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MULTIDISCIPLINARY DESIGN OPTIMIZATION TO FUTURE SPACE TRANSPORTATION VEHICLES

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Many candidate concepts of future reusable launch vehicles (RLVs) have been proposed in the world. From the present technology level, however, it is difficult to realize the RLVs. This requires multidisciplinary analysis and optimization, which is a methodology to cooperate among the disciplines and find the best system and design. This paper presents the method to integrate analysis tools in a conceptual design process and to apply an optimization method, and shows some examples of the optimal RLV concepts. The vehicle concepts in this study are classified in the number of stages, takeoff styles, and whether air-breathing engines are installed or not. Feasibility of each concept is demonstrated.

INTRODUCTION

Fully reusable launch vehicles (RLVs) in the next generation have recently been developed in institutes all over the world. These RLVs are classified into two types: the vehicles with wings and the vehicles with no wings. The former can take off and/or land horizontally by lift force from the wings. The latter takes off and lands vertically by engines. The winged horizontal takeoff RLVs are generally called spaceplanes. These are also classified in terms of the number of stages, takeoff and landing styles, and engine types. For the number of the stage, the RLVs are Single-Stage-To-Orbit (SSTO) vehicles or Two-Stage-To-Orbit (TSTO) vehicles. The takeoff styles of these vehicles are also classified into the horizontal style and the vertical style. In addition, the RLVs have the options of installed engine types: only rocket engines or both rocket engines and air-breathing engines.

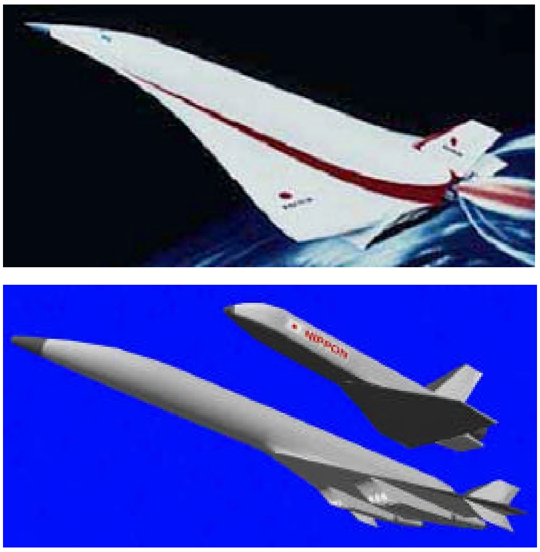


Fig. 1 RLV concepts, SSTO and TSTO

In this paper, a multidisciplinary optimization method is applied to seven typical concepts of the winged RLVs by the above classification. A variety of the concepts is analyzed in the same manner, and an optimization method is applied to obtain the best vehicles. One of characteristics of optimization problems in this paper is to include trajectory optimization problem. Thus, the ascent and return flight trajectories are not computed in accordance with supposed guidance laws, but simultaneously optimized as well as the other variables of vehicle size. Then the optimum vehicles obtained in each concept are evaluated, and one concept is weighed against another. Through the studies, analysis tools are provided for conceptual designs of the various RLVs, and we pursue integrating the tools and applying the optimization methods.

PROBLEM DEFINITION

Design variables and Analyzed Models

The variables in need of our decision are classified into three types: the variables representing geometric shapes of the vehicles, flight performance, and flight trajectories. The design variables concerning the body shape are shown in Fig. 3. The variables regarding the flight performance are composed of vehicle gross weight, air capture area of air-breathing engine, rocket engine thrust in vacuum, and maximum limit of load factor, axial acceleration, dynamic pressure, and air-breathing engine maximum thrust.

Figure 2 outlines disciplines and data flow in this paper. If a set of values is inserted into the variables, the disciplines are analyzed sequentially. The "analyze" means that the disciplines do not only calculate the intermediate variable passed to other disciplines, but also compute function values of the equality and inequality constraint conditions, which the variables should satisfy. It is minimum demand that the feasible variables satisfying all the constraint conditions are found. In order to choose the best values of them, we define optimization problems. The following summarizes the analyzed models, constraint conditions, and a performance index in the optimization problem.

