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Abstract: The overall sizing of launch vehicles is of interest, especially when air-breathing is also included. The sizing of a launch vehicle is dictated by the State of Art technologies present and the need to match the challenging demands of high-payload fraction, low cost, and also ensure reliability. This paper presents some of the important design requirements. An ideal velocity approach, which assumes various velocity losses, is generally followed for initial vehicle sizing. However, as this approach is approximate and sometimes incorrect, a new concept of accounting the drag and thrust losses during the atmospheric phase for conventional rockets and air-breathing launch vehicles using scramjet propulsion is evolved complementing the ideal velocity sizing approach. A simplistic two-dimensional trajectory simulation program with graphics for quick interactive design was developed for this purpose. The air-breathing launch vehicle trajectory is split into three flight phases. The sizing of the vehicle considering, especially, the intermediate air-breathing regime is also dealt with. A method to determine the maximum-load envelope expressed in terms of the product of flight dynamic pressure and angle of attack, namely Q-alpha, for all weather launches useful for initial design purposes is also suggested. The design program meant for initial design sizing purposes gives a quick insight on the vehicle performance prior to detailed design with minimum basic vehicle data for conventional rockets and also for air-breathing scramjet vehicles. The various design factors, such as optimum velocity requirement for two stage to orbit vehicles and the sizing requirement of the orbital stage after end of air-breathing phase, are also discussed through representative typical values highlighting the design sensitivities.

Keywords: launch vehicle design, air-breathing vehicle sizing, trajectory design sizing program, launch vehicle performance

1 INTRODUCTION

The overall sizing of launch vehicles to meet a particular mission requirement is an important aspect, especially in the initial vehicle design phase. The choice of the propulsion system and its sizing, apportionment of the stage system structural masses and deriving a broad mission sequence is very important, as it has a very large impact on the launch vehicle development programme. As the overall reliability increases with lower number of stage systems, it is also necessary to reduce the system complexities and maintain operational convenience. In actual practice, the selection of a particular launch vehicle configuration meeting a defined mission is an elaborate painstaking process, which also considers the state of art, development feasibility, cost and schedule aspects.

Towards the previous-mentioned factors, numerous studies are reported in the published literature on the various aspects of launch vehicle design including cost and reliability. As the area of launch vehicle design is vast, studies are done in various phases from the initial configuration design to the detailed design stage including interactive design disciplines and overall optimization studies. Hence, it would be very difficult for any single paper to cover the whole gamut of design issues. Still many papers have addressed the overall configuration design aspect to a large extent.

Ryan and Townsend [1] address the salient performance parameters of the space shuttle and Saturn vehicle as a benchmark example, starting from the idealized rocket performance equation to determine the key design drivers. Robustness is the key to uncoupling the design factors so that optimization can occur, but typically robust designs define low-performance systems and also the future space launch vehicles must develop new technologies to reshape the design parameter sensitivities of robustness and performance functions [1]. Detailed studies on the conceptual design of two types of reusable two stage to orbit (TSTO) vehicles considering the impact of mission requirements and constraints are dealt with in reference [2].

Olds [3] dwells comprehensively on the design of a reusable single stage to orbit (SSTO) vehicle making use of rocket-based combined cycle (RBCC), which combines the operating modes of an ejector, ramjet, scramjet, and rocket in a single engine. The RBCC SSTO design uses various advanced conceptual disciplinary areas on performance, aerodynamics, aero-heating, propulsion, and weight estimation [3]. Incidentally, the author has derived inspiration from reference 3 for writing the present paper as a SSTO air-breathing rocket (ABR) vehicle had served as the benchmark for the TSTO versions using scramjet propulsion. There are also various reported literature in each or selective areas of design, to name a few like natural environment definition for aerospace launch vehicle design given in reference [4] and atmospheric wind models [5] related to aerospace launch vehicle design.

The purpose of this paper is to discuss some of the important design parameters and sensitivities that need to be addressed during the initial configuration design phase itself, so as to arrive at the most appropriate workable specifications for the propulsion modules and stages besides satisfying the vehicle configuration requirements on staging and overall vehicle drag and loads with respect to Q-alpha load limits. The paper addresses towards initial sizing of launch vehicles with and without air-breathing. A simplistic design approach for sizing the launch vehicle complementing an ideal velocity method is highlighted in the following sections. The paper has attempted to make use of typical design values or factors to highlight the design sensitivities in order to have a quantitative feel, especially for air-breathing vehicles using scramjet propulsion. The aim of the design is to arrive at a skeletal wire frame type of trajectory, which is feasible, leading to system specification after that detailing and detailed design studies can follow.

2 DESIGN CONSIDERATIONS

Some of the important considerations for launch vehicle sizing are mainly the following: (a) fixing the number of stages; (b) choice of propulsion system and sizing; (c) range safety constraints; (d) state-of-art technologies existing and near time goals; (e) reliability and cost; (f) desired payload maximized to the extent possible; and (g) ground and launch support constraints and other relevant factors. In the present paper that addresses on the design considerations and sensitivities, certain assumptions are made with respect to the ideal velocity, structural factors, and propulsion Isp for various stages mainly for highlighting a particular trend or variation and emphasizing a particular design feature. The ideal velocity required to meet a particular mission given in equation (1) can be used for initial vehicle sizing

$$\text{ideal velocity}(V_I) = V_{ORB.VEL} + V_{LOSSES} \pm V_{E.ROT} \quad (1)$$

The ideal velocity should be suitably chosen by the designer on the basis of experience on the various velocity losses due to drag, thrust, gravity losses, type of propulsion system, flight sequence, range safety factors, and launch azimuth. The ideal velocity for which the vehicle is to be sized is given by

$$\text{vehicle ideal velocity}(V_I) = g \times \sum_{i=1}^{n} \mathrm{Isp_i} \times \log_e \frac{Wi}{WFi} \quad (1a)$$

The optimum sizing of the stages with respect to the propulsion system depends on the staging velocity for each stage. The optimum staging velocity will depend on the stage structural factors and propulsion system performance, namely Isp and ideal velocity assumed. On the basis of the ideal velocity sizing approach, the effect of staging velocity on the payload fraction for a TSTO vehicle is shown in Fig. 1 for an expendable first

