Adaptive Guidance Law for Trajectory Control of a Reusable Launch Vehicle during Air-Breathing Ascent Phase

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Abstract
An adaptive guidance scheme is developed for air-breathing ascent phase of a Reusable Launch Vehicle (RLV). The guidance law controls the vehicle lift force using a Proportional Derivative (PD) controller. A gain adaptation algorithm is developed that modifies the feed back controller gains on-line, in response to the changes in vehicle performance and the nature of disturbance. The system dynamics is propagated to the end of atmospheric ascent phase considering angle of attack as the active control variable. The adaptive guidance law is validated through extensive flight simulations for air- breathing engine off nominal performance, aero parameter uncertainties and atmospheric density perturbations. The simulation results establish the robustness of the newly developed algorithm to meet the mission requirements, satisfying the path constraints and terminal constraints.

1. Introduction

Reusable Launch Vehicle (RLV) with air-breathing propulsion are being considered as promising candidates for the future low cost space transportation systems. These vehicles provide more effective way to launch satellites and other vehicles to Low Earth Orbit (LEO) than rockets. The near minimum fuel trajectory for such vehicles is, however, substantially different from that of a rocket powered expendable vehicle. Whereas a rocket powered vehicle leaves the dense atmosphere quickly to minimize the drag losses, an air-breathing vehicle dwells much longer in the dense atmosphere where the air-breathing propulsion is more efficient. Thrust generated by the air-breathing engine is highly sensitive to flight path and angle of attack (α). This has a major impact on the nature of the optimal trajectories. Moreover, the amount of aerodynamic uncertainty is more compared to conventional launch vehicles. This points to the fact that guidance and control technology dependent on pre-launch, predetermined trajectory as used in conventional launch vehicles is inadequate for air-breathing RLVs .

Much research is being vigorously pursued in the area of optimal trajectory synthesis and guidance for the ascent phase of air-breathing hypersonic vehicles. A J. Calise et al. are using the energy state approximation method for trajectory optimization and the guidance law is developed using singular perturbation theory[1],[2],[3]. Ping Lu proposes inverse dynamic approach for solving the ascent problem for a hypersonic vehicle [4]. A trajectory tracking guidance law is developed to meet the constraints and to track a reference altitude verses velocity path in [5],[6]. C. R Hargraces et al. obtains optimal solution by Nonlinear Programming and collocation method [7]. Brinda.V et al. uses a nonlinear predictive control law for generating the fuel optimal ascent profile for an air-breathing ascent phase in [8]. A real time optimal guidance law is developed to trace the maximum dynamic pressure trajectory using a Proportional Integral Derivative (PID) controller by Hirokazu et. al for an air breathing vehicle [9].

RLV needs a fully autonomous guidance scheme with on-board trajectory planning for generating reference profile on-line along with an adaptive guidance law for generating the commands required to follow the reference profile. The guidance approach has two loops. The outer loop is a trajectory planning loop (parameter adjustment loop). The inner loop is a normal feed back control loop with adaptive feature of modifying the feed back gains on-line depending upon the current performance of the vehicle and nature of disturbance. The onboard trajectory planning is achieved using simplified trajectory optimization based on energy state approximation method discussed in [10]. Present study addresses the development of an adaptive guidance law that controls the vehicle lift force using a Proportional Derivative (PD) controller. The feedback gains of the controller are made adaptive by on-line computation based on altitude and velocity deviations from desired reference trajectory based on the current estimate of states from Navigation.

2. System Model

The system model considered is a Reusable Launch Vehicle (RLV) during its ascent phase. During the atmospheric ascent phase, the thrust generated by the air-breathing engine is highly sensitive to flight path and angle of attack (α).The aerodynamic forces acting on the vehicle play a key role in deciding the flight path of the vehicle. The aerodynamic coefficients are nonlinear functions of altitude (h), Mach number (M), control deflections and angle of attack. Off nominal flight environments to be tackled by the vehicle include, engine performance dispersions, winds, atmospheric density perturbations and dispersions in the aerodynamic characteristics of the vehicle. Considering the complexity of the problem and the need to meet the mission requirements and objectives successfully, the development of an autonomous guidance strategy with on-line trajectory planner and adaptive guidance law to realize the planned trajectory is inevitable.

