria for the optimisation. The significance of this is shown by the following examples, considering three different optimisation criteria :

1. Maximise final energy for a given final time,
2. Maximise final energy for a fixed fuel burn with a free final time,
3. Approach to a launch envelope, i.e. extend launch range for earliest shot.

In cases 1 and 3 the final time is set to 120 seconds. Case 2 burns the same fuel as case 1. A large variation in the climb profiles is obtained, as shown in figures 4 and 5. The variation between aircraft types is also shown to be quite substantial. It is worth noting that for CF, the profile for case 1 covers some 4 km. less horizontal distance than case 3. Case 3 has a distance element in the criteria, i.e. earliest intercept of a target.

Two methods have been considered to implement the optimal controls in the AWSEM model. Application of neural networks[6] may ultimately offer a flexible and robust method, but further work is required to look at the implementation of such a system within a combat simulation.

The method chosen for this study is to define a 'master curve', which represents the optimal profile to be followed from low speed, low altitude to the practical limits of the aircraft. This is achieved by optimising over a long time. The curve is defined in speed, altitude and climb angle γ. A typical curve is shown as Mach no. vs. altitude in figure 6. Controls are then developed to bring the fighter from any point smoothly

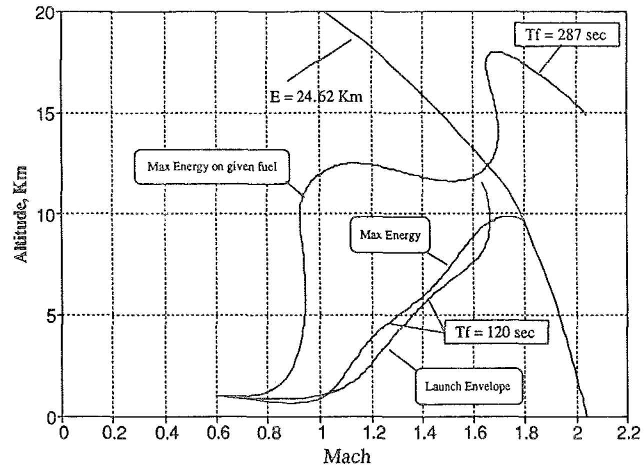

FIGURE 4. Optimal Climb Profiles for FF

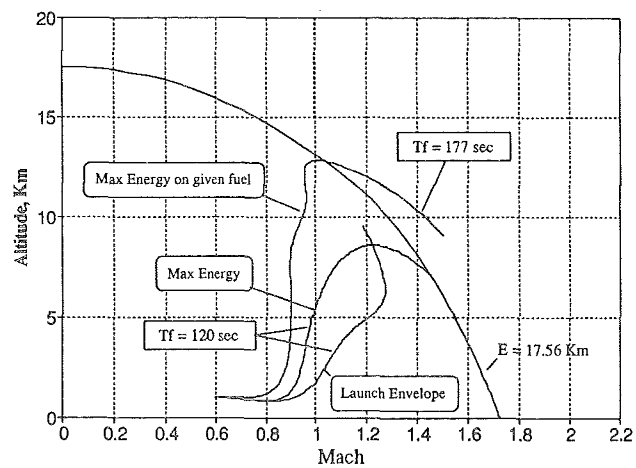

FIGURE 5. Optimal Climb Profiles for CF

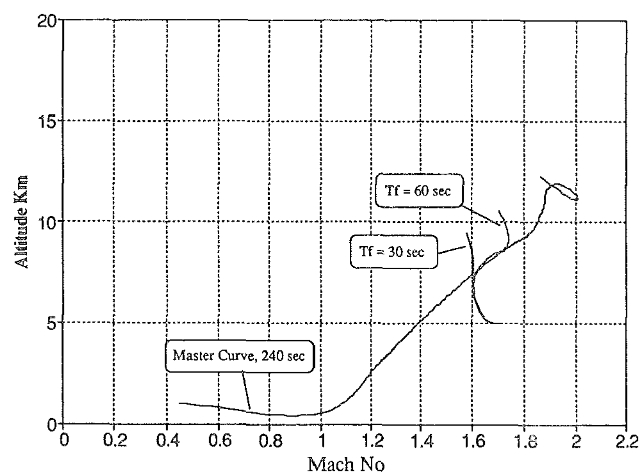

FIGURE 6. Example Master Curve for FF

towards the curve. This method is shown to be a good approximation as indicated by the other optimal trajectories in figure 6.

