Mission design and performance of RLV-TD

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Renewed interest in re-usable launch vehicles has led to the evolution of technology demonstration concepts, where the prime objective is to demonstrate new technologies at reduced cost and shorter turnaround time. This article presents details of both ascent and descent mission design of a low-cost Reusable Launch Vehicle Technology Demonstration (RLV-TD) programme. The technology demonstrator vehicle is boosted to hypersonic Mach number using a solid booster. During ascent phase, the vehicle was flown in a gravity turn trajectory to minimize structural loads on it. In the descent phase, an optimum angle of attack profile as a function of Mach number was computed to limit dynamic pressure, load factor and achieve vehicle trim with minimum control surface deflection. The mission design parameters were evaluated using Monte Carlo analysis utilizing six degrees of freedom simulations. Comparison of actual flight performance with pre-flight prediction is also made this article. Flight performance exhibits close match with the pre-flight predictions.

Keywords: Flight performance, reusable launch vehicles, mission design, pre-flight predictions.

Introduction

RE-ENTRY technology demonstrator missions are a common feature nowadays. Automatic landing flight experiment (ALFLEX), hypersonic flight experiment (HYFLEX) and orbital reentry experiment (OREX) of JAXA[1], X43A and X-51 of national aeronautics and space administration (NASA)[2] and IXV of ISA[3] are some examples. All these demonstrator missions focus on mastering various re-entry-related technologies at reduced cost and turnaround time. The underlining concepts of all these missions are identical, which is to boost the technology demonstrator vehicle (TDV) to the required re-entry conditions using existing hardware/booster. This concept is a cost- and time-effective way of proving technologies that will lead to the development of two stage to orbit (TSTO) or single stage to orbit (SSTO) concepts in the near future.

In this article the mission design and validation process of the hypersonic flight experiment (HEX) of the Reusable Launch Vehicle Technology Demonstrator (RLV-TD) are addressed. The objective of the mission was to demonstrate controlled hypersonic re-entry of a winged-body vehicle. To achieve this, the TDV is boosted to hypersonic re-entry conditions using a 9 tonne class of solid motor called HS9. Once the vehicle reaches the hypersonic entry conditions, it performs a controlled unpowered re-entry. This article presents details of the ascent and descent mission and its validation using Monte Carlo (MC) simulations. These simulations provide an insight into the many mission design aspects and help revise the mission strategies to improve the performance of TDV and achieve mission objectives with higher confidence level. The article also provides a comparison of the pre-flight design values and MC bounds with the flight-observed performance parameters. The mission was successfully accomplished in May 2016 from Sriharikota, the space port of India.

Mission objectives

The objectives of the mission are: (i) Hypersonic aerothermodynamic characterization of winged body configuration. (ii) To evaluate autonomous navigation guidance and control schemes under the environment of re-entry from hypersonic Mach numbers to touchdown. (iii) Integrated flight management from hypersonic to subsonic speeds simulating landing manoeuvres. (iv) Design, development and demonstration of carbon/carbon elements. (v) Thermal protection system (TPS) evaluation.

The ascent trajectory with HS9 booster was designed precisely to achieve flight conditions that would allow relevant hypersonic aero-thermodynamic characterization of the TDV. Attainment of these flight conditions was also subject to constraints that would enable a descent flight that goes through sufficiently low and high dynamic pressure regimes so as to allow the integrated flight management system to perform a seamless transition between reactive control system (RCS)-based and aerosurface-based control schemes. Besides this, the ascent and descent trajectories were additionally tuned to result in descent flight conditions that would enable the closed loop guidance system to function suitably after it takes

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*For correspondence. (e-mail: pillai_jr@vssc.gov.in) over from open loop guidance at Mach 2 (even with off-nominal ascent performance).

Configuration and mission

Figure 1 shows the TDV ascent launch configuration. The TDV is a winged body of 1800 kg with double-delta wing having a hypersonic *L*/*D* of 2.5. It has elevons and twin vertical tails for control in the longitudinal and lateral plane. In the ascent configuration, the TDV is mounted on a solid booster with 9 tonne propellant loading. The fins on the booster are sized for stability and control during the ascent phase of the mission. Figure 2 shows a typical mission profile from liftoff till touchdown. After a vertical rise to clear the tower, the vehicle follows an optimum wind-biased gravity turn trajectory till booster separation. The booster burns out at around 96 s at 33 km altitude. After burnout the booster and TDV continue in a combined coast till the dynamic pressure falls sufficiently to allow for a safe separation at around 44 km. After separation from the booster, the TDV continues its unpowered coast to peak altitude of 65 km and that starts the descent mission. During descent, the vehicle flies in a predetermined optimum Mach versus angle of attack programme till it reaches Mach number 2 at around 20 km, from where the closed loop guidance takes over and accomplishes a safe touchdown in the Bay of Bengal at around 550 km from Sriharikota range (SHAR).