2.1 Vehicle Simulation

The model used for vehicle simulation includes equations of motion of the vehicle, the atmosphere, the aerodynamics and the propulsion. In the present approach the vehicle is treated as a point mass model performing planar motion over spherical, non rotating Earth. The Vehicle configuration is shown in figure 1. Forces acting on the vehicle are, L-Lift, D-Drag, T-Thrust and W-Weight of the vehicle. V - is the vehicle velocity,α- angle of attack,γ-fligh pthangle from local horizontal.

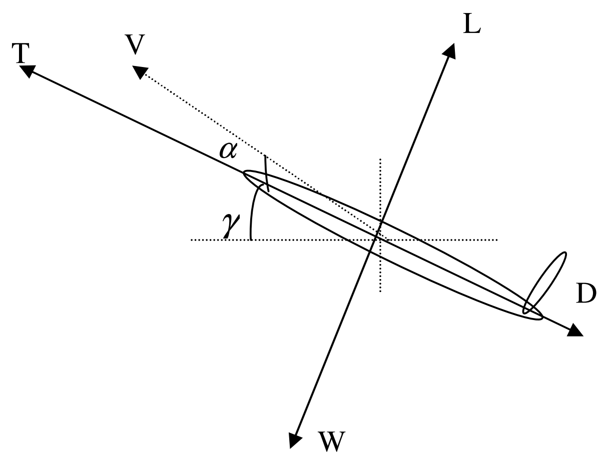

Figure.1 Forces Acting on the Vehicle

Objective of numerical simulation is to determine the vehicle parameter relationships and model the performance. The two steps involved in this stage are simulation of two degree freedom motion of a point mass, and integrate the equations of motion to track altitude, velocity, flight path angle and weight. Equations of motion simulating the vehicle dynamics (1) to (4) are numerically integrated using MATLAB routine.

2.2 Equations of Motion

The vehicle is considered to exhibit a planar motion over spherical, non-rotating Earth. The wind effects are not considered. The equations of motion are given by

$$\dot{v} = -g \sin\gamma + \frac{(T\cos\alpha - D)}{m} \quad \textbf{(1)}$$

$$\dot{\gamma} = \left(\frac{v}{r} - \frac{g}{v}\right)\cos\gamma + \frac{(L + T\sin\alpha)}{mv} \quad \textbf{(2)}$$

$$\dot{r} = v\sin\gamma \quad \textbf{(3)}$$

$$\dot{m} = -\frac{T}{gI_{sp}} \quad \textbf{(4)}$$

Where v -is the vehicle velocity, g- acceleration due to gravity, r- radial distance of the vehicle from the center of Earth, m- vehicle mass, γ- flight path angle, α- angle of attack, I_{sp}- specific impulse. Thrust, lift and drag forces are given by T, L and D.

2.3 Atmospheric Model

The Indian Standard Atmosphere comprising of density, temperature and pressure as a function of altitude is used for the design and analysis. Knowing altitude from sensors, interpolate density and pressure from atmospheric table. This density and pressure are used to compute speed of sound and hence Mach number

2.4 Vehicle Aerodynamic Model

Lift and drag 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 follows

$$L = \frac{1}{2}\rho V_r^2 S_{ref} C_L \quad \textbf{(5)}$$

$$D = \frac{1}{2}\rho V_r^2 S_{ref} C_D \quad \textbf{(6)}$$

Where ρ is the air density, Vr is earth relative velocity and S_{ref} is the reference area. Aerodynamic coefficients C_L and C_D are functions of Mach number and α .

$$C_L = A_0 + A_1\alpha + A_2\alpha^2 \quad \textbf{(7)}$$

$$C_D = B_0 + B_1\alpha + B_2\alpha^2 \quad \textbf{(8)}$$

Where A_0 , A_1 , A_2 and B_0 , B_1, B_2 are functions of Mach number.