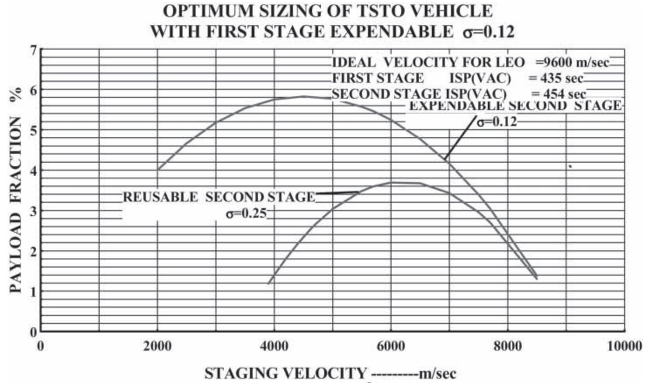

Fig. 1 Effect of staging velocity with expendable first stage

stage. The ideal velocity assumed is 9600 m/s, and the payload fraction (as a typical example case) is plotted for an all-cryogenic TSTO vehicle, considering the stage structural factors for the expendable and reusable stage as 0.12 and 0.25, respectively. The ideal velocity for the TSTO vehicle given in equation (2) has been derived suitably in terms of the first stage total mass WT1 and W_{PAYL} so as to arrive at the payload fraction percentage that corresponds to a particular staging velocity assumed for plotting the graph in Fig. 1, for a known ideal velocity

$$(V_{\mathrm{I}}) = g \times \mathrm{Isp}_1 \times \log_e \frac{W_{\mathrm{O}}}{W_{\mathrm{O}} - \mathrm{WT1}(1-\sigma_1)} + g \times \mathrm{Isp}_2 \times \log_e \frac{W_{\mathrm{O}} - \mathrm{WT1}}{(W_{\mathrm{O}} - \mathrm{WT1} - W_{\mathrm{PAYL}})\sigma_2 + W_{\mathrm{PAYL}}} \quad (2)$$

The first stage could also be reusable and can be of different types, with respect to type of landing and its location, namely land or sea recovery at predetermined sites. The reusable stage structural factors are bound to vary say, if it is to land back with return fuel supported by suitable propulsion systems depending on whether it is to be recovered as a sub-orbital or orbital stage. The designer has to choose the suitable stage structural factors felt as appropriate for a particular mission.

From Fig. 1, the optimum staging velocity for the first stage is ~4500 m/s and the payload fraction is 5.8 per cent for an expendable TSTO. Similarly, the optimum staging velocity for a reusable first stage can be arrived at. When there are range safety considerations, there is every possibility that the optimum staging velocity derived thus may pose spent stage impact problems. Hence, under such cases, a near optimum staging velocity giving the maximum payload fraction can be suitably chosen, which can also consider the range safety considerations of the spent booster stage impact.

Generally, the initial sizing of the rocket is based on the ideal velocity requirement derived by experience from various trajectory and mission studies. The ideal velocity will include the various losses due to atmospheric drag, thrust losses in atmosphere, gravity losses including maneuvers, and so on. An overall mission profile for a normal trajectory of an expendable rocket versus an ABR trajectory is shown in Fig. 2.

Figure 2 also shows the reusability of the first stage landing at a predetermined site, whereas the second stage could be an expendable stage or reusable, which would depend on the mission requirements envisaged. For the air-breathing trajectory using scramjets, it can be considered to be essentially in three phases namely: (a) ascent phase till Mach numbers 2–4 (phase-I); (b) ABR phase that is from end of phase-I to Mach numbers that can be as high as >12 (phase-II); and (c) pull-up to orbit phase in LEO (phase-III).

The ascent phase could be a pure rocket, ejector-ram rocket or turbo-ram rocket, etc. and the take-off mode could be either horizontal or vertical. The air-breathing phase (phase-II) is essentially the rocket flight through atmosphere preferably altitudes between 10 and 35 km. The vehicle will be gaining the required velocity or Mach number, say 12, the

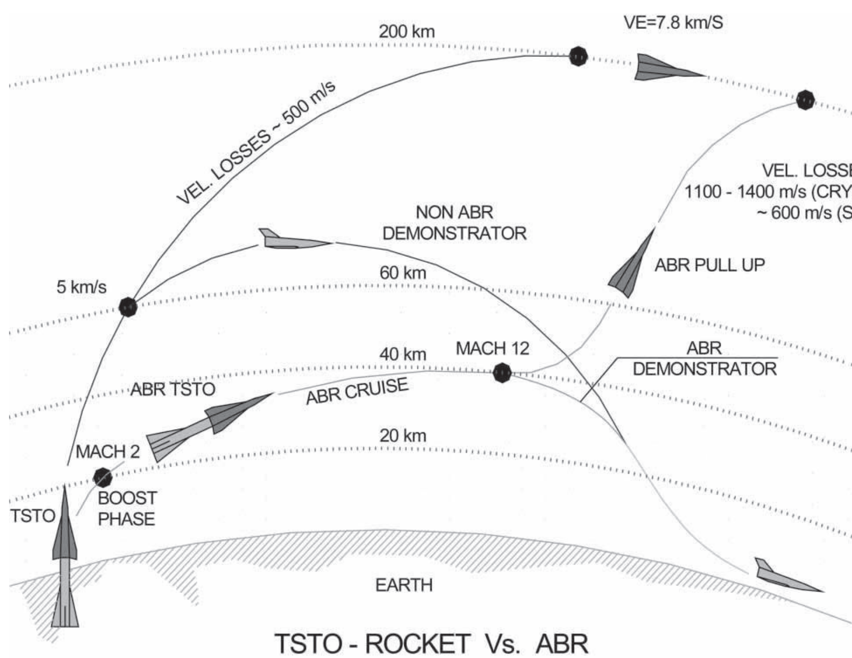

Fig. 2 Typical trajectory of expendable rocket versus ABR

maximum possible on the basis of ABR technology and thermal constraints. The flight will be at very low angle of attacks just enough to sustain a steady altitude gain within the desired constant dynamic pressure limit ~75 kPa and as low as 30 kPa during the end of ABR phase. Phase-II is critical in ABR vehicles. Depending on the terminal Mach number at the end of the ABR phase-II, the upper second stage mass and thrust requirements will be largely influenced. Lower the terminal ABR Mach number, greater will be the challenge on the propulsion system thrust rating requirements for the upper stage sizing.

An SSTO vehicle using RBCC has an in-built propulsion system capable of delivering advantageously larger thrust even during the beginning of phase-III, i.e. the rocket pull-up to orbit phase [**3**]. In the case of TSTO rocket configurations, the above advantage, namely higher thrust usually required during beginning of phase-III regime, could become a constraint and sometimes difficult to achieve. Therefore, as an SSTO-ABR vehicles require lower stage structural factors and demanding propulsion requirements, the SSTO design will provide immense challenge and will be the dream and driving force for future ABR vehicle systems.