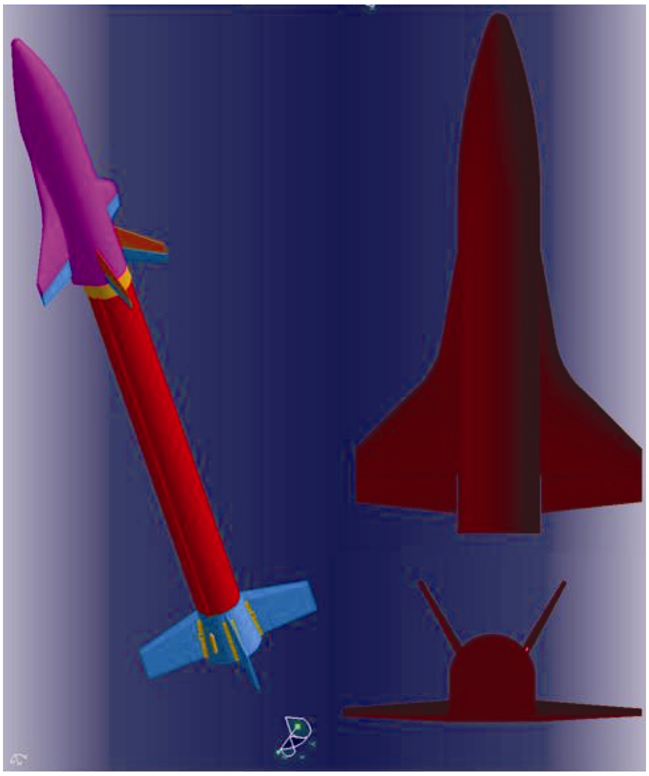

Figure 1. Ascent and descent launch configuration.

Ascent and descent mission design

Ascent mission

The ascent phase of the mission begins at booster ignition and ends at the separation of the TDV. The objective of the ascent mission is to deliver the TDV at maximum Mach number for suborbital re-entry. With the existing fast-burning thrust profile of the booster, the ascent phase dynamic pressure exceeded 150 kPa and the mission was not feasible. Hence an optimum thrust profile was worked out by simultaneous optimization of thrust profile and steering programme. Details of the optimization process are discussed in Joseph *et al.*[4]. The optimum thrust profile thus generated was used as a reference by the solid motor designers to arrive at a feasible thrust profile to meet the mission requirements. Figure 3 shows the original thrust profile and the new profile realized for the mission. Optimum pitch and yaw steering programme for the ascent phase was computed in order to fly an optimum wind-biased gravity turn trajectory till booster separation. In conventional launch vehicles we fly the gravity turn trajectory in zero angle of attack, because the vehicle being symmetric, the normal force acting on it is zero at zero angle of attack and hence the bending moment will be minimum. In HEX mission the ascent configuration being asymmetric, the normal force is not zero at zero angle of attack. Figure 4 shows the normal force as a function of angle of attack for various Mach numbers for the ascent configuration. For each Mach number, the angle of attack at which the normal force is zero is a non-zero value. In Figure 5, this angle of attack value is plotted as a function of Mach number. During gravity turn, the vehicle is flown at this angle of attack to achieve minimum normal force and hence reduce the bending moment on it. However, during extensive simulation studies with vehicle flexibility models, it was found that there was an excursion in angle of attack during the transonic region resulting in excessive normal load on the vehicle. The reason for this was later attributed to a nonlinearity in the pitching moment characteristics (Figure 6), which was not captured in the control system design. It is seen from Figure 6 that at –0.5 deg angle of attack at which the vehicle is flown during transonic region, the nonlinearity is severe. To circumvent this issue the angle of attack profile during gravity turn was modified from the one shown in Figure 5 to that shown in Figure 7. Though zero normal force angle of attack is not flown till Mach number 2, due to better performance of the control system for this angle of attack, the angle of attack excursion at transonic and hence the structural load on the vehicle were significantly reduced. During ascent phase the velocity azimuth at booster separation was constrained to 90 deg. If the velocity azimuth is not constrained during trajectory design, during separation it will depend on the wind used for biasing the trajectory. There can be