At a time close to launch time, a pull up is shown to be optimal in order to loft the missile.

Note that the master curves involving a distance function, i.e. approaching a launch point, differ considerably from energy time curve. The emphasis moves to speed, forcing the aircraft to go supersonic early on at quite low altitude. This is particularly true for the CF, which suffers more from the supersonic drag rise than the FF, and so when purely gaining energy remains in the subsonic region for longer.

This type of profile is of use when attempting to achieve the quickest shoot down or intercept of another aircraft. It is applicable as long as the opponent does not threaten counterfire.

For this situation, a fourth criterion is also considered. When maximising our own launch range, we should also consider the effect our energy gain is having on the opponents launch range against us. We then obtain a game in the two launch conditions :

$$\text{Maximise } \{ \text{Range}(\text{Mach}, \text{Alt}, \gamma, \text{Mach}_T, \text{Alt}_T) - \text{Range}_T(\text{Mach}_T, \text{Alt}_T, \gamma_T, \text{Mach}, \text{Alt}) \}$$

where Mach, Alt and γ is the launch condition, and the sub-index T stands for the opponent launch condition. We cannot control the opponents state, but we can to some extent influence his launch range through our own state. For this optimisation, we assume a fixed, typical opponent state, with both sides armed with equal missiles.

Optimising to this criteria produces a very different profile. The emphasis on covering horizontal distance is no longer so important, allowing the aircraft more freedom to use altitude and climb angle. This is shown particularly by the strong pull up at the end of the profile, gaining altitude and climb angle to loft the missile, even at the expense of speed.

If no practical / operational limitation is applied to the manoeuvre, the aircraft will pull up to a very high altitude and climb angle (see figure 3), with consequent large speed reduction. Although this gives the optimal launch range advantage, it would be impractical to operate an aircraft at these conditions in combat. If the climb angle and altitude advantage are too high, the target will fall outside the radar angular limits, and the aircraft will have very poor manoeuvre performance for continuing the combat. For this reason some operational limits are applied to the optimal solutions. The climb angle, γ, is limited to a maximum of 30° and the altitude limited to a maximum of 11 km. These limits are arbitrary, but ensure that the aircraft will maintain target track and have sufficient manoeuvre performance following missile launch. Examples of the final profiles are shown in figures 7 and 8.