3 DESIGN SIZING PROGRAM

Although the initial sizing of the vehicle by the ideal velocity approach is required, it is very approximate, and sometimes the vehicle so configured may be incorrect, especially for ABR vehicles due to the errors in accounting for the vehicle drag with its effect on vehicle velocity, and gravity losses, a strong function of the individual stage thrust levels. Hence further to the ideal velocity sizing approach, a two-dimensional trajectory design sizing program was developed considering the flat earth basically for arriving towards a feasible vehicle configuration. The program needs the initial sizing of the individual stages including the stage structural factors, propulsion data, vacuum Isp of stages, and total take-off mass as derived from ideal velocity estimates for conventional rockets highlighted in the earlier section. For ABR vehicles, the baseline input requirements to carry out the trajectory analyses is discussed in the following sections.

3.1 Additional design requirements for ABR rockets

The thrust/drag profile for a general ABR-TSTO rocket including an SSTO-ABR rocket [**3**] is shown in Fig. 3. Olds [**3**] has graphically portrayed the thrust/drag profile versus Mach number for an

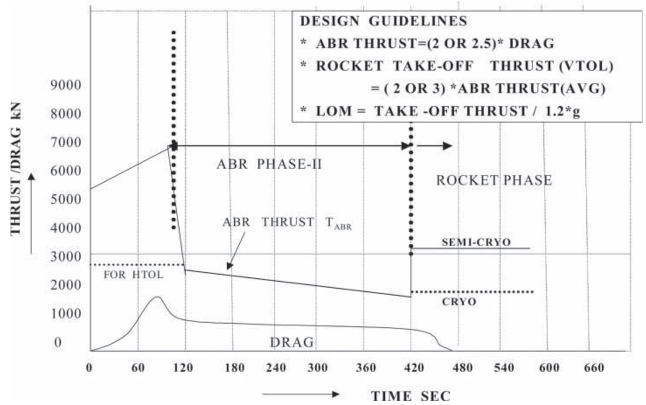

Fig. 3 Typical ABR-SSTO/TSTO: thrust /DRAG profile

SSTO vehicle with 230 tonne lift-off weight. The dry empty weight was around 42 ton with a core liquid hydrogen tank diameter of 6.8 m. Considering the SSTO as a benchmark or reference configuration [**3**], various TSTO-ABR versions using jettisionable solid boosters were conceived [**7**], which will give a similar payload to the above SSTO vehicle as depicted in Fig. 4.

In air-breathing rockets, the generation of thrust and the presence of drag are critical during phase-II. Hence the initial vehicle sizing with respect to diameter, type of propulsion system for this phase, the estimation of drag and feasible thrust pattern are first estimated. The method chosen to estimate the vehicle take-off mass is by working backwards, namely considering the take-off thrust (vertical take-off and landing, VTOL) to be around three times the ABR thrust (T_{ABR}) that would be generated, a design assumption purely for initial sizing purposes. The maximum take-off mass of the vehicle should be around 20 per cent lower than the take-off thrust. The ABR thrust required at the beginning of phase-II depends on the operating dynamic pressure that is kept at constant ~60–70 kPa and the overall vehicle drag coefficient that will fix the approximate drag force. The ABR thrust is taken to be 2–2.5 times the drag force. In the design program, the equivalent C_D value assumed is for the main core/booster stage reference diameter (as against conventional wing areas for computational convenience). The core/booster stage diameter is decided on the propellant requirement and to be compatible with the upper stages.

The enormous influence of the overall vehicle drag co-efficient, the ABR operating dynamic pressure and the diameter/size of the stage, is shown in Table 1 as an illustrative example. The amount of fuel required during the ABR phase and the size of fuel tank (LH2) alone in order to accelerate the

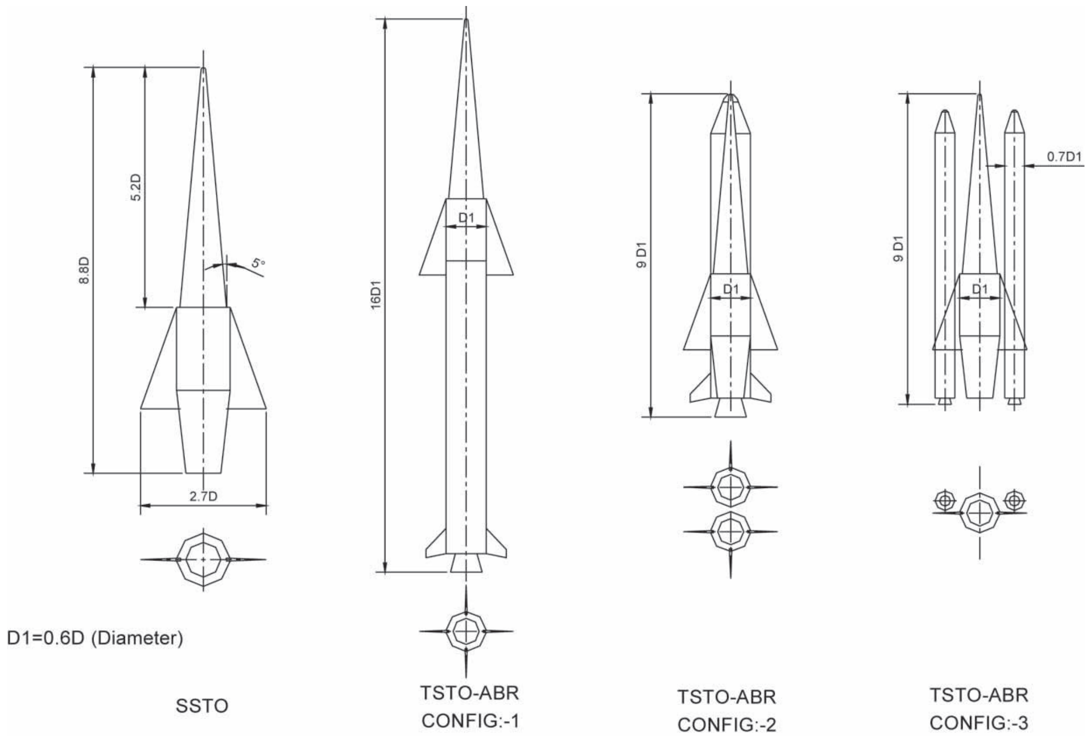

Fig. 4 Air-breathing stage vehicle configuration (schematic)

vehicle from Mach number 3 to 10 as a typical study [**7**] is shown in Table 1. It is seen from Table 1 that the ABR stage fuel length to diameter ratio is lower, when the overall drag coefficients are lower and the vehicle operates at lower dynamic pressures in phase-II regime. For various vehicle stage/booster diameters, dynamic pressures and drag coefficients the corresponding propellant required for the booster phase and ABR cruise till Mach number 10 with solid propellant for the booster phase is worked out as shown in Table 1.