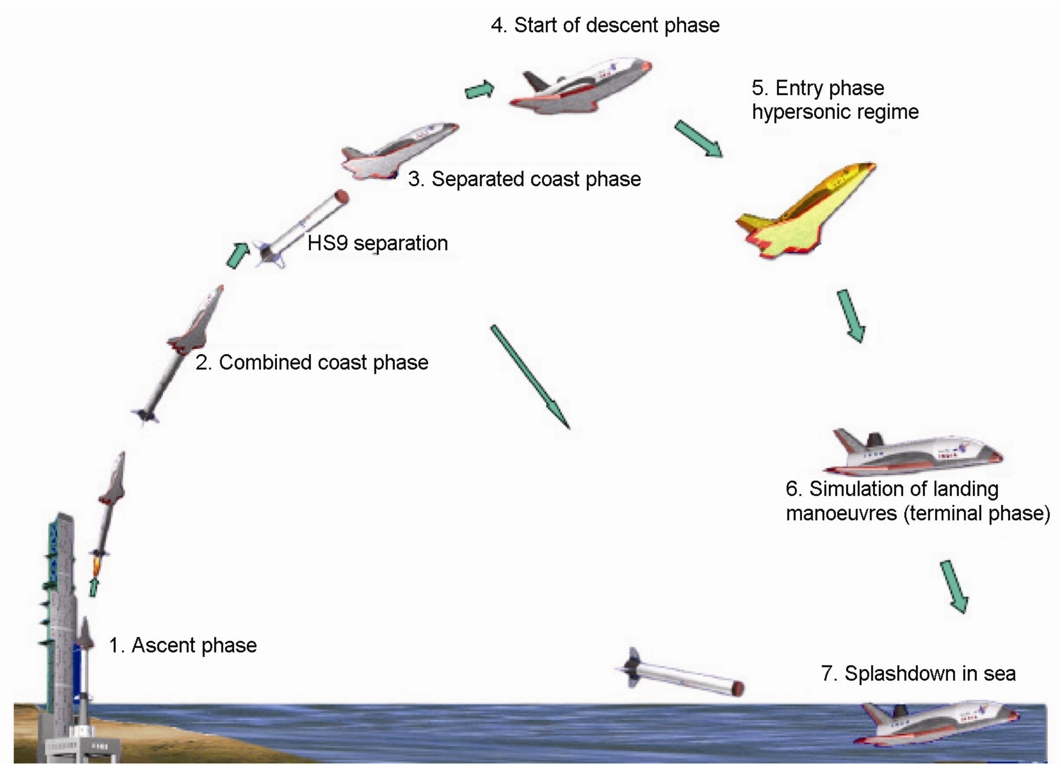

Figure 2. Mission profile.

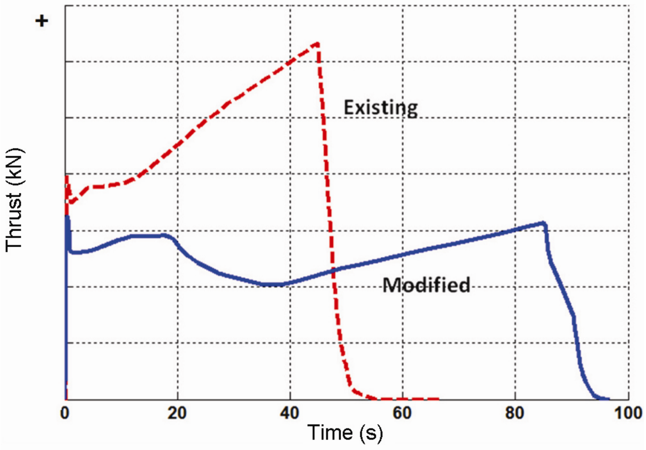

Figure 3. Booster thrust profiles.

variation in azimuth up to 4–6 deg. This variation in velocity azimuth depending on the wind will result in substantial cross-range error when closed-loop guidance is initiated during descent phase at an altitude of 20 km and Mach number 2. In Figures 8 and 9, the ground trace of the vehicle biased to various wind profiles without and with velocity azimuth constraint is compared. The large dispersion in cross range at closed loop guidance initiation can be seen in Figure 8, when velocity azimuth at separation is not constrained. During the ascent trajectory design in addition to the basic aerodynamic forces, the incremental aerodynamic forces due to fin deflection are also accounted. For this purpose a static moment balance computation is carried out along the trajectory, which gives the booster fin deflection required for moment balance and hence the incremental aerodynamic forces. Typical trajectory parameters and the ascent fin deflection for static trim as computed by the optimum steering program generation program ATOM (Aerospace Trajectory Optimization Module) are shown in Figures 10 and 11 respectively. It is seen that the peak dynamic pressure during ascent is around 50 kPa, and the peak altitude is around 65 km and maximum Mach number at entry (beginning of descent) is around Mach number 4.

Descent mission

Descent mission starts from the peak altitude and ends at touchdown or splashdown at sea. The objective of the mission is to deliver the TDV from hypersonic Mach number to supersonic Mach number without violating the thermal and structural constraints on the vehicle. These constraints form a re-entry corridor in the altitude – velocity plane. The vehicle is guided to fly through this corridor so as to ensure non-violation of the constraints. The re-entry corridor for a vehicle dynamic pressure limit of 20 kPa, load factor limit of 4 *g* and equilibrium glide is shown in Figure 12, along with the descent trajectory. The equilibrium glide constraint is a soft constraint which can be violated in flight (Figure 12). Since entry is from Mach number 4, the thermal constraints are not active and hence not shown in the figure. Now to fly the vehicle in this corridor, an optimum angle of attack schedule needs to be worked out. The scheduled angle of attack should not violate the control capability (trim) of the vehicle. The control capability is computed for the entire angle of attack range for the complete range of re-entry Mach