3. Adaptive Guidance Strategy

The guidance approach should have one or both of the following elements to be called "adaptive". The reference trajectory should be generated in response to actual flight condition or there are on-line closed-loop adjustments of guidance parameters. An adaptive guidance has a guidance law with adjustable parameters and a mechanism for adjusting the parameters. The guidance parameters can be modified in response to the changes in the vehicle performance (eg. propulsion and aerodynamic characteristics) and the nature of the disturbances (eg. wind and atmospheric density perturbations). Adaptive guidance law works well over a wide range of operating conditions. It can be thought of as having two loops. Inner loop is a normal feed back control loop with the guidance and vehicle. The outer loop is the parameter adjustment loop, here, a trajectory planning / predicting loop. Block diagram of an adaptive guidance system is shown in figure.2. The parameter adjustment loop is often slower than the normal feed back loop.

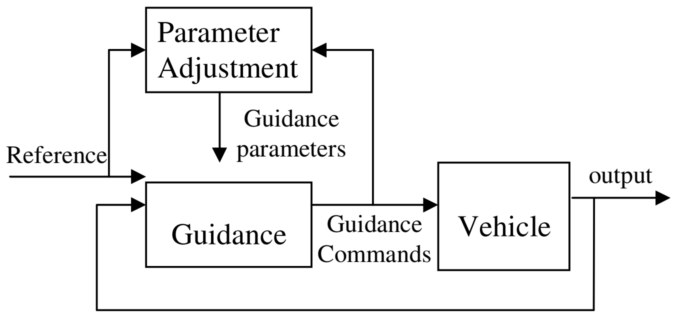

Figure.2 Adaptive Guidance System

4. Ascent Phase Design Using Adaptive Control

This section highlights the architecture of adaptive guidance strategy and discusses the feed back controller design aspects along with the strategy of on line computation of adaptive guidance gains. The controller performance for dispersion cases are discussed along with analysis of simulation results. The robustness of the adaptive guidance algorithm to performance dispersions in flight is clearly established.

4.1 Architecture of Adaptive Guidance Scheme

The architecture of adaptive guidance strategy used in present study is shown in figure.3 below.