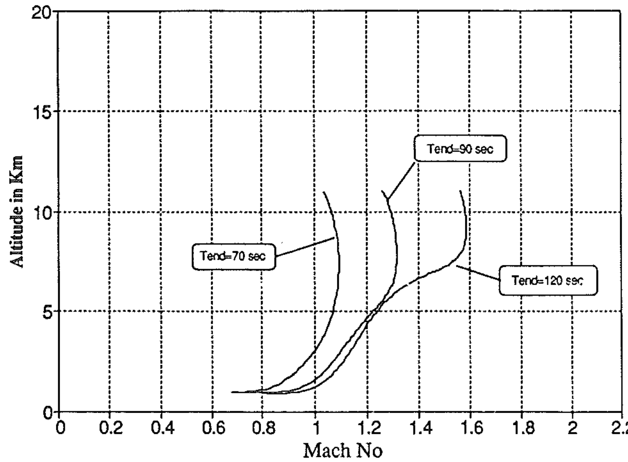

FIGURE 7. Launch Game Optimal Profiles for FF

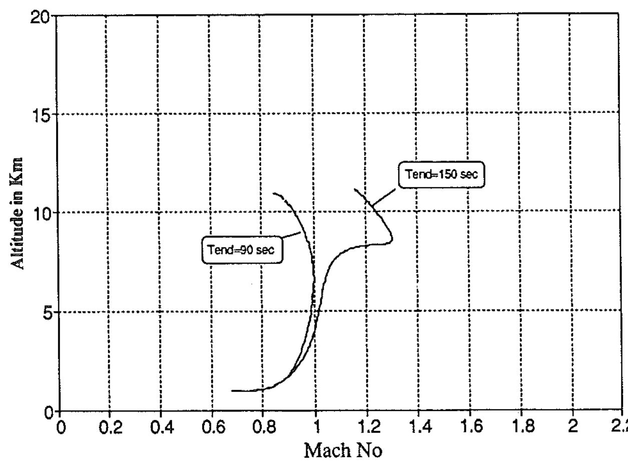

FIGURE 8. Launch Game Optimal Profiles for CF

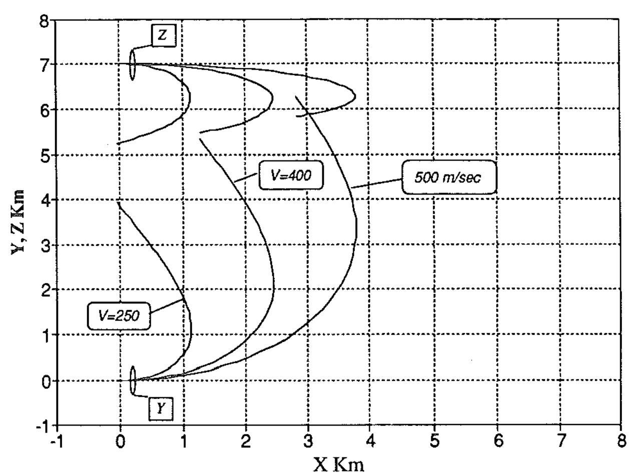

FIGURE 9. Example Optimal Evasive Turns

Missile Evasion

The purpose of the missile evasion is to make a turn to put the missile on the tail, then accelerate to outrun the missile.

The objective is to maximise the distance flown away from the start point along the threat axis in a given time available.

Analysis of typical engagements of the type considered for this study show a turn of order 120°, with a total time available for the evasion of order 20 seconds.

The resulting three dimensional trajectories shown in figure 9 show that a high starting speed is of more value than a good turn rate (low starting speed) in the cases considered. The times used are typical evasive times taken from combat simulations. A dive is also shown to be beneficial, particularly if the speed is low.

5. Application of Optimal Controls

As discussed earlier, the ultimate aim of this method will be to apply optimal tactics to a typical multiple aircraft combat. Such a typical engagement is shown in figure 10. This shows 2 interceptors (Aircraft 1 & 2) engaging a raid of 2 bombers (Aircraft 5 & 6) with 2 escorts (Aircraft 3 & 4). Even with this small number of aircraft, the complexity of the engagement is shown, with multiple shots against different targets, BVR and CIC. In this combat, the aircraft are using existing tactical assumptions for manoeuvre control. For the development and application of optimal tactics, a more restricted subset of the engagement needs to be considered to allow us to see more clearly the influence of optimal trajectories, and allow us to more easily adapt the tactical logic to suit.

This paper examines some of the aspects of implementing optimal tactics in a 1 versus 1 BVR duel between equal weapon systems. One side uses existing tactical assumptions, and the other uses manoeuvre controls developed from the optimal solutions. In these cases, this means the climb to attack trajectory uses a master curve developed from the optimal trajectories for the launch range game. The pre-fire *pointing consists of a pull up to close to 30° γ. Both sides use* a simplified high speed diving turn for missile evasion, as this is a standard assumption for current combat modelling. This has been validated in principle by the optimisation process, although further work may lead to a more optimal manoeuvre.