For TSTO vehicle, the booster will boost the vehicle to Mach number 3 or so, and is assumed to be a jettisionable solid-rocket motor. However, it could be a high-pressure liquid propellant engine or, in addition, can also work in the ejector mode-RBCC for an SSTO vehicle [**3**]. For Turbo-fan rocket taking off in the horizontal mode and landing horizontally; the *T*/*W* would be much lower and will be near T_{ABR} value, and is not discussed in the Table 1. The quantity of LH2 fuel required during the ABR phase-II is estimated on the basis of a average

Table 1 Sizing of typical air-breathing vehicles (for VTOL launch vehicle)

DIA (m)	Dynamic pressure (kPa)	Co-efficient of drag CD*	Drag (kN)	ABR thrust (kN) 2.5 × DRAG	Booster thrust × (kN) 3 × ABR thrust	Max T.O.mass (ton) B.T/1.2 × g	Propellant required to Mach ∼ 3 (ton) solid	Fuel LH_2 for ABR Mach 3–10 (ton)	Fuel tank *L*/*D* ratio
2.8	50	1.2	366	915	2740	228	100.0	22.6	18.5
	50	0.35	107	267	801	67	29.2	6.3	5.25
	30	1.2	220	550	1650	137	60.0	13.7	11.1
4.0	50	1.2	746	1865	5600	466	204.0	46.3	12.9
	50	0.35	217	544	1640	136	59.5	13.7	3.6
	30	1.2	449	1125	3370	280	122.0	28.0	7.7
5.0	50	0.35	340	850	2550	213	93	21.2	2.8
	30	1.2	700	1754	5260	438	191	44.5	6.1
6.8 SSTO[3]	30	0.35	360	920	2760	230	∼76 (LH2 + LOX)	23.0	1.1

Note: *REF DIA taken for booster/upper stage DIA quantitiative estimates are only indicative in nature.

air-breathing Isp of ~1700 s in order to get the additional velocity from Mach number 3 to 10. Hence we may broadly conclude that the LH2 fuel tank size reduces considerably with lower dynamic pressure and lower drag coefficient. Hence if the ABR configuration does not have a low aero-drag coefficients and the dynamic pressures are even in the high range of 60–80 kPa, then the vehicle design could become impossible. Ideally, we would require a high thrust (which is a function of vehicle dynamic pressure) and with a very low overall drag co-efficient. This is a very challenging requirement, as it has to consider the intake sizing and positioning, the booster phase, and orbital phase stage sizing requirement besides the severe aerodynamic heating environment. Hence, the ABR configuration design requires the thrust levels to be properly matched at various flight phases in order to ensure the desired vehicle performance. The overall ABR vehicle configuration design is difficult, especially for multi-stages and on the arrangement of stages whether it is in tandem or parallel.

3.2 Conventional rockets

3.2.1 Aerodynamic velocity losses

For the conventional rockets, the flight phase is essentially in two phases, namely the atmospheric flight phase (phase-I) and the flight phase to orbit that is in near vacuum. As only the initial sizing of the vehicle is being addressed to, the program has included a new concept of accounting the vehicle drag and atmospheric thrust losses. The drag force curve for conventional rockets follows close to a half-sine curve, whereas the nozzle thrust losses can be assumed to follow a triangular distribution varying from sea level thrust to vacuum thrust levels. Figures 5 and 6 show the variation of flight

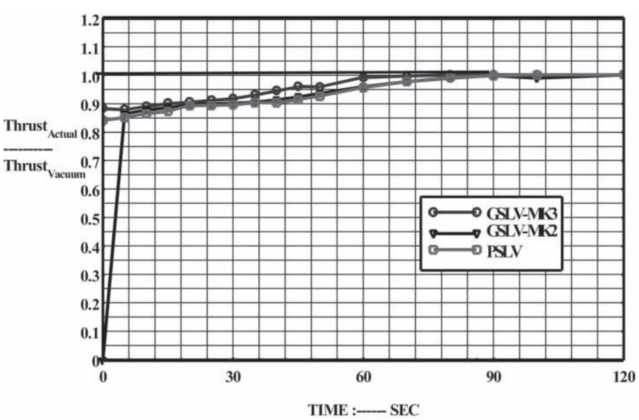

Fig. 5 Variation of actual delivered thrust versus vacuum thrust

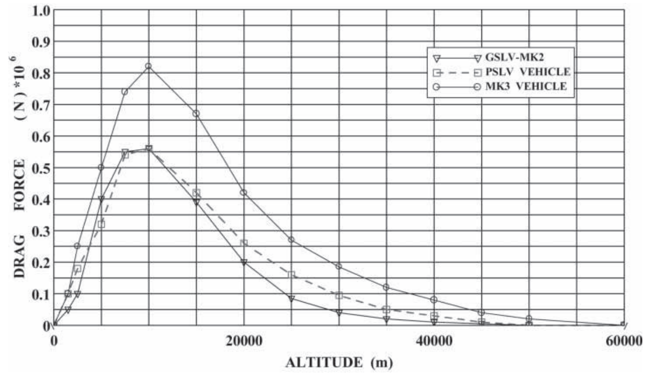

Fig. 6 Drag force versus altitude

delivered thrust and drag force profile, respectively, observed in the flight tests. The variation pattern observed has been approximated as simple triangular and half sine for the delivered thrust and drag profile mainly from simplicity considerations. As the above assumption had given encouraging sensible results the present method was adhered to. Regardless of the above, better simulation profiles can be tried out on the basis of study of the numerous flight data results.