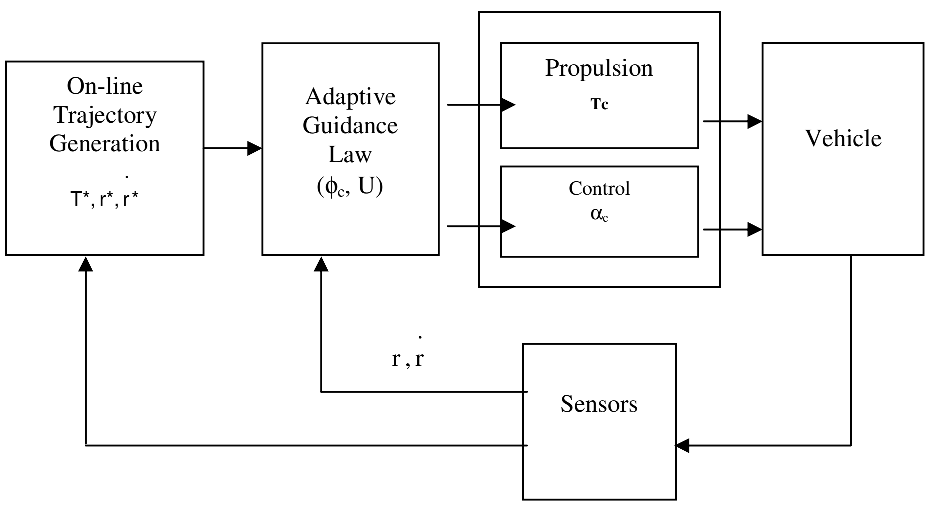

Figure.3 Architecture of Adaptive Guidance Strategy

The most adaptive approach to guidance problem requires no nominal trajectory and in fact continuously selects a new path for the remainder of the flight based only on the current state vector, the constraints to be met and the desired end conditions. In the present strategy, optimal trajectory re-shaping algorithm updates the trajectory at longer intervals (10s) of time. This is the outer guidance loop. The adaptive guidance commands are generated by the inner loop guidance at shorter intervals of time (2s). The inner loop (feedback control loop) includes a gain adaptation algorithm that modifies the feedback gains on-line, based on the estimation of flight path deviations from the desired trajectory. The outer loop design using on-line trajectory reshaping algorithm is given in detail in [10].This paper addresses the inner loop design, ie., design of a gain adaptation algorithm that offers good performance even under off nominal flight environments like engine off nominal performance, aerodynamic dispersions and atmospheric density perturbations. Guidance law uses a PD controller to generate pseudo control (U) which controls the lift and hence angle of attack. Thrust control can be achieved by changing fuel equivalence ratio (Φ) which is not attempted in the present study.

4.2 Feedback Controller Design

A Proportional Derivative (PD) controller is used to track the optimal trajectory generated on-line. The guidance law feeds back position and velocity. The performance of the controller depends upon the values of position feed back gain, k_p and velocity feedback gain, k_d. The controller is made adaptive by estimating these gains on-line as functions of position and velocity deviations from reference in actual flight. The guidance law controls the vehicle lift using the PD controller.

Consider the flight path angle and altitude dynamics given in (2) and (3). We have the system equations in block triangular form as

$$\dot{x}_1 = f(x_1, x_2) \quad \textbf{(9)}$$

$$\dot{x}_2 = g(x_1, x_2, u) \quad \textbf{(10)}$$

where x_1=r, x_2=γ and control u=L. To proceed we take successive total time derivatives of r until dependence on the control appears.

$$\ddot{r} = -g\sin^2\gamma + \frac{L\cos\gamma}{m} - g\cos^2\gamma + \frac{V^2\cos^2\gamma}{r} \quad \textbf{(11)}$$

Since the control**,** L appears in the second time derivative define U, the pseudo control as

$$U = \ddot{r} \quad \textbf{(12)}$$

$$U = k_p\left(r^* - r\right) + k_d\left(\dot{r}^* - \dot{r}\right) \quad \textbf{(13)}$$

where r* denotes the reference optimal solution at the current energy level and the time derivative of r* denotes the climb rate required to stay on the reference optimal solution as energy is gained. Solving for lift control L, in (12), using (11)

$$L = \left[U + g - \frac{V^2\cos^2\gamma}{r}\right]\frac{m}{\cos\gamma} \quad \textbf{(14)}$$

Lift control solution is referred as Non Linear Transformation (NLT) control solution. A block diagram depicting the conceptual implementation of the nonlinear transformation technique to yield the controller defined in (14) is presented in figure.4a. This is mathematically equivalent to the linear system depicted in figure. 4b, which is used to design the controller.

The closed loop transfer function of the system can now be defined as

$$G(s) = \frac{k_d s + k_p}{s^2 + k_d s + k_p} \quad \textbf{(15)}$$

where the gains k_p and k_d for the second order system can be written in terms of the damping ratio, ξ, and natural frequency, ω_n, as $k_p=\omega_n^2$ and $k_d = 2\xi\omega_n$. The performance of this controller can be dictated by selecting the values of k_p and k_d to yield the desired dynamic response.