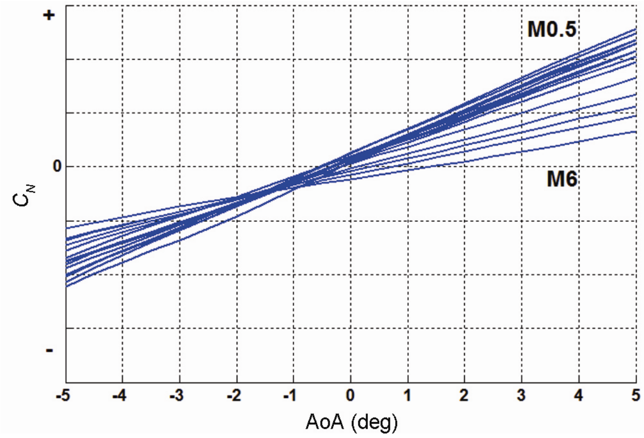

Figure 4. Ascent : normal force. C_N, Normal force coefficient; AoA, Angle of attack.

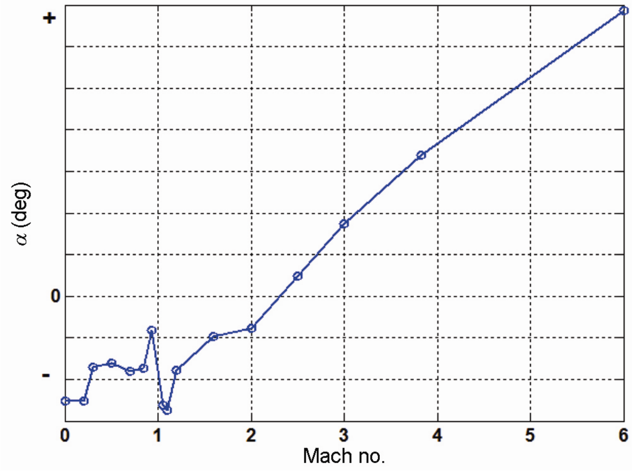

Figure 5. Ascent : angle of attack for zero normal force.

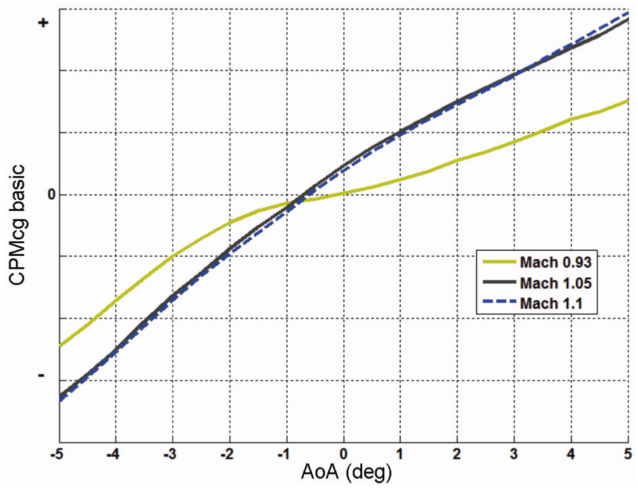

Figure 6. Moment characteristic at transonic. CPMcg basic, Basic pitching moment coefficient about CG.

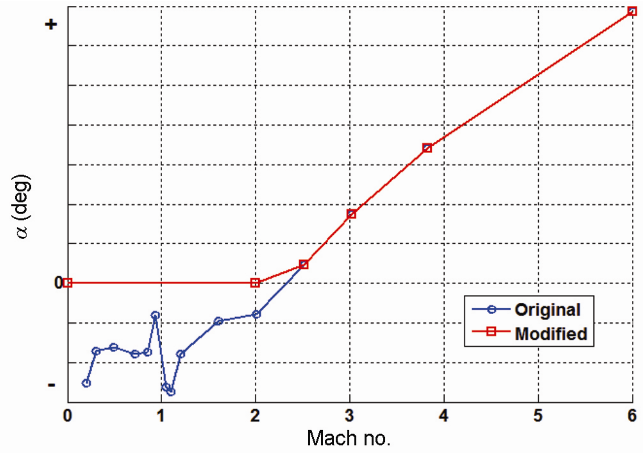

Figure 7. Modified angle of attack.

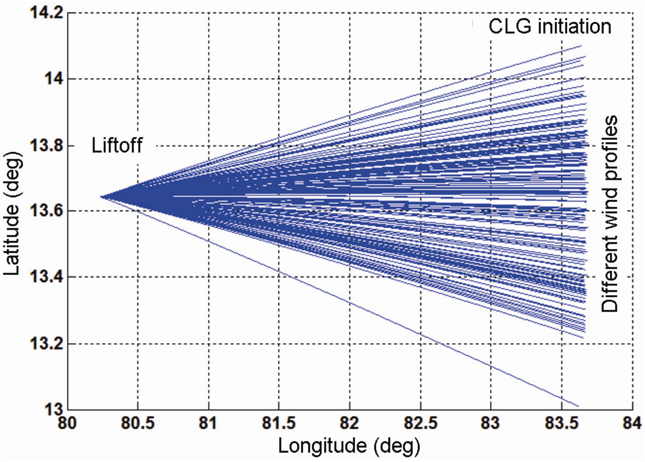

Figure 8. No constraint on velocity azimuth.