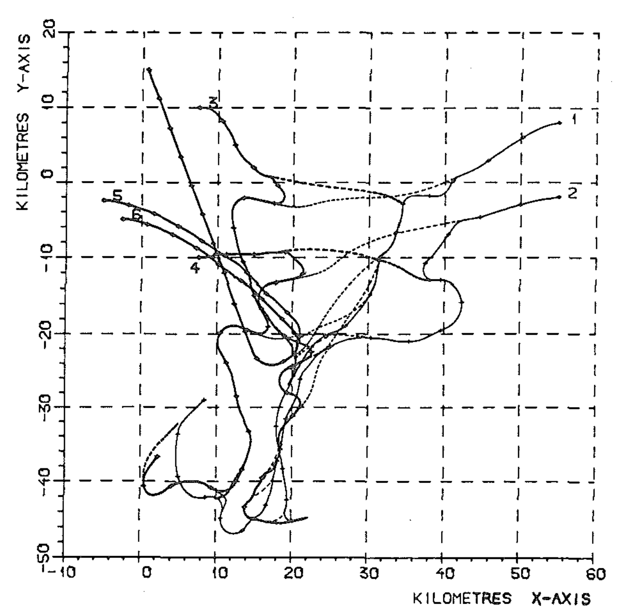

FIGURE 10. Typical Multiple Aircraft Combat

As an illustration, the development of an engagement between 2 CF aircraft is considered. The engagement is started at long range (150 km.) and from low energy (M0.7, 3 km. altitude), which implies some degree of outside control to initiate the climb and acceleration before the aircraft are within autonomous radar detection range. The maximum effective range of the 'optimal' missile is further than that of the opponent. If both aircraft launch at long range, it is possible for the 'optimal' aircraft to kill the opponent with minimal risk. An example of this type of outcome is shown in figure 11.

However, the opponent can delay his shot up until the time at which he is forced to evade. This can lead to a mutual kill or even a victory for the non-optimal opponent, as shown in figure 12. This demonstrates that even though the use of optimal trajectories provides a large effective missile range advantage, this must still be applied in the most effective way.

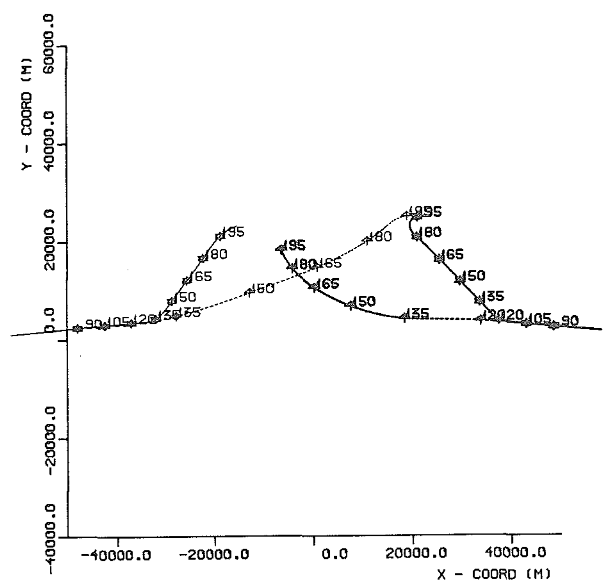

FIGURE 11. CF Duel, Both Launch Early

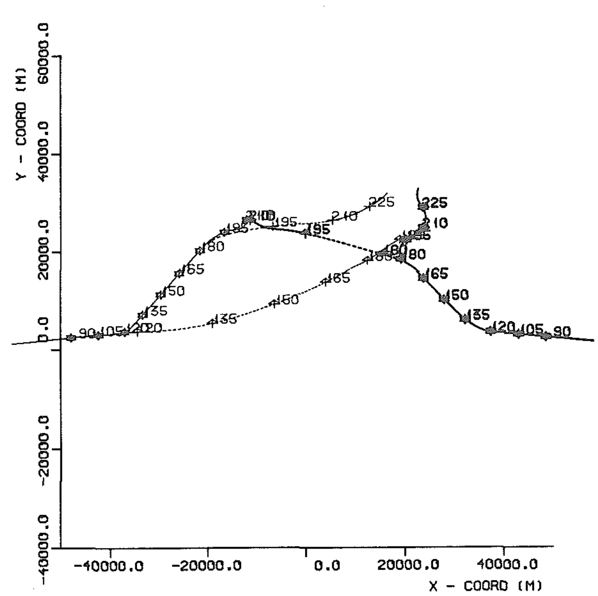

FIGURE 12. CF Duel, Opponent Delays Launch

In order to maximise the benefit of the advantage, care must be taken in selecting the launch timing. A logic has been developed experimentally, which aims to build on the first shot advantage, exposing the 'optimal' aircraft to minimal risk of counterfire. In doing this, it is recognised that the opponent can always launch a missile, and that this first shot cannot be denied by optimal tactics. The first missile should be launched such that if the opponent delays his launch until the moment of his evasion, the opponents missile can still be evaded. The effectiveness of the opponents shot will be degraded anyway, due to the denial of command updates, although as mentioned earlier, this process is not modelled for this study. A second missile should be launched and timed to force opponent evasion just before he is in a position to launch his second missile. This will allow the optimal aircraft to keep the opponent turned away for the maximum time whilst closing to a range which will allow an unopposed killing shot. Figure 13 shows how such a duel might develop for these early shots. In this case, two early shots are used to keep the opponent turned away. This is a limitation of the current combat model logic and it could be extended to use more missiles for a more robust solution. As mentioned earlier, all these results are heavily dependent on the firing logic of both the 'optimal' aircraft and the opponent.

