TRAJECTORY CONTROL OF A TYPICAL RE-ENTRY VEHICLE USING PREDICTIVE CONTROL CONCEPT

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Abstract

This paper presents the development of a guidance law for the atmospheric re-entry phase of a typical Reusable Launch Vehicle (RLV). A nonlinear guidance law is designed based on a continuous time predictive control concept applicable to vehicles with general nonlinear dynamics. Trajectory control is achieved based on a feedback control law that minimizes the difference between the predicted and desired responses. Flight path is controlled by regulating two of the state variables, altitude and climb rate. In the present study, angle of attack is used as the control variable and out of plane motion is not considered. The guidance law generates necessary angle of attack steering command considering the present state of the vehicle, the constraints to be met and the desired touch down conditions. The guidance law guarantees the satisfaction of constraints on the normal load as well as the dynamic pressure and also ensures that the vehicle flies within the specified trim boundary on angle of attack. Extensive simulation studies are carried out in ground to test and establish the performance of the guidance law for nominal as well as a variety of off nominal flight environment.

1. INTRODUCTION

Low cost, high reliability and operational flexibility are the most important features for space transportation systems. Reusability of vehicle is believed inevitable for low cost system. Trajectory control employing efficient Closed Loop Guidance (CLG) and Control strategy plays a major role in performance and reliability of RLVs. A Technology Demonstrator Vehicle (TDV) is considered which is developed to test the technologies needed for the full scale RLV. The TDV will perform a suborbital flight and the re-entry dynamics of this class of vehicles is different from that of the ascent. Optimal re-entry needs the development of guidance strategy, that is generally considerably different from the one used in ascent phase. The aim of re-entry guidance is to steer the vehicle within the entry corridor bounded by maximum dynamic pressure, maximum heat flux and peak load factor. The guidance also ensures that the vehicle flies within the specified trim boundaries on angle of attack. The required conditions at touch down are also to be met accurately. The re-entry phase is hence very demanding in terms of mechanical, structural and thermal considerations.

Methods generally used for re-entry phase guidance are the traditional profile following guidance, predictor-corrector and planner-follower methods. Approach presented by Harpold, J.C., and Graves, C. A.,[1] is considered as a benchmark for shuttle entry guidance. The entry-guidance algorithm controls range to a specified landing site by issuing bank angle commands (and limited angle of attack modulation commands) which will cause the re-entry vehicle to track a nominal drag acceleration verses relative energy profile. Hanson, J.M., etal.,[2] developed an adaptive nonlinear tracking control law for X-33 re-entry phase, using the technique of feed back linearization. Roenneke, A. J., and Markl, A.[3] proposed to schedule the drag profile as function of energy for the entire trajectory for more accurate range prediction and the reference profile is then parameterized by cubic splines determined by numerical optimization. They employed a linear feedback control law, whose gain is scheduled with respect to the energy for the trajectory control. Later Ping Lu.,[4] and Ping Lu.,

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and J. M., Hanson [5] considered the reference drag profile as a piecewise linear continuous function of the energy. A simple and elegant guidance approach based on continuous time predictive control concept has been successfully used for trajectory control of powered atmospheric ascent phase of an RLV with air-breathing propulsion in ref [6] and solid rocket propulsion in ref [7]. This paper addresses the extension of the methodology for un-powered re-entry phase of a typical RLV.

In the present study the trajectory control is achieved based on a feedback control law that minimizes the difference between the predicted and desired responses. A pre-computed nominal trajectory that satisfies all the mission requirements and constraints is generated off line and is available. The aim of the closed loop guidance algorithm is to determine the guidance commands necessary to make the vehicle track the reference trajectory, in presence of performance dispersions and external disturbances. Flight path is controlled by regulating two of the state variables, altitude and climb rate. In the present study, angle of attack is used as the control variable and out of plane motion is not considered. Extensive simulation studies are carried out in ground to test and establish the performance of the guidance law for a variety of off nominal flight environments such as, dispersions in initial entry states, aerodynamic dispersions and atmospheric perturbations and the results are presented. The proposed guidance law can cater to ascent as well as re-entry phases of any RLV mission, irrespective of the type of propulsion being employed, rocket or air-breathing. This work suggests that a single integrated guidance scheme can be defined to steer the vehicle from lift off to touch down for various RLV missions.