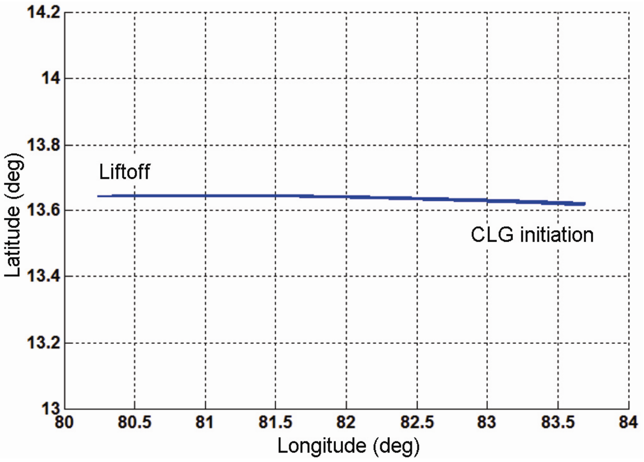

Figure 9. Velocity azimuth constraint at separation.

numbers. The trim boundary for TDV is shown in Figure 13, along with the scheduled angle of attack. Figure 14 shows the control surface deflection required to trim the vehicle for the schedule angle of attack. Figure 15 shows the important trajectory parameters till the start of guidance. It can be seen that to fly the angle of attack profile or to trim the vehicle both elevon and rudder deflections are necessary. If the vehicle is trimmed using elevons alone,

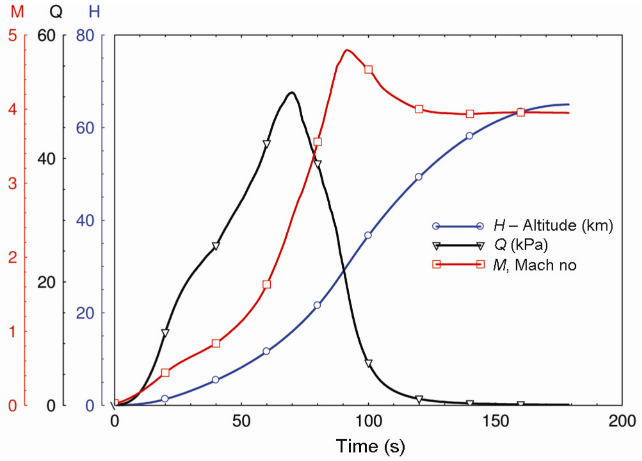

Figure 10. Ascent trajectory parameters. Q, Dynamic pressure.

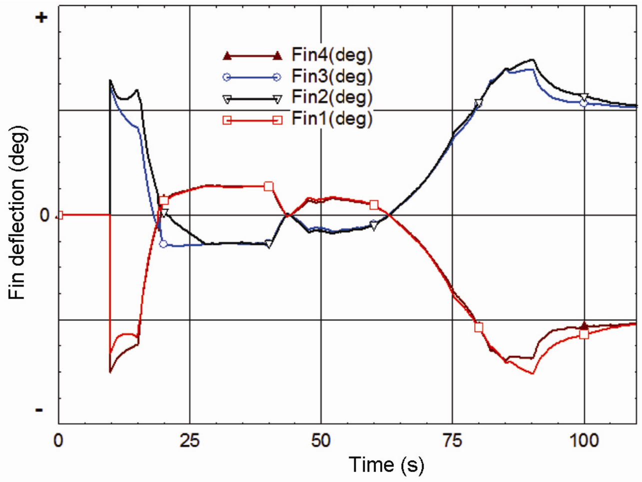

Figure 11. Fin deflections during ascent.

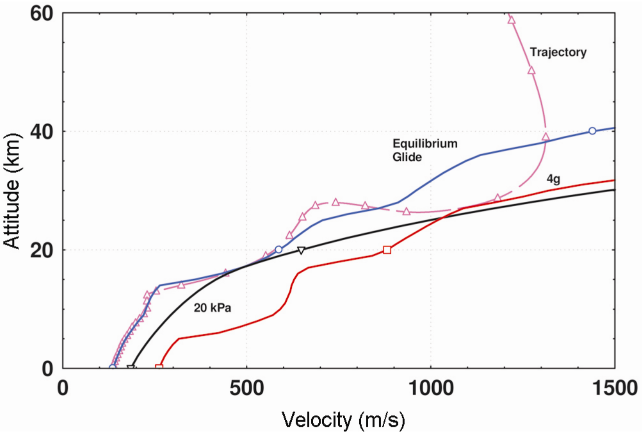

Figure 12. Re-entry corridor.