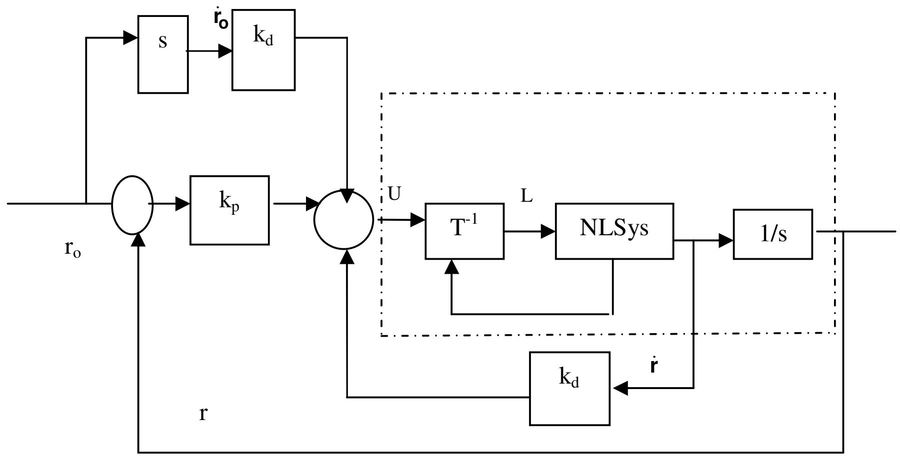

Figure.4a. Block diagram depicting conceptual formulation of NLT control law

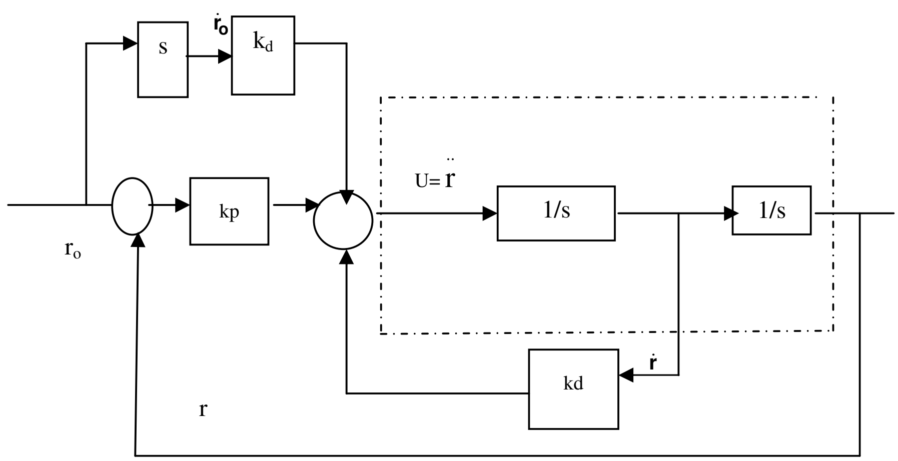

Fig.4b. Block Diagram of Equivalent Linear System

4.3 Adaptive Law for Control Gains

The gains k_p and k_d are made adaptive by computing them on-line as a function of the deviation of current position(hc) and velocity (vc) from the reference trajectory (hr-vr) computed by the outer loop. The information on current position and velocity will be available from navigation system. The deviation in altitude, ‘dh’ and deviation in velocity ‘dv’ can be computed on-line. The gains are estimated on-line using the following second order adaptive control law

$$kp=k1p*dh*dh+k2p*dh+k3p \tag{16}$$

$$kd=k1v*dv*dv+k2v*dv+k3v \tag{17}$$

The coefficients, k1p,k2p,k3p,k1v,k2v and k3v are pre-computed based on a large number of simulations carried out in ground for estimating the best fit that ensures robust performance even under off-nominal conditions of flight.

4.4 Controller Performance

The controller performance was evaluated for the range of k_p values 0.01 to 1 predicted by the guidance law. The step response is shown in figure.5.