It is generally seen from various launch vehicle trajectories [**5**], the loss due to drag in terms of a booster or motor Isp varies ~10–20 s for expendable vehicles and may be called as equivalent drag Isp. The equivalent drag Isp is derived by integrating the area under the drag force curve and dividing by the propellant mass consumed during the booster phase/stage of flight mainly in the atmospheric region. Hence, the drag Isp is considered to vary at every instant in flight in the form of a half sine given by an approximated equation (3). On similar lines as discussed in the case of vehicle drag, the equivalent thrust loss Isp due to atmospheric thrust losses is ~15–20 s the thrust losses varies nearly in a linear triangular fashion and is approximately given in equation (4). The program developed estimates the instantaneous velocity of the rocket by accounting the drag and thrust velocity losses through an equivalent Isp approach depicted in Fig. 7 and is described subsequently. The gravity losses are estimated as per a predetermined pitch trajectory on the basis of various vehicle trajectory studies and the vehicle is steered along

$$\text{drag Isp (at any instant, } t) = 1.5 \times \text{equivalent drag Isp} \times \sin(\pi \times t/T_{\mathrm{BO}}) \quad (3)$$

$$\text{thrust loss Isp (at any instant, } t) = 2.0 \times \text{equivalent thrust loss Isp} \times \left(1 - \frac{t}{T_{\mathrm{BO}}}\right) \quad (4)$$

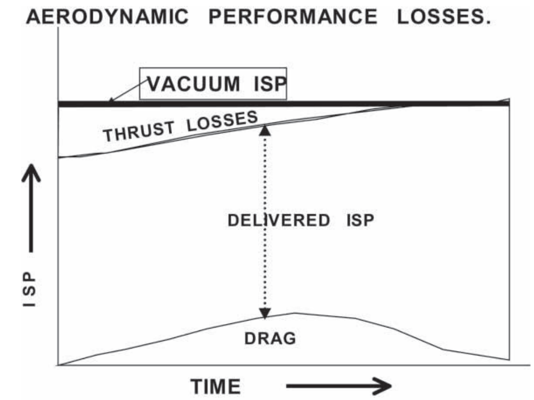

Fig. 7 Drag and thrust losses

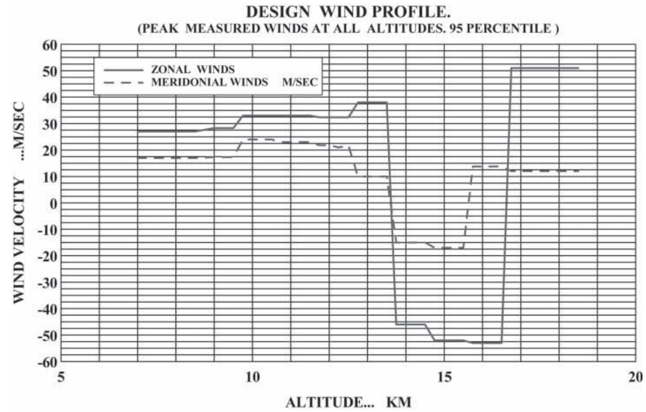

Fig. 8 Typical design wind profile

delivered Isp

$$= \text{stage Isp} \times \left(1 - \frac{\text{drag Isp}}{\text{stage Isp}} - \frac{\text{thrust loss Isp}}{\text{stage Isp}}\right) \tag{5}$$

effective thrust (T_{eff})

$$= \text{propellant mass flow rate (WPct)} \times \text{delivered Isp} \tag{6}$$

$$V_t = \oint \frac{T_{\text{EFF}}}{M_{Vt} - \text{WP}_{Ct}t}\,\partial t - gt \sin\beta \tag{7}$$

The above velocity equation is used to arrive at the orbital velocity (excludes earth rotational component) at the desired altitude by suitably pitching the vehicle flight path angle β. Once the instantaneous velocity is estimated the range and altitude, the point of spent stage impact can be easily estimated.

3.2.2 *Design winds*

As an additional requirement, the possibility of maximum peak wind speeds [**5**] occurring (95%), namely, zonal (equatorial) and meridonial are considered as shown in Fig. 8. These winds are assumed to occur at each of the key altitudes simultaneously as an extreme design condition (all weather design) during the atmospheric flight phase in the program. By including such a wind profile, corrected for the launch azimuth, and superimposing on the derived vehicle instantaneous velocity allows us to get the maximum vehicle angle of attack and the envelope of maximum Q-alpha (Pa rad) boundary or design limits. The critical loads due to in-flight winds would actually and possibly occur at any one of the key altitudes (6–20 km). Hence, the above approach gives us the worst case Q-alpha design envelope that could occur at any time during the flight and is a very important vehicle design parameter both for vehicle load estimation and vehicle controllability studies. The extent and need for vehicle trajectory wind-biasing or active load relief system can then be decided on the basis of the actual wind profile and its probability of occurrence at each of the key altitudes. Nevertheless, the maximum Q-alpha boundary will give us the maximum possible loads at various altitudes and the nature of load variation during the entire flight regime.

The above program had been demonstrated [**6**] for conventional rockets with reasonable accuracy within 30–40 m/s on the relative velocity estimates besides arriving at the various vehicle parameters, namely altitude, dynamic pressures, Q-alpha, range, instantaneous vehicle mass, and other such design parameters. The results are compared with the flight test results of the Operational Indian polar satellite launch vehicle and the above exercise was also done for other launch vehicles ranging from SLV-3 with a 40 kg satellite to GSLV-MK2 that carries a 2000 kg GTO payload. The designer could improve on this prediction technique by going into a more elaborate three-dimensional trajectory program with spherical earth and assume suitable changes in the drag and thrust losses distribution pattern.

Although the present program was done using the simplistic GWBASIC software language, the ability to accommodate graphic presentations of the results, namely dynamic pressure, drag, thrust altitude, and range within the program itself had leant an easy access for viewing the results and carrying out the necessary iterations effectively. A typical launch vehicle performance study during the initial flight period as derived from the design program is shown in Fig. 9. The flight data points for the instantaneous velocity and dynamic pressures are also shown as discrete marker points for comparison.