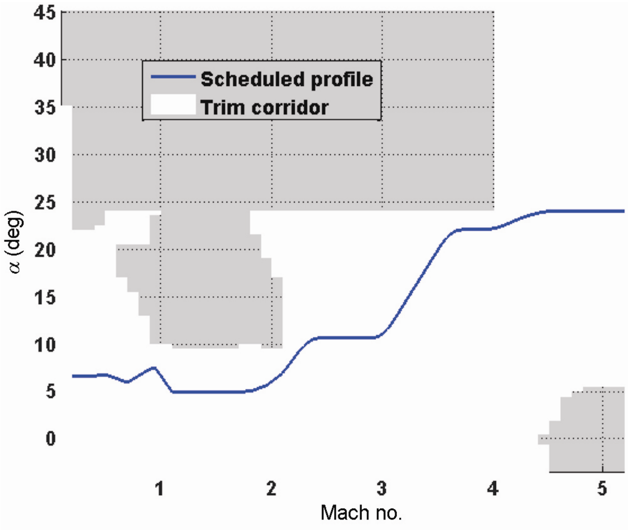

Figure 13. Trim boundary.

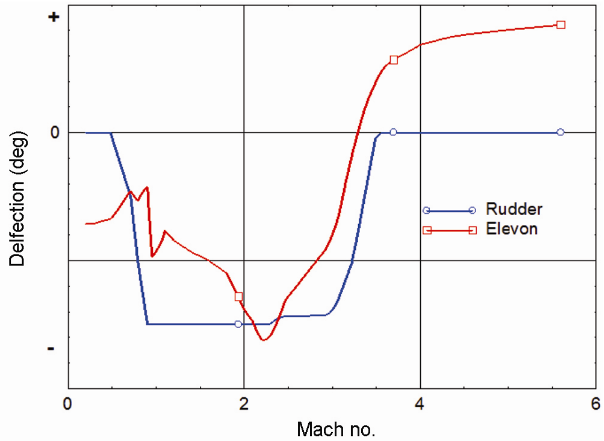

Figure 14. Control surface deflection for trim.

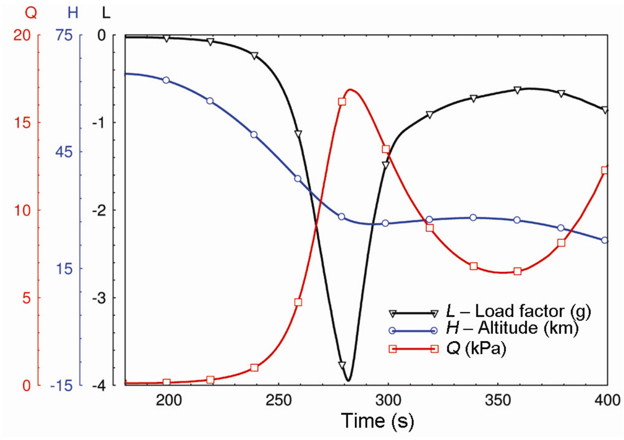

Figure 15. Descent trajectory parameters.

Table 1. Error sources, their nominal values and dispersion

N	Parameter	3σ
1	Structural mass (kg) (HS9, TDV)	(20, 30)
2	Thrust misalignment HS9 (deg)	0.15
3	Secondary injection thrust vector control (SITVC)	
	Propellant mass (kg)	2
	Control force (kN)	10%
4	Reactive control system (RCS)	
	Vacuum thrust (N)	10%
5	Centre of gravity (mm)	
	At lift off: (*X*-axis, *Y*-axis, *Z*-axis)	35, 2.5, 6.5
	TDV after separation: (*X*-axis, *Y*-axis, *Z*-axis)	15.5, 3.5, 7.0
6	Moment of inertia (kg m^2)	
	At liftoff	4%
	TDV after separation	3.5%
	Product of inertia (kg m^2)	
	At liftoff	7%
	TDV after separation	6.5%
9	Wind	Altitude-based wind correlations
10	Aero parameters	20%
12	Control system mounting errors (deg)	
	Movable fins	0.2
	Elevons	0.1
	Rudders	0.1
13	Radar altimeter error	1 m, for 10–200 m altitude, 0.5–2.0%, linearly varying from 200 m to 2 km
14	GPS noise	30 m for altitude, 0.3 m/s for velocity
16	HS9 motor	
	Segment propellant mass (kg)	
	(head end, middle, nozzle end)	(9, 9, 2)
	Propellant burning rate (mm/s)	
	(head end, middle, nozzle end)	(0.1, 0.1, 0.1)