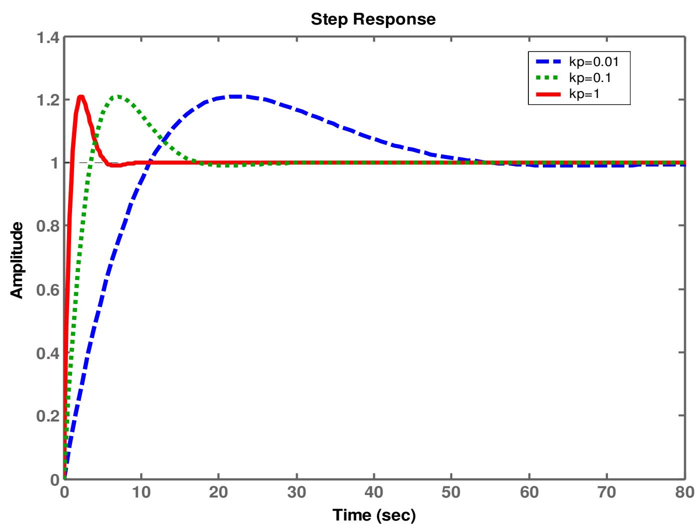

Figure.5 Controller Step Response

The system is found to be stable for the range of gains predicted by the adaptive guidance law. The step response shows good dynamic response with overshoot always less than 20%. Step response results are summarized in table.1. Tr- Rise time, Ts- Settling time.

Table.1 Step Response Results

Gain (kp)	Tr(s)	Ts(s)
0.01	8.5	48.8
0.1	2.69	15.5
1.0	0.85	4.89

4.5 Simulation Results

The adaptive guidance algorithm implemented as explained in the previous section is applied to a generic RLV during air-breathing ascent phase. Extensive flight simulations are carried out to validate the algorithm. Initial conditions and desired end conditions are given in table. 2.

Table-2 Initial and Desired End Conditions

Flight Parameters	Initial Values	End Conditions
Altitude	5.50 km	27.297 km
Velocity	431.41m/s	2119 m/s
Flight path angle	28.8 °	2.2 °
Mass	176 t	160.18t
Mach number	1.3	7.00

The adaptive guidance algorithm is validated for air-breathing engine off nominal performance, aerodynamic parameter uncertainties and atmospheric density perturbations. Following cases are simulated.

Case 1	Engine Thrust +5%		
Case 2	Engine Thrust -5%		
Case 3	C_L+20%		
Case 4	C_L-20%		
Case 5	C_D +20%		
Case 6	C_D -20%		
Case 7	Thrust +2%	C_D -20%	C_L+20%
Case 8	Thrust -2%	C_D +20%	C_L-20%
Case 9	Atmospheric density -2%		
Case 10	Atmospheric density +2%		

Guidance command to shut off the engine is issued once the target Mach number is reached. Maximum dispersion in achieved altitude is 6m. Maximum velocity dispersion is less than 1m/s and the maximum error in flight path angle is 0.6deg. This clearly establishes the efficiency and robustness of the adaptive guidance strategy for meeting the mission requirements and specifications. Dispersions in achieved terminal conditions are given in table 3.

Table-3 Dispersions in Achieved End Conditions

Cases	$\lvert\Delta h_f\rvert$ m	$\lvert\Delta V_f\rvert$ m/s	$\lvert\Delta\gamma_f\rvert$ deg
1	2	0.3	0.01
2	5	0.5	0.42
3	4	0.4	0.32
4	3	0.3	0.01
5	6	0.8	0.60
6	5	0.7	0.01
7	1	0.1	0.04
8	3	0.1	0.39
9	4	0.6	0.41
10	1	0.1	0.42

Variation of altitude and velocity for four worst cases are shown in figures. 6 and 7 respectively.. Figure.8 shows dynamic pressure variation and for all cases dynamic pressure lies within the specified limits of 63±1kPa.