This paper is structured as follows: Section 2 presents the model of the vehicle. Section 3 provides a brief description of the mission and the constraints to be ensured. In Section 4, closed loop guidance law formulation is described highlighting Predictive Control method and tracking guidance law as implemented for un-powered hypersonic re-entry phase of typical RLV mission. Section 5 presents the validation of guidance law through extensive simulations for nominal and off nominal flight environments such as, dispersions in initial entry states, aerodynamic dispersions and atmospheric perturbations. Section 6 provides the conclusion.

2. REUSABLE LAUNCH VEHICLE MODEL

A conceptual RLV is used for the study which is assumed to be a wing- body vehicle with aerodynamic control surfaces and about 1.5T lift off mass. RLV will be boosted to about Mach 6 using a solid booster. RLV then performs a controlled descent through the atmospheric entry phase, followed by impact on sea within a specified zone.

2.1 Equations of Motion

The vehicle motion is considered planar over spherical, non-rotating Earth. Here the wind effects are not considered. The dynamics of vehicle (shown in fig.1) during the re-entry phase can be represented by the following point mass equations of motion[8],

$$\dot{r} = v \sin\gamma \tag{1}$$

$$\dot{v} = \frac{-D}{m} - \frac{\mu \sin\gamma}{r^2} \tag{2}$$

$$\dot{\gamma} = \frac{L}{mv} - \left(\frac{\mu}{r^2} - \frac{v^2}{r}\right)\frac{\cos(\gamma)}{v} \tag{3}$$

For planar flight, $\alpha = \theta - \gamma$ where α is angle of attack, θ is pitch angle and γ is the flight path angle. v is the vehicle velocity, μ gravitational parameter, r radial distance of the vehicle from the center of Earth and m vehicle mass.

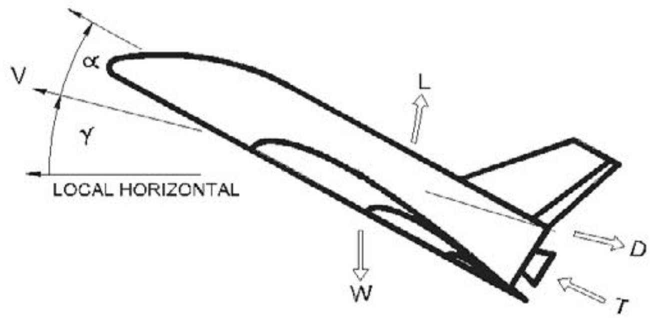

Fig.1 Vehicle Dynamics

2.2 Aerodynamic model

The Lift (L) and Drag (D) are the aerodynamic forces acting on the vehicle. The lift and drag forces are related to the lift coefficient C_l and drag coefficient C_d as shown by the following equations.

$$L = \frac{\rho v^2 S_{ref} C_l}{2} \quad (4)$$

$$D = \frac{\rho v^2 S_{ref} C_d}{2} \quad (5)$$

Where S_{ref} is the reference area of the vehicle which is assumed to be a constant, v is the velocity of the vehicle and ρ is the altitude dependent atmospheric density. The lift and drag coefficients are functions of angle of attack (α) and Mach number.

2.3 Atmospheric model

The Indian Standard Atmosphere comprising of density, pressure and temperature as a function of altitude is used for the design and analysis. Pressure data is used for thrust correction and temperature data for the computation of speed of sound.

3. MISSION AND CONSTRAINTS

Present study deals with trajectory control during atmospheric re-entry phase of a typical hypersonic sub-orbital mission.