Table 2. RLV-TD HEX-01 mission dispersions: Monte Carlo technique

Parameter	Time (s)	Altitude (km)	Inertial velocity (m/s)	Flight path angle (deg)	Velocity azimuth (deg)	Mach number	Angle of attack (deg)	Side slip angle (deg)	Dynamic pressure (kPa)
At HS9 separation									
Nominal	115.14	46.5296	1756.36	70.3991	89.8817	4.12262	1.94584	–0.3792	1.36627
Mean	112.054	44.4756	1754.19	69.7101	89.9989	4.13548	2.1004	–0.0905	2.06156
3σ	3.87217	1.889	61.1612	0.84685	0.5033	0.23167	1.06707	0.62669	0.73456
Minimum	108.66	42.8632	1695.31	69.0696	89.488	3.89132	1.11497	–0.7064	1.39787
Maximum	116.16	46.3869	1822.42	70.5273	90.3755	4.37528	3.14734	0.36053	2.77521
At maximum Mach number									
Nominal	94.86	32.6206	1828.72	64.8587	89.7983	4.69152	1.51209	–0.1172	11.6025
Mean	91.8456	30.1979	1838.96	64.1516	89.9147	4.76699	1.4313	–0.0003	18.9668
3σ	4.02325	2.13535	60.4911	0.86013	0.49812	0.21442	0.58325	0.53563	7.15726
Minimum	88.46	28.7377	1784.06	63.4914	89.4021	4.54865	0.89206	–0.5423	11.73
Maximum	96.06	32.5549	1900.19	64.9999	90.2796	4.97381	1.95272	0.37128	24.3567
At end of mission									
Nominal	305.36	26.015	1337.71	88.0004	90.8118	2.99912	10.6363	–0.0631	12.6947
Mean	304.403	26.637	1340.55	88.3306	90.7433	2.99898	10.6886	0.02808	12.6277
3σ	8.63942	1.55632	16.4165	2.44772	0.86272	0.00195	0.27571	0.4546	2.89748
Minimum	295.76	25.1314	1324.04	86.0909	89.8927	2.99684	10.4118	–0.44	10.4064
Maximum	312.86	28.1314	1358.13	91.3849	91.6955	2.99999	11.0304	0.46192	15.2406

then the elevon deflection for trim exceeds 20 deg with no control authority left for disturbance rejection. Using rudder for trim has ensured that the elevon deflection for trim does not exceed 15 deg. It is also seen that the rudder deflection for trim is constrained to 15 deg so as to allow sufficient control authority for lateral direction control.

Mission performance and its deviation

MC simulation study is one of the most widely used simulation techniques to assess the adequacy of the launch vehicle mission design[5]. Mission performance deviations from the targetted performance can be statistically assessed by the MC technique. An important step in MC technique is the listing of all error sources and assignment of numerical values to each of them, apart from their nominal values (design specification), that can provide an indication of how much can be the expected variation and its statistical characterization. Table 1 gives a list of error sources as identified for the HEX mission specification panel along with the 3σ dispersions.

It has been the practice to assume these error dispersions to be Gaussian[6], as all measurement uncertainties follow Gaussian distribution. It may be remarked that the method of approach of the analysis remains unaltered even if it obeys a different distribution. The dispersions as provided in Table 1 have been obtained on the basis of the present state of technology at VSSC, Thiruvananthapuram taking into consideration the performance data of ground tests. In the MC technique all these error sources are simultaneously sampled and the values are supplied through the simulation program to obtain the performance parameter values. This sampling is repeated many times and the resulting output variable values are subjected to statistical analysis. Four hundred simulations were carried out to assess the deviation of mission critical parameters during pre-flight studies. Table 2 provides a brief summary of the reusable launch vehicle (RLV) mission dispersions at several salient instants of the trajectory. That this sample size (due to availability of May month wind profiles) is adequate to draw inferences

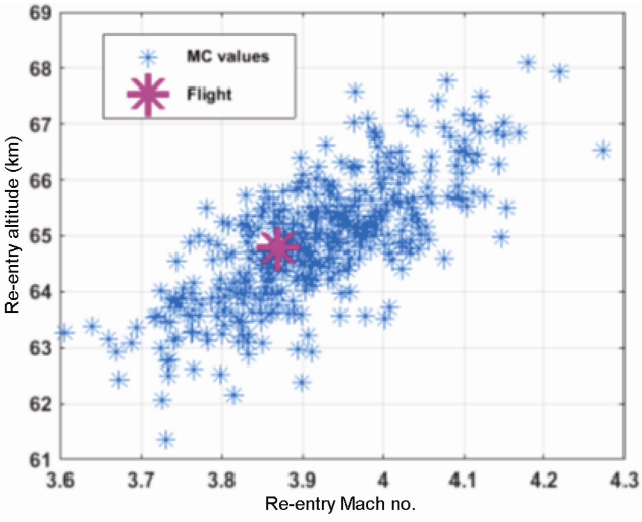

Figure 16. Re-entry altitude vs Mach number.