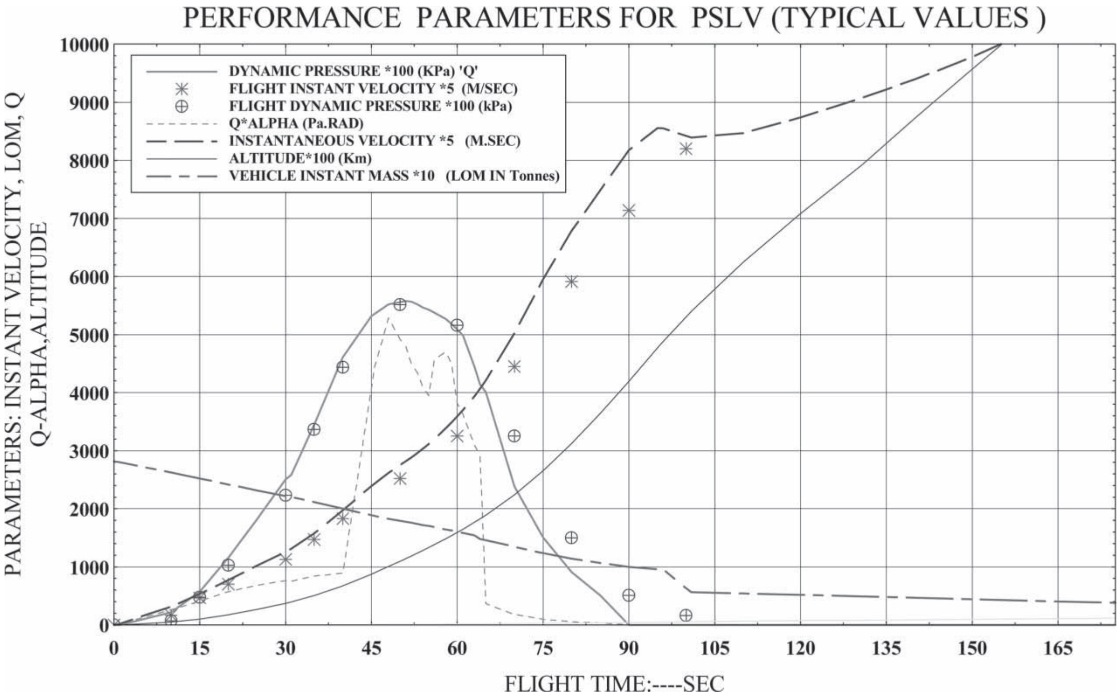

Fig. 9 Comparison of typical launch vehicle performance from two-dimensional program results with flight data

3.3 Air-breathing rockets

In the case of ABR, the propulsion requirements are derived mainly on the basis of the near independent nature of the three ABR phases (i.e. phase I to phase III) and the effect of drag on the performance of the ABR during the air-breathing cruise phase-II. In the design program, the actual vehicle drag and lift coefficients are not required as these are estimated only after the initial design sizing is completed and would require time consuming analyses and supported by wind tunnel tests. However, when a workable trajectory is arrived at, the overall drag co-efficient (C_D) can be specified meeting the particular vehicle configuration choice, which will ensure the required T_{ABR}/D ratio as derived from the program results.

3.3.1 Drag profile for ABR rockets during the atmospheric phase (phase-I and phase-II)

During the ascent phase of the trajectory (phase-I), the drag Isp would be higher than the normal rockets as it dwells more in lower altitudes and would vary from 30 to 40 s. In the case of rockets with air-breathing propulsion, both the dynamic pressure and drag pattern for the ascent phase would also follow partially the half-sine curve till the end of phase-I when the ABR module/stage will be initiated at a convenient altitude and desired Mach number. During the beginning of phase-II flight that is essentially an accelerating cruise phase, the dynamic pressure will be aimed to be of near constant value and will taper off steeply at the end of the ABR phase-II. A typical drag/dynamic profile of an ABR is depicted in Fig. 10. In Fig. 10 during the ascent phase, the drag force curve will be an incomplete near half-sine curve, as the air-breathing phase-II will take over at an altitude of 10–15 km and the drag pattern will be dictated by the ABR cruise phase characteristics as discussed in the following paragraph.

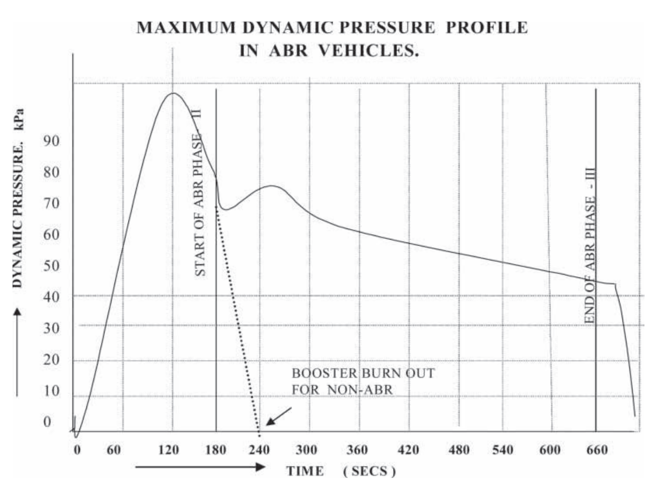

Fig. 10 Variation of dynamic pressure (typical) for an ABR vehicle during phase-I and phase- II

During the air-breathing phase (phase-II) in which the rocket gains the velocity from say, Mach number 2 (or 4) to 12, the drag force (D) is considerable in proportion to the air-breathing propulsion derived thrust (T_{ABR}). This thrust also varies and decreases with increasing Mach number mainly due to lower Isp at higher altitudes arising from lower combustion efficiency at hypersonic regimes beside intake efficiency.

3.3.2 *Instantaneous vehicle velocity estimation during ABR phase-II*

As it is not easily possible to estimate the ABR thrust and its distribution in the beginning stages of vehicle sizing itself, the following method is suggested. Generally, the ratio of the air-breathing thrust generated during phase-II to drag, namely, T_{ABR}/D is desired to be around 2–2.5. This aspect is mainly considered in the design program in which the delivered or effective thrust is derived by reducing the drag component. The air-breathing thrust at the beginning of phase-II is estimated as an initial estimate from the vehicle drag force during the ABR cruise phase on the basis of the selected vehicle stage/booster diameter and the desired overall drag coefficient of the vehicle and operating dynamic pressure regime.

Hence, the thrust T_{ABR} (propellant mass flow rate $\times$ $\mathrm{Isp}_{\mathrm{ABR}}$) generated during the initiation of the ABR cruise phase can be estimated as evident from the discussions above. The vehicle instantaneous velocity is derived using this effective thrust (that is reducing the drag component) and the variation of thrust follows from a typical anticipated ABR-Isp profile versus Mach number. The ABR-Isp that could be taken for design would possibly vary from 2300 s at lower Mach numbers to 1100–900 s at hypersonic Mach numbers of 12 or so. That is the T_{ABR} thrust profile during the ABR regime will follow the Isp profile

$$\text{delivered ABR-thrust} = (T_{\mathrm{ABR}} - \text{drag}) \tag{8}$$

$$\text{where drag} = \frac{T_{\mathrm{ABR}}}{2.5} \quad \text{for} \quad \frac{T}{D} = 2.5 \text{ in phase-II flight}$$

Nevertheless the whole ABR design is a highly iterative exercise. The design suggestions only serve to reduce the iterative exercise in the beginning stages of vehicle sizing and will lead to a firm skeletal design over which the finer details can be built or worked out. Similarly, the sizing of the second stage, namely the final stage to orbit can be independently sized after assessing the terminal ABR Mach number that can be achieved considering various technology options, state of art, and feasibility. The sizing aspects of the second stage are discussed in the subsequent sections. For phase-I, we can see that the delivered Isp pattern for the ABR rocket can also be worked out in a similar way to that of the conventional rockets; except that the thrust losses are near constant (sea level) and the drag force profile would vary similar to as shown in Fig. 10 for phase-I flight. The main governing equations for deriving the vehicle instantaneous velocity for phase-II is given subsequently

$$\text{delivered ABR}(T_{\mathrm{eff}}) = \text{propellant fuel mass flow rate (WPct)} \times \text{IspABR} \tag{9}$$

$$\frac{\partial V_t}{\partial t} = \frac{T_{\mathrm{EFF}}}{M_t} \quad \text{(ABR phase-II flight, lift trimmed for near constant 'Q')} \tag{10}$$

The vehicle instantaneous velocity estimation for phase-I and phase-III for ABR vehicle is similar to as given in section 3.2.