3.1 Mission

The mission objective is to perform hypersonic flight experiment using a winged re-entry vehicle. For this, the vehicle is required to be boosted to hypersonic speed (Mach no >5) at booster burn out and the vehicle then performs un-powered, controlled descent through the atmospheric entry phase. Achieving this is a challenging task, since the vehicle has to be guided to fly within an entry corridor bounded by constraints on dynamic pressure, heat flux, normal load factor and equilibrium glide. The re-entry guidance scheme provides steering commands to control the entry trajectory from atmospheric penetration to a specified landing site ensuring that the vehicle has the correct energy level for approach and landing. The vehicle is controlled using appropriate angle of attack commands. The angle of attack controls the lift to drag ratio and thus the down range capability.

3.2 Constraints

Angle of attack (α) is used as the control and out of plane motion is not considered. The guidance problem is to determine the control commands that would guide the vehicle to the required touch down point without violation of mission constrains on maximum dynamic pressure (q_{max}) and normal load factor(n).

$$q_{max} \leq 20 \text{ k Pa} \tag{6}$$

$$n_{max} \leq 3g \tag{7}$$

The angle of attack should be within vehicle trim boundary. The above constraints have to be satisfied to ensure controllability and maintain the structural integrity of the vehicle. These constraints have to be honoured for nominal as well as off- nominal conditions such as dispersions in initial entry states, aerodynamic and atmospheric parameters.

3.3 End Conditions

The end conditions to be ensured are given below

$$h_f = 100 \text{ m}, \qquad V_f = 71 \text{ m/s} \tag{8}$$

V_f and h_f are the final velocity and altitude at terminal point, before splash down into the sea.

4. CLOSED LOOP GUIDANCE LAW FORMULATION

This section gives a brief description of the Predictive Control Method and then its implementation for RLV re-entry phase. The guidance law thus obtained does not require linearization of the equations of motion.

4.1 Predictive Control Method

In Predictive Control Method, the error between the present state and the immediate future state is predicted using the current control. Then a quadratic cost function of predicted errors and control effort is minimized, resulting in an optimal feedback guidance law design.

To get an overview of Predictive Control Method let us consider a nonlinear dynamic system of the form

$$\dot{x}_1 = f_1(x) \tag{9}$$

$$\dot{x}_2 = f_2(x) + g_2(x,u) \tag{10}$$

Where state vector and control vectors are respectively:

$$x = [x_1^T \; x_2^T]^T \tag{11}$$

$$u(t) \in U = \{u(t) \setminus L_i[x(t)] \leq u_i(t) \leq U_i[x(t)]\} \tag{12}$$

Where the bound L_i and U_i are specified and allowed to be state dependent and the functions f_1, f_2 and g_2 are continuously differentiable nonlinear functions. Assume the desired trajectory $x^*(t)$, $t \in [0,t_f]$ is already known which satisfies the system equations (9) and (10) with a corresponding control $r^*(t) \in U$. If the state $x(t)$ is known for an arbitrary instant $t \in [0,t_f]$, then the current control $u(t)$ determines the system response in the immediate future. Suppose the response of the system at an instant 't' is $x_1(t)$ and $x_2(t)$ with a control command $u(t)$. Now the predicted response of the system at an immediate future instant 't+h', where h is a small increment of time, with the same control $u(t)$ is

x_1(t+h) and x_2(t+h) respectively. Since $\ddot{x}_1$ and $\dot{x}_2$ depend on u(t) explicitly, predict the influence of u(t) on x_1(t+h) by second order Taylor series expansion at t and on x_2(t+h) by a first order expansion. Let the predicted responses at t+h, be x_1(t+h) and x_2(t+h) and the desired responses x_1*(t+h), and x_2*(t+h), then the tracking error at (t+h) can be approximated by,

$$e_1(t+h) = x_1(t+h) - x_1^*(t+h) \approx e_1(t) + h\dot{e}_1(t) \quad + 0.5h^2[F_{11}(x)f_1(x) + F_{12}(x)f_2(x) + F_{12}(x)g_2(x,u) - \ddot{x}_1^*] \tag{13}$$

$$e_2(t+h) = x_2(t+h) - x_2^*(t+h) \qquad \approx e_2(t) + h[f_2(x) + g_2(x,u) - \dot{x}_2^*] \tag{14}$$