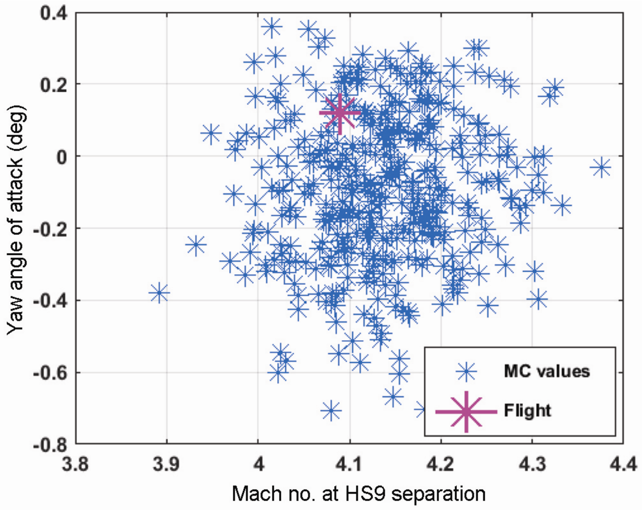

Figure 17. Sideslip angle at HS9 separation.

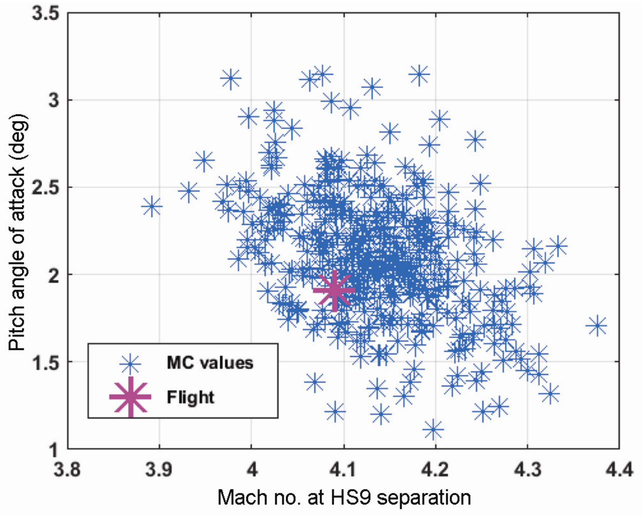

Figure 18. Angle of attack at HS9 separation.

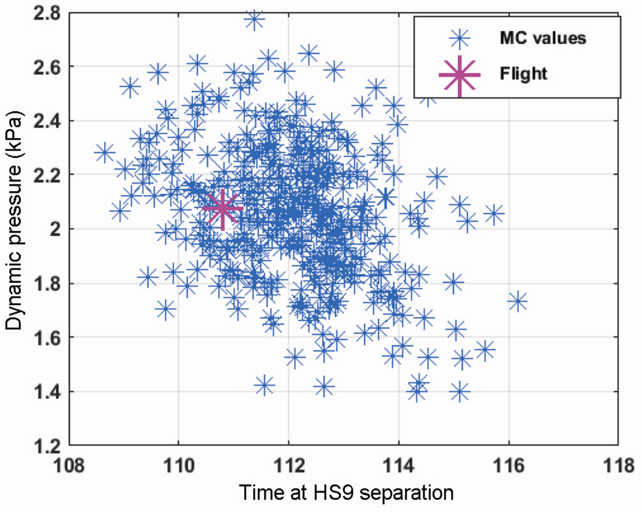

Figure 19. Dynamic pressure at HS9 separation.

has been justified by considering the effect of number of replications on standard deviation and mean of peak altitude and peak Mach number, which are crucial for the success of the mission. Some of the highlights of the MC technique are as follows: altitude dispersion at gravity turn initiation is 21.77 m with structural integrity in terms of the product of dynamic pressure (*Q*) and angle of attack is benign. Maximum dynamic pressure during ascent phase transonic region is 34.01 kPa; HS9 separation maximum dynamic pressure is 2.77 kPa. Maximum altitude that the vehicle can attain is 68 km and the minimum re-entry Mach number is 3.6. Maximum Mach number that the vehicle can experience is between 4.55 and 4.97, which increases the confidence of a successful design. As defined, the end of the HEX mission is the instant when the vehicle experiences Mach number 3 during descent phase. MC simulation results at the end of the HEX mission have a small dispersion of 0.002, which reaffirms that that mission will be 100% successful. Comparisons of the MC results with flight-observed values are plotted in Figures 16–19 respectively, for a few parameters like re-entry Mach number, re-entry altitude, sideslip angle and angle of attack at separation and dynamic pressure during separation. A good agreement can be noticed between pre-flight values obtained using MC technique and the flight values.

Conclusion

The hypersonic flight experiment of RLV-TD demonstration mission is discussed in this article. The mission objectives, the ascent and descent mission configurations, and details of design for the ascent and descent mission has been discussed highlighting the important results. The mission performance due to uncertainty in various parameters is evaluated using MC simulations. A comparison of mission performance and actual flight values is given. It is observed that the flight values are in good agreement with the pre-flight predictions.

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doi: 10.18520/cs/v114/i01/101-108