The altitude, range, vehicle dynamic pressures, and angle of attack due to winds are estimated using the above derived velocity directly through simple trajectory equations and are not elaborated in this paper. The flight path angle β is suitably varied on a initial predetermined path to meet the desired velocity requirements at the end conditions of each phase of flight (i.e. phase-I to phase-III) and would require modifications of propulsion inputs with respect to propellant loading and burn time. During the ABR cruise phase-II, the vehicle flight path (β) is so adjusted to give the near desired constant dynamic pressure that will ensure the required thrust. At the same time, the drag force is also plotted using the assumed overall C_{D} values with instantaneous velocity generated to ensure that the T/D ratios are nearly maintained. The whole exercise is repeated untill the overall requirements are met. Although this seems to be a non-optimum approach, it nevertheless serves the purpose for initial launch vehicle sizing.

3.3.3 *Summary of design inputs and program highlight*

The inputs for the program are (a) initial take-off mass of the vehicle based on ideal velocity approach and as highlighted in Table 1 for ABR; (b) the booster thrust, Isp, flight path angle, maximum measured peak wind speeds (95 per cent) probability of occurrence at each of the key altitudes (8–20 km), structural masses, and atmospheric data; (c) for the ABR phase, the thrust distribution, Isp variation, C_{D}; (d) upper orbital stage propulsion thrust and Isp; (e) flight path angle; (f) ejectable masses as desired. The program actually traces out the predetermined two-dimensional trajectory by consuming the booster propellant untill phase-I conditions are achieved and the booster thrust is terminated. The vehicle mass after booster burnout and ejection would form the initial condition for phase-II flight. In this manner, the whole trajectory is traced out meeting the end conditions and operating conditions for all the flight phases specified.

The whole trajectory simulation exercise calling for an iterative procedure is programmed using GWBASIC language and is made easier by an interactive mode having graphics inbuilt for this purpose. As the program was developed basically as an initial engineering tool, it is limited to making system choices and predict a mission feasibility. It is advantageous mainly because the normal and axial aerodynamic coefficients are not needed for initially running the program. However, when the actual aerodynamic coefficients are once estimated, the drag force distribution can be calculated using the derived vehicle instantaneous velocity and altitude and the revised drag pattern compared with the initial assumptions. Any design mismatches arising will be sorted out and a revised trajectory run can be made. This can be followed up by detailed trajectory studies, which includes lifting bodies, after each of the system designs including aerodynamic coefficients are finalized.

4 DESIGN CONSTRAINTS FOR SIZING ABR ROCKETS FOR PHASE-III

Generally for ABR, the primary fuel choice is LH2/LOX for both during the ABR phase-II and the second or final stage, which takes the payload to orbit. However, there are the following factors/constraints that influence the vehicle sizing to a large extent namely: (a) low density of LH2 leads to large tankage size; (b) terminal Mach number at the end of ABR phase-II; (c) rocket thrust available at the pull-up stage after end of ABR phase-II; (d) expendable or re-usable second stage.

The last three factors influence the second stage rocket sizing to a large extent and combining with the first factor makes the design very challenging. The velocity losses due to gravity for the second stage to orbit rocket for ABR can be as high as 1500 m/s compared with 500 m/s for a direct rocket mode. Sometimes the mission will simply, just not succeed because of the low thrust /weight ratios of cryogenic LOX/LH2 rockets combined with higher stage mass structural factors that are associated with re-usability. Table 2 shows typically the sensitivity of the second stage propellant mass required with the variation of terminal Mach number at the end of that phase. The second stage is sized for the

Table 2 Sizing of rocket from end of ABR phase to orbit (for LEO payload of 10 ton)

Velocity at the end of ABR phase-II (m/s)	Structural factor	Propellant mass (ton)	Diameter (M)	Stage length (m)
3700 (near $M = 12$)	1…0.20	1…50		1…12
	2…0.25	2…75	4.0	2…16
	3…0.275	3…125		3…28
2400 (near $M = 8$)	1…0.15	1…75		1…16
	2…0.20	2…150	4.0	2…32
	3…0.22	3…300		3 Large

ideal velocity that is further required from the end off ABR phase-II to the relative velocity required for LEO orbit in addition to the velocity losses of 1300 m/s for a typical cryogenic (LOX/LH2) stage. The values shown in Table 2 are only indicative and are mainly for portraying a particular trend as discussed subsequently. The diameter 4 m is again taken as a typical case for the rocket stage. The stage diameter basically depends on the overall configuration sizing of the vehicle, the propellant loading, aerodynamics, and propulsion.

From Table 2, the dependency of the stage structural factor and velocity at the end of air-breathing phase is clearly seen. The propellant mass requirement increases three times, i.e. 50–150 t on for the same structural factor of 0.20, when the velocity at the end of ABR phase is reduced from Mach number 12 to 8. The propellant mass is estimates for LOX/LH2 propellant that is normally low thrust cryogenic-engines. The velocity losses are high for low thrust to stage mass ratios and could be in some cases as high as 1500 m/s from the end of ABR phase-II, i.e. pull-up to orbit. On the basis of the above especially due to the limitations of cryogenic stage thrust, sometimes it is more feasible to go in for a LOX/kerosene stage as it has a higher equivalent density and higher thrust rating. The higher thrust capability engines allows for lower velocity losses due to gravity from ABR pull-up to orbit phase and can be as low as 600 m/s.