Where, $F_{11} = \dfrac{\partial f_1[x(t)]}{\partial x_1}$, $F_{12} = \dfrac{\partial f_1[x(t)]}{\partial x_2}$

In order to find a control command u(t) that minimizes the tracking error continuously, introduce a performance index as;

$$J = \frac{1}{2}e_1^T(t+h)Q_1(t)e_1(t+h) + \frac{1}{2}e_2^T(t+h)Q_2(t)e_2(t+h) + \frac{1}{2}[u(t) - r^*(t)]^T R(t)[u(t) - r^*(t)] \tag{15}$$

The controller minimizes a weighted function of tracking errors, where Q_1 & Q_2 are positive semi definite matrices and R is positive definite. Applying the necessary condition for optimality ∂J/∂U=0 leads to continuous time control law u(t) as follows.

$$u(t) = r^*(t) - hR^{-1}(0.5h\left[F_{12}(x)\frac{\partial g_2(x,u)}{\partial u}\right]^T Q_1\{e_1 + h\dot{e}_1 \quad + 0.5h^2[F_{11}(x)f_1(x) + F_{12}(x)f_2(x) + F_{12}(x)g_2(x,u) - \ddot{x}_1^*]\} \\ + \left[\frac{\partial g_2(x,u)}{\partial u}\right]^T Q_2\{e_2(t) + h[f_2(x) + g_2(x,u) - \dot{x}_2^*]\}) \tag{16}$$

$$u(t) = r^*(t) - hR^{-1}N(x, x^*, u) \tag{17}$$

Where

$$N(x, x^*, u) = 0.5h\left[F_{12}(x)\frac{\partial g_2(x,u)}{\partial u}\right]^T Q_1\{e_1 + h\dot{e}_1 \quad + 0.5h^2[F_{11}(x)f_1(x) + F_{12}(x)f_2(x) + F_{12}(x)g_2(x,u) - \ddot{x}_1^*]\} \\ + \left[\frac{\partial g_2(x,u)}{\partial u}\right]^T Q_2\{e_2(t) + h[f_2(x) + g_2(x,u) - \dot{x}_2^*]\} \tag{18}$$

In order to bound the control equation, introduce a vector saturation function 's', which guarantee the convergence of the algorithm :

$$s_i(y) = \begin{cases} U_i, & y_i \geq U_i \\ y_i, & L_i < y_i < U_i \\ L_i, & y_i \leq L_i \end{cases} \tag{19}$$

such that

$$u = s[r^* - hR^{-1}N(x, x^*, u)] \tag{20}$$

4.2 Trajectory Control during re-entry phase of RLV

In this section, the preceding approach is applied to track the reference trajectory for the un-powered re-entry phase of a typical RLV. The guidance algorithm uses angle of attack as the control variable. The algorithm generates the necessary steering commands for effectively tracking the reference altitude and climb rate profiles. For better numerical conditioning, the following dimensionless variables are used:

$$\tau = \frac{t}{\sqrt{r_o / g_o}} \;, \quad Y = \frac{r}{r_o} \;, \quad V = \frac{v}{\sqrt{g_o r_o}}$$

$$A_T = \frac{T}{m_o g_o}, \quad A_D = \frac{D}{m_o g_o}, \quad A_L = \frac{L}{m_o g_o} \tag{21}$$