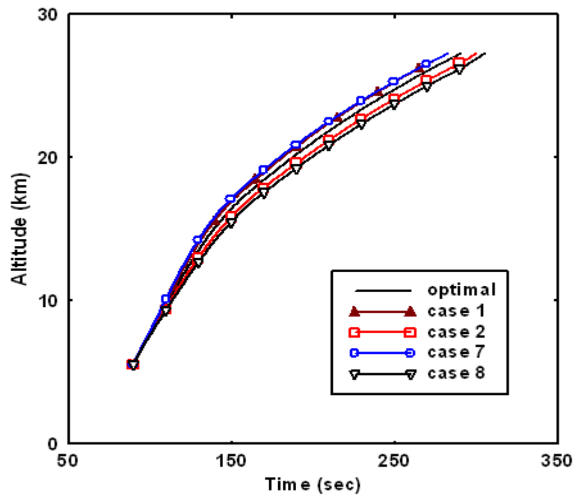

Figure.6 Altitude Profiles

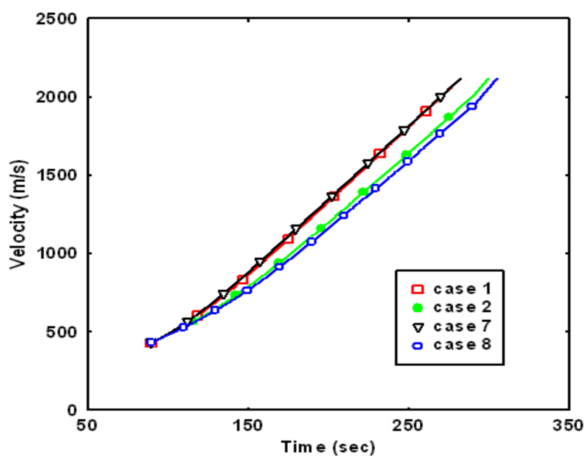

Figure.7 Velocity Profiles

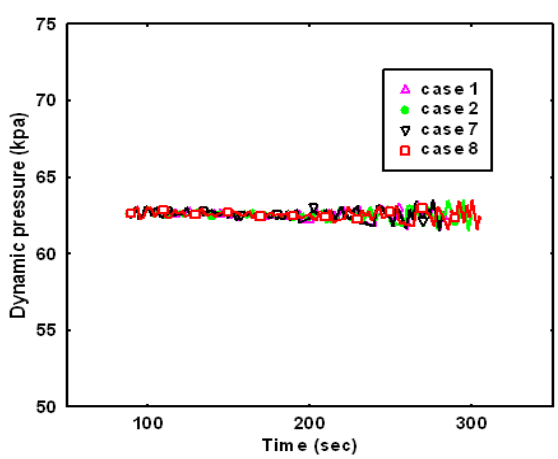

Figure.8 Dynamic Pressure Profiles

Figure.9 shows (angle of attack profile) control required for the vehicle to follow reference trajectory. If we examine figures.10 and 11 we can see how efficiently the adaptive guidance algorithm reduces the altitude and velocity error to zero.