Since both aircraft are identical, and the missiles are capable of autonomous guidance, this process is likely to use up many missile shots (and a great deal of time and fuel) until a sufficient advantage is established. The simplified tactical rules in the combat modelling do not allow for the optimal aircraft to make a pre-emptive turn away beyond radar limits to further spoil the opponents shots, which would allow a quicker build up of advantage. However, the validity of such manoeuvres is debatable, particularly if applied in a multiple opponent environment, where the loss of awareness could be critical.

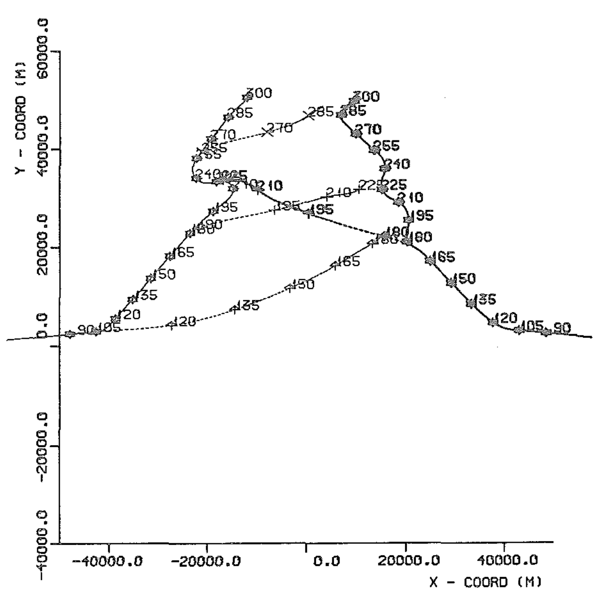

FIGURE 13. CF Duel, Improved Firing Logic

6. Summary and Conclusions

This study has analysed the beyond visual range air to air combat engagement, and has identified elements which can be optimised.

The climb and acceleration phase of the engagement has been optimised and has shown very different characteristics, depending on the criteria used.

If there is no threat of counterfire from the opponent, then the profile to be followed is strongly influenced by the horizontal distance covered, forcing the aircraft supersonic early in the flight at quite low altitude. If the threat of counterfire is included in the criteria, the influence of the distance element is reduced, and altitude gain becomes a strong driver. In both cases, a pull up to loft the missile is used prior to launch.

The large difference between the optimal profiles shows the importance of using a good tactical logic, in order to select the profile most appropriate to the situation.

The technique of defining a 'master curve' to represent the optimal trajectory, with controls to bring the aircraft onto the profile and maintain it has been developed and successfully implemented into a combat model. Neural networks may also have an application in this area.

The use of these profiles compared to a simplified energy gain has shown a large potential advantage in effective missile range with the models used. This potential advantage in isolation is shown to be of little benefit unless combined with an effective (optimal) missile firing policy. This optimisation has been attempted experimentally for this study. Against closely matched opponents using autonomous missiles, this will lead to an engagement which uses many missile shots before achieving a kill.

The evasive manoeuvre for turning and outrunning a missile shows that a high speed is more important than a high initial turn rate. The manoeuvre should also be combined with a dive. This supports assumptions made for combat modelling, which have used a simplified high speed diving turn.

The extent of elements which can be isolated for optimisation, and then applied practically to combat scenarios is difficult to define. For a 1 vs. 1 duel such as that considered in this study, it is possible to see clear and unchanging aims for the whole combat. The limits for the optimisation should be expanded to include the timing of the first and subsequent missile firings, and the trajectories to be flown throughout the engagement. For such an engagement it is possible to see the consequences of early actions influencing the outcome, and therefore all elements need to be considered when deriving optimal tactics.

For a complex multiple aircraft engagement, the aims are not so clear and may change as the fight develops. Targets and threats may change rapidly. Apart from the broader objectives of survival and defeating the opponents, long term objectives for optimisation are difficult if not impossible to define. In such a scenario, it is likely that the elements for optimisation will have much tighter limits.

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