Where m_o is the vehicle initial mass, r_o is the Earth radius , $g_0=\mu/r_0$, μ is gravitational parameter, r is the current radial distance, v-the velocity, T-thrust (if powered) , D-drag, L-lift. In addition, the climb rate $Z=dY/d\tau$ is used in the place of flight path angle γ. This has the advantage that the feedback control law will depend on Z which is easier to measure than γ.Thus, the system equations take the following form in the new dimensionless variables,

$$Y' = Z \tag{22}$$

$$Z' = (V^2/Y) - (1/Y^2) - (Z^2/Y) + [A_T \cos(\theta-\gamma) - A_D] \times (Z/V) + [A_T \sin(\theta-\gamma) + A_L]\sqrt{1-(Z/V)^2} \tag{23}$$

$$V' = A_T \cos(\theta-\gamma) - A_D - (Z/VY^2) \tag{24}$$

Where the prime(′) stands for differentiation with respect to τ. Throttle is set at maximum value and hence it is difficult to achieve feedback velocity regulation effectively. Therefore, flight path control is achieved by regulating two of the state variables, x_1=Y(altitude)and x_2=Z(climb rate). By using the dimensionless variables, the guidance law by Eq.(20) for angle of attack (α)control can be written as

$$\alpha(\tau) = s(\alpha^*(\tau) - hR^{-1}\{0.5hQ_1 G_{21}\{\Delta Y + h\Delta Z + 0.5h^2(f_{22} + g_{22} - Z'^*)] \\ + G_{21}Q_2[\Delta Z + h(f_{22} + g_{22} - Z'^*]\}) \tag{25}$$

In Eq.(25), s is the saturation function and

$$f_{22} = (V^2/Y) - (1/Y^2) - (Z^2/Y)$$

$$g_{22} = [A_T \cos(\theta-\gamma) - A_D](Z/V) + [A_T \sin(\theta-\gamma) + A_L]\sqrt{1-(Z/V)^2}$$

$$G_{21} = -[A_T \sin(\theta-\gamma) - \frac{\partial A_D}{\partial \alpha}](Z/V) + [A_T \cos(\theta-\gamma) + \frac{\partial A_L}{\partial \alpha}]\sqrt{1-(Z/V)^2}$$

Where

$$\frac{\partial A_L}{\partial \alpha} = \frac{\rho v^2 S_{ref}}{2mg_0}\frac{\partial C_L}{\partial \alpha}, \quad \frac{\partial A_D}{\partial \alpha} = \frac{\rho v^2 S_{ref}}{2mg_0}\frac{\partial C_D}{\partial \alpha}$$

The guidance law can be written as,

$$\alpha(\tau) = s[\alpha^*(\tau) - hR^{-1}N] \tag{26}$$

The specific form of N is defined by comparing Eq.(26) with Eq.(25). The control command α is obtained from the above Eq. (25). The angle of attack controls the lift to drag ratio and thus the down range capability. The non-linear vector term N involves the weightings Q_1, Q_2 and the tracking errors. The algorithm is made adaptive by on-line computation of the weightings Q_1 ,Q_2 ,R and the step size h in guidance law as functions of dispersion in altitude and altitude rates.

4.3 Choice of Saturation bounds on angle of attack

The saturator s in Eq.(25) is used to ensure that the constraints on dynamic pressure q_{max} and load factor n_{max} as in Eq.(6) and (7) are satisfied. So the saturation limits on angle of attack (α) are chosen as

$$U = \max\left(\frac{n_{max}.m}{qS_{ref}C_{L\alpha}}, \frac{L}{q_{max}S_{ref}C_{L\alpha}}, \alpha_{uptrim}\right) \tag{27}$$

$$L = \left(\alpha_{lowtrim}\right) \tag{28}$$

Where α_{uptrim} is upper boundary for angle of attack for trim, $\alpha_{lowtrim}$ is lower boundary for angle of attack for trim. $C_{L\alpha}$ is $\frac{\partial C_L}{\partial \alpha}$

5. VALIDATION OF GUIDANCE LAW

In this section, features of the un-powered re-entry flight are considered in detail. Vehicle dynamics is simulated and the trajectory parameters are generated for re-entry phase. The initial conditions for this flight phase correspond to peak altitude (flight path angle,γ=0) point . There can be dispersions in altitude and velocity at this point due to off nominal performance of the booster and aerodynamic and atmospheric dispersions during ascent phase. The vehicle control is via the use of Reaction Control Systems (RCS) as long as the dynamic pressure remains low. A gradual switching to aerodynamic control, as the dynamic pressure increases during re-entry, is then performed. During re-entry very important constraints should be respected: the normal g-load factor $n \leq n_{max}$, the admissible dynamic pressure $q \leq q_{max}$ (structure design stress limitations) and the heat flux limitations. The steering command α is limited to meet the above constraints and at the same time to ensure that the values are within the specified trim limits of the vehicle configuration. The algorithm was validated by simulating both nominal and off-nominal flight conditions. The off-nominal performances considered include, dispersions in initial entry conditions and aerodynamic and atmospheric perturbations.

5.1 Initial Conditions for Guidance

Altitude	=	74 km
Velocity	=	1771 m/s
Flight path angle	=	0 °
Mass	=	1.5 T
Angle of attack	=	40 °

5.2 Desired Touch Down Conditions

Altitude (h_f)	=	100m
Velocity (V_f)	=	71 m/s

5.3 Specified bounds on end conditions

$0 < h_f < 600$m
$0 < V_f < 81$m/s

5.4 Off nominal cases studied

Re-entry guidance law was validated for various types of off nominal conditions. The off nominal cases studied fall under the following categories namely, 1) aerodynamic dispersions in re-entry phase, 2) off nominal initial conditions, 3) atmospheric dispersions and 4) additive perturbations.

Aerodynamic Dispersions

Case1- C_L + 20%
Case2- C_L - 20%

Case3- C_D + 20%
Case4- C_D - 20%
Case5- C_L + 20%, C_D - 20%
Case6- C_L - 20%, C_D + 20%

Off Nominal Initial conditions

Case7- ΔH = +10km, ΔV = +50m/s
Case8- ΔH = -10km, ΔV = -50m/s

Additive Perturbations

Case9- ΔH = +10km, ΔV = +50m/s, C_L + 20%, C_D - 20%
Case10- ΔH = -10km, ΔV = -50m/s, C_L - 20%, C_D + 20%

Atmospheric Dispersions

Case 11- Atmospheric density +10%
Case 12- Atmospheric density -10%

5.5 Performance of Trajectory Control Guidance Law for re-entry phase of RLV

Performance of the trajectory control guidance law designed and developed for the re-entry phase of the RLV can be analyzed based on the achieved terminal conditions on altitude and velocity given in table-1. In the present formulation the down range is not constrained since recovery is not planned, the impact being in sea. The ability of the guidance law to ensure the constraints on dynamic pressure, normal load factor and angle of attack within trim boundary specified for the vehicle is also established.

Table-1

Dispersion cases	h_f m	V_f m/s	Mach No
Case0	104	70.75	0.20
Case1	585	70.73	0.20
Case2	99	77.70	0.22
Case3	421	70.76	0.20
Case4	164	70.73	0.20
Case5	598	70.73	0.20
Case6	99	75.22	0.21
Case7	144	70.75	0.20
Case8	144	70.75	0.20
Case9	598	70.76	0.20
Case10	99	75.23	0.21
Case11	509	70.73	0.20
Case12	99	76.43	0.22

Guidance is terminated on reaching either an altitude of 100m or a velocity less than 71m/s, which ever condition occurs first. As can be seen from Table.1, maximum velocity dispersion is less than 7m/s and the maximum dispersion in altitude is <500m. This clearly establishes the efficiency and robustness of the trajectory control strategy for meeting the mission requirements and specifications even during extreme performance dispersions as indicated in case9 and case10 (additive perturbations). For lower level of dispersions in aero, ±15%, the velocity error is <5m/s and altitude error is <100m. In all the cases the peak value of dynamic pressure is constrained to 20k Pa as shown in fig.2. Maximum normal load factor is limited to 3g as shown in fig. 3. The angle of attack control history is always within the trim boundary as shown in fig 4. Variation of altitude and velocity for the above dispersion cases are shown in fig.5 & fig.6

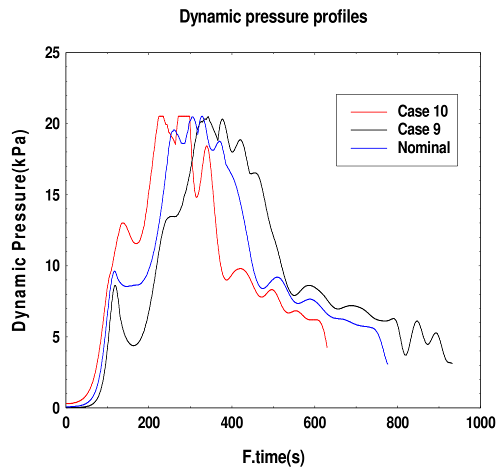

Fig .2 Dynamic pressure histories

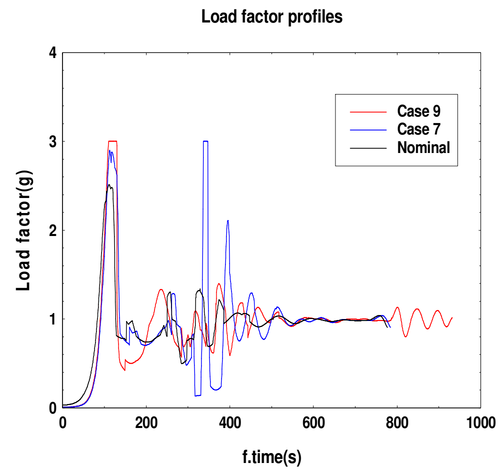

Fig.3 Load factor Histories

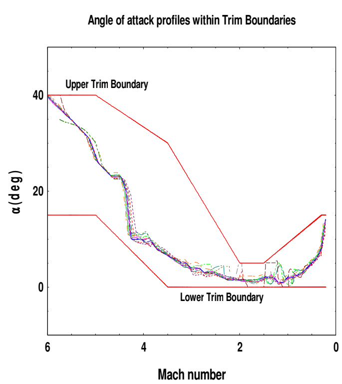

Fig.4 Mach vs α

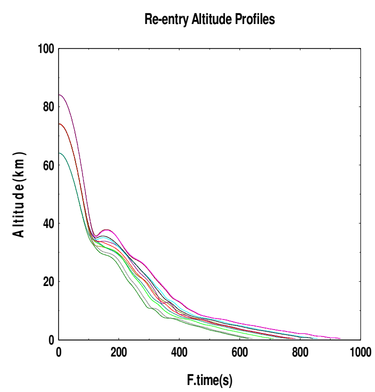

Fig.5 time vs altitude

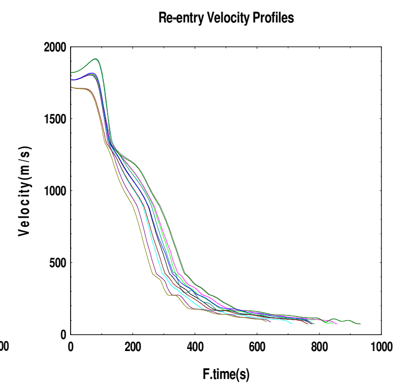

Fig.6 time vs Velocity

5.5 Comparison of CLG with OLG

A performance comparison made with energy based Open Loop Guidance (OLG) for the above dispersion cases revealed that the constraints on dynamic pressure and load factor are violated in OLG mode of steering. Comparison of load factor and dynamic pressure curves for CLG and OLG are shown in fig.7 & 8 respectively for case 9. (additive over performance case).