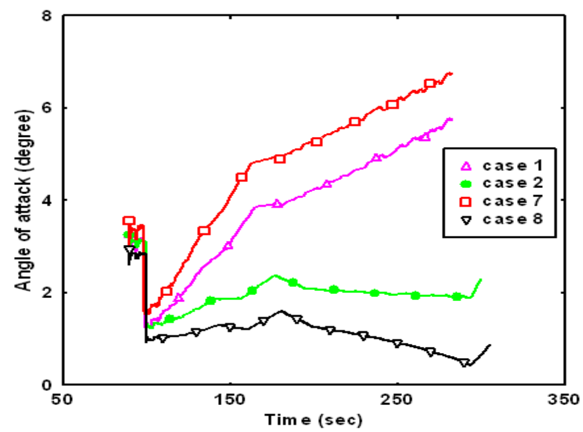

Figure.9 Angle of Attack Profiles

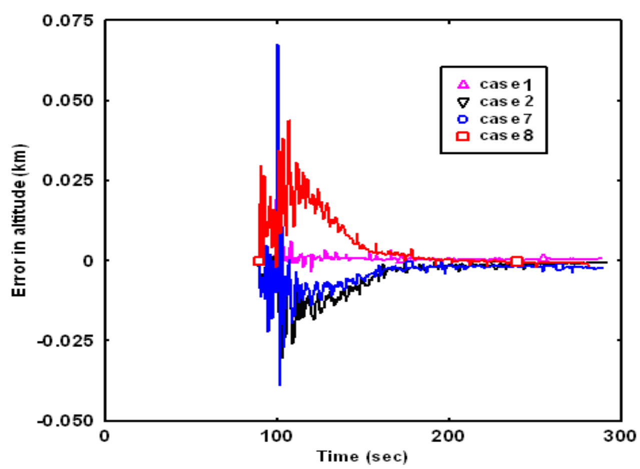

Figure.10 Position error

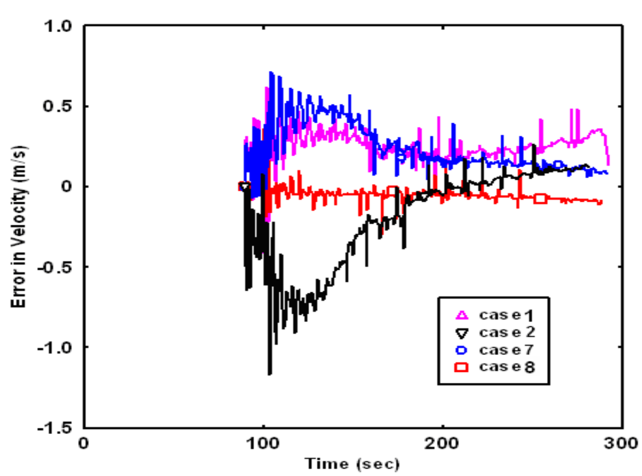

Figure.11 Velocity error

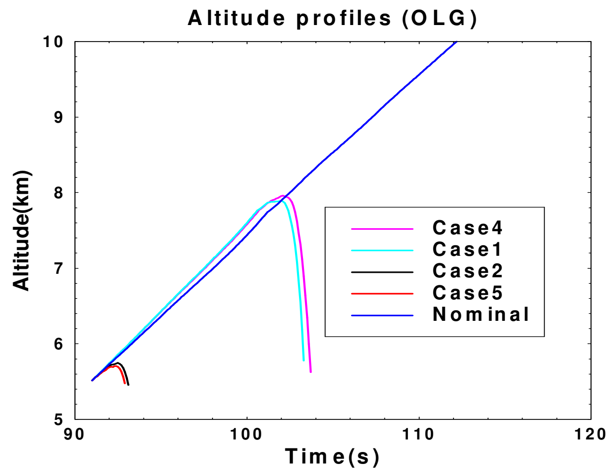

Figure.12 Altitude Profiles (OLG)

A performance comparison made with open loop guidance for the above dispersion cases revealed that the vehicle would impact on ground (fig.12) shortly after take off for under performance cases (case1,2,4 & 5) . This highlights the importance of appropriate angle of attack profile required for controlling the RLV in the air-breathing ascent phase in the presence of propulsion and aerodynamic dispersions. This feature is captured very effectively in the adaptive guidance law by generating appropriate lift commands that controls the vehicle angle of attack to follow the reference trajectory.

5. Conclusion

This paper presented the formulation and design of a suitable adaptive guidance law for the air-breathing ascent phase of an RLV. The Guidance law controls the vehicle lift force using a Proportional Derivative controller. Adaptive control feature is introduced in the guidance law by providing the feature of on-line adjustment of guidance parameters in response to actual flight environments by way of adjustable feed back gains. The robustness of the controller design is established through extensive flight simulations under off nominal conditions of engine performance, aerodynamic dispersions and atmospheric density perturbations. The guidance law proves to be computationally efficient and suitable for real time implementation. The guidance law ensures that path and terminal constraints are always satisfied meeting the mission requirements accurately.

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