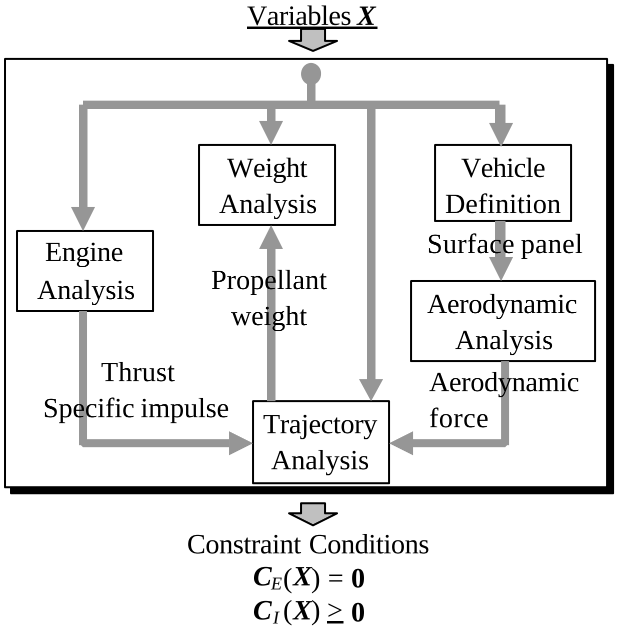
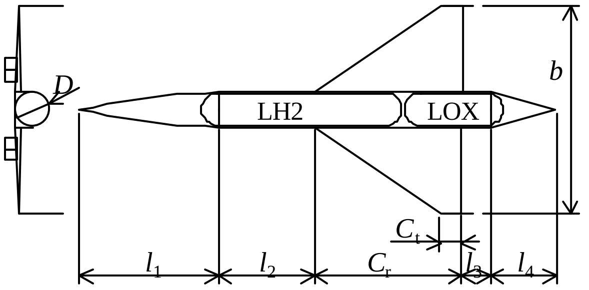
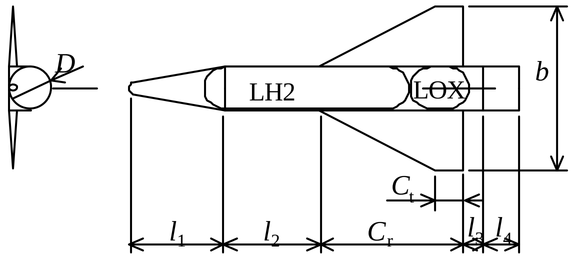


Fig. 2 Analyzed models



Booster type vehicle



Orbiter type vehicle

Fig. 3 Vehicle shape variables

Vehicle Definition

Figure 3 shows the vehicle shape in this study. The vehicles are classified into the orbiter type vehicles, which can reach orbit and reenter the atmosphere (the SSTO vehicles and the second stage vehicles of the TSTO systems), and the booster type vehicles of the TSTO systems. The former image hypersonic transport vehicles, and the latter are derived from Space Shuttle Orbiter and HOPE-X [1] of Japan. The air-breathing engines are suspended on the lower surface of the wing, and the rocket engines are installed in the aft body. The vehicle has either a vertical tail plane or tipfins and a body flap to keep their stabilities. Their areas are specified by tail volume values required for HOPE-X, and their shapes are the same as those of HOPE-X.

The "Vehicle Definition" has a surface mesh generator, which makes panels on the vehicle surface used in the following aerodynamic analysis. The optimum meshes are formed automatically, as illustrated in the following section.

Aerodynamic Analysis

Aerodynamic vehicle properties have to be estimated in the different flowfield regimes encountered during atmospheric flight ranging from subsonic to hypersonic speed. Simple methods are employed in this study. In the subsonic flight, a panel method [2] is employed. From supersonic to hypersonic speed, Prandtl-Meyer expansion flow theory and tangent cone/wedge method are applied to the panelized vehicle surface. These methods are simpler than latest sophistical computation methods but useful, because aerodynamic characteristics are analyzed over and over in the optimization method proposed in this paper. In spite of the problems of propulsion integration, control surface efficiencies, etc., which need more sophistical methods, these methods are applied widely for aerodynamic preliminary analysis [3].

In this analysis, we select seven cases of Mach numbers and Reynolds numbers, where the aerodynamic analysis computes the lift, drag, and moment coefficients at several angles of attack. These values are approximated with polynomial expressions to estimate the coefficients at an arbitrary flow condition. It follows that the aerodynamic analysis requiring much computation time is implemented only after the body shapes are changed. The stored coefficients' values of the polynomial can drastically shorten the computation time of the aerodynamic analysis iterated in the trajectory analysis.

Besides, longitudinal static stability is evaluated in subsonic and hypersonic regions, and aft location limit of the center of gravity is calculated. Forward location limit, which should be decided to achieve trim performance and maneuverability, is supposed to be 10 % forward location of the body length from the aft location limit.

Engine Analysis

The installed engines are classified into the air-breathing engine (ABE) and the rocket engine (RE). Each engine has different analyzing process.

In this study, a pre-cooled turbojet (PCTJ) engine (Fig. 4) is chosen as the air-breathing engine. The PCTJ engine can work in less than about Mach 6 cruise. Standard thrust force and specific impulse values are provided in response to Mach number and altitude. Air capture area is one of the design variables, and the thrust force is proportional to its value. Besides, the engines are located on the wings, but air compression by the fore body is not considered in this study.

The rocket thrust in vacuum is one of the design variables and its specific impulse in vacuum is fixed to be 445 sec. It is assumed that nozzle exit area is in proportion to the thrust in vacuum, and the thrust and specific impulse in the air are calculated.

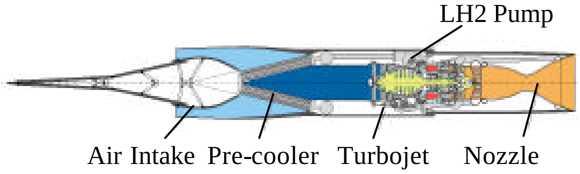


Fig. 4 A pre-cooled turbojet engine

Weight Analysis

The component weight is obtained with HASA program [4] from the body shape, flight performance, and the propellant weight provided by the trajectory analysis. The HASA program is modified in the following.

- The engine weight is given in our own ways, because they are not included in the HASA program.
- Landing gear weights of the vertical takeoff SSTO vehicles and the orbiters of the