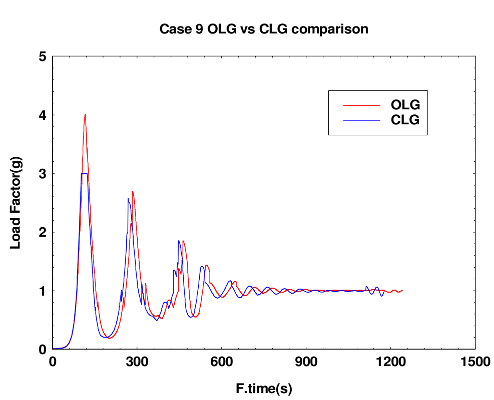

Fig .7 Load factor OLG vs CLG

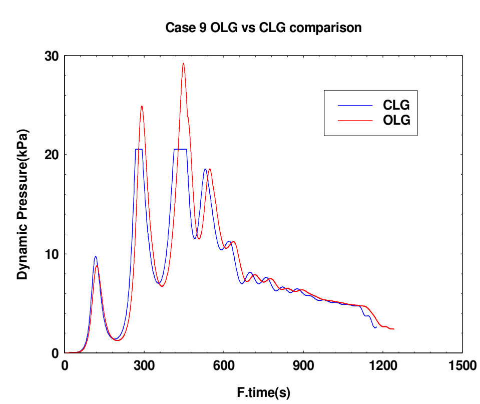

Fig.8 Dynamic Pressure OLG vs CLG

This highlights the importance of appropriate angle of attack profile required for controlling the RLV in the presence of off beat initial conditions and aerodynamic and atmospheric perturbations. This feature is very effectively captured in the trajectory control guidance law by generating appropriate angle of attack commands that controls the re-entry vehicle trajectory.

6. CONCLUSION

A trajectory control guidance law is developed for steering the vehicle during atmospheric re-entry phase for a typical RLV sub-orbital flight mission. The guidance algorithm generates the angle of attack control commands based on non linear predictive control concept. Guidance law has been validated through extensive simulations for nominal and off-nominal flight environments like aerodynamic dispersions, atmospheric perturbations and dispersions in initial entry conditions. Analysis of results reveals that the newly developed guidance algorithm meets the mission requirements effectively in terms of mission constraints as well as touch down conditions. Guidance law always ensures that the constraints on dynamic pressure, aerodynamic load and trim boundary on angle of attack are met. In the present study wind effects are not considered. Proposed guidance law can cater to ascent as well as re-entry phases of any RLV mission. This work along with the study described in [6 & 7] suggests that the present scheme can be used as a unified guidance scheme to steer the vehicle from lift off to touch down for various RLV missions irrespective of the type propulsion employed, Rocket or Air-breathing.

REFERENCES

[1] Harpold,J. C., and Graves, C.A., (1979), " Shuttle Entry Guidance", *The Journal of the Astronautical Sciences*, Vol.27,No.3. pp.239-268

[2] Hanson, J.M., Dan J. Coughlin., Gregory A.Dukeman., John A. Mulqueen., and James W.Mc Carter.(1998),"Ascent, Transition, Entry and Abort Guidance Algorithm design for the X-33 vehicle", AIAA- 1998-4409.

[3] Axel J. Roenneke and Markl, A. (1994), "Re-entry Control of a Drag vs. Energy profile", *Journal of Guidance, Control and Dynamics,* Vol.7, No.5, pp.916-920.

[4] Ping Lu., (1994), "Nonlinear Predictive Controllers for Continuous Systems", *Journal of Guidance, Control and Dynamics,* Vol.17, No.3, pp.553-560.

[5] Ping Lu., and J. M., Hanson, (1998) "Entry Guidance for X-33 Vehicle", *Journal of Spacecraft and Rockets*, Vol.35, No.3, pp.342-349.

[6] V. Brinda and S. Dasgupta , "Guidance Law for an Air-Breathing Launch Vehicle Using Predictive Control Concept", *AIAA Journal of Guidance, Control, and Dynamics*, Vol.29 No.6, pp.1460-1464, November-December 2006.

[7] V. Brinda and K.Sivan , " Guidance law for Atmospheric Ascent Phase of a Typical Re-entry Vehicle using Predictive Control Concept ", *Proceedings of IISc Centenary International Conference and Exhibition on Aerospace Engineering, ICEAE 2009,* pp.931-939

[8]Miele,A.,*Flight Mechanics:Theory of Flight Paths,*Addison Wesley, Reading,MA,1962.