Hence a LOX/kerosene upper stage is competitive, although the propellant mass is much larger. The overall sizing of ABR vehicles is finally dictated by the overall vehicle hypersonic drag coefficients, which has to be kept low, perhaps between 0.35 and 0.50, assuming reference area to be the main vehicle booster/rocket largest diameter. Figure 11 shows a typical design sizing curve for both LH2 and kerosene fuel systems. Figure 11 shows the estimate of propellant mass, stage structural factors versus overall stage volume required for every

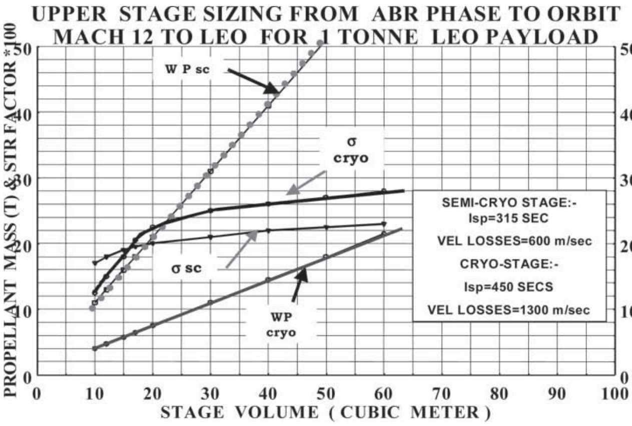

Fig. 11 Upper stage sizing from end of ABR phase to LEO orbit

tonne of LEO payload from the end of ABR phase-II, i.e. Mach number 12 to LEO orbit. It is seen that as an example from Fig. 11; for a 30 m^3 stage volume, the propellant mass for a cryogenic propellant would be around 10 ton, whereas it can accommodate 30 ton of LOX/kerosene semi-cryogenic propellant system. However, the above propellant masses are valid when the stage structural factors are 0.25 and 0.21 for cryogenic and semi-cryogenic systems, respectively. It is also seen that for a lower stage structural factor of 0.20, both the structural factor curves have a common point a favourable case for semi-cryogenic systems. Figure 11 helps to clearly know beforehand what thrust rating would be required to minimize the velocity losses due to low thrust. Similar such graphs can be drawn for various sizing velocities including varying velocity losses and specific impulse of the propellant. As ABR vehicles are drag sensitive, the stage volume and hence diameter size selection are important aspects.

5 CONCLUSIONS

A preliminary design approach is arrived at for sizing launch vehicles with rocket and air-breathing propulsion. The ABR vehicle trajectory is separated into three flight phases, namely, the initial booster or ascent phase, the air-breathing cruise phase from the desired Mach number to a maximum of Mach number 12, and lastly the pull-up to orbit phase for optimum vehicle sizing. An attempt has been made to bring in the various design sensitivities and their effects on vehicle sizing. A new concept of including the drag and thrust losses considering their nature of distribution as equivalent Isp losses for estimating the vehicle instantaneous velocity was suggested for rocket in the atmospheric region and for phase-I flight in the case of ABR vehicles. The intermediary flight phase-II for ABR vehicles could be independently designed meeting the end conditions of phase-I and also to deliver the appropriate velocity at the beginning of phase-III flight. A simplistic two-dimensional trajectory simulation program with graphical interaction has been developed, which considers the velocity losses due to drag, gravity, and propulsion. The program helps in sizing the launch vehicle and for evaluating the various stage modules that will give the desired velocities at the end of each flight phase satisfying the overall vehicle design requirements.

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REFERENCES

1 **Ryan, R. S.** and **Townsend, J. S.** Fundamentals and issues in launch vehicle design. *J. Spacecraft Rocket*, 1997, **34**(2), 192–198.
2 **Rahn, M., Schottle, U. M.,** and **Messerschmid, E.** *Impact of mission requirements and constraints on conceptual launch vehicle design*. AIAA Paper 98-1554, April 1998.
3 **Olds, J. R.** *Results of a rocket-based combined-cycle SSTO design using parametric MDO methods*. SAE technical paper series, 941165; presented at Aerospace Atlantic Conference, OH, 18–22 April, 1994.
4 **Batts, G. W.** and **Pearson, S. D.** Natural environment requirements definition for aerospace launch vehicle design. AIAA paper 1996-397, Aerospace Sciences Meeting and Exhibit, 5–18 January 1996, 34th, Reno, NV.
5 **Smith, O. E.** and **Adelfang, S. I.** Atmospheric Density Models for Launch Vehicle Design (Dispersed Atmospheric Models 0–25 km altitudes, KSC). AIAA Paper 95-0057, AIAA, Aerospace Sciences Meeting and Exhibit, 33rd, Reno, NV, 9–12 January 1995.
6 **Sundaresan, M., Ramani, K.,** and **GeethaiKrishnan, C.** *A comparative study on the existing launch vehicles performance with specific reference to vehicle Q-alpha distribution*. Internal report no. VSSC:LVDG:TM:2:95, January 1995.
7 **Sundaresan, M.** *An overview of an air-breathing vehicle with reference to some of the critical performance parameters*. International Study report, Head, Vehicle Configuration division, ILVP, VSSC, December 1995.

APPENDIX

Notation

C_D	overall vehicle drag coefficient (reference area: with booster/stage diameter)
D	drag force (kN), diameter (m)
g	gravitational constant (9.807 m/s^2)
Isp	vacuum specific impulse (s)
Isp_i	vacuum specific impulse of the ith stage (s)/burnout altitude specific impulse
$\mathrm{Isp}_{\mathrm{ABR}}$	Isp of air-breathing rocket during cruise phase (s)
M	mach number
M_{Vt}	mass of vehicle at any flight instant (ton)
n	number of stages
t	time of flight instant (s)
T_{ABR}	thrust generated by ABR in the air-breathing or cruise regime (kN)
T_{BO}	time at booster burnout (s)
T_{eff}	effective thrust generated at any instant (kN)
V_I	vehicle ideal velocity (m/s)
V_t	vehicle velocity at any flight instant (m/s)
$V_{\mathrm{ORB.VEL}}$	orbital velocity as required by mission
V_{LOSSES}	velocity losses (m/s)
$V_{\mathrm{E.ROT}}$	earth rotational velocity
WF_i	final mass of the stage at the ith stage/event burn out
W_i	initial mass of vehicle at ith stage/event ignition
Wp_i	propellant mass of the ith stage
Wp_{Ct}	propellant mass flow rate consumed at any instant (ton/s)
W_{PAYL}	payload mass
W_{o}	overall vehicle mass
WT_i	total mass of the ith stage
α	angle of attack in degrees
β	flight path angle in degrees
σ_i	stage structural factor of the ith stage
σ_{cryo}	cryogenic stage structural factor
σ_{SC}	semi-cryogenic stage structural factor
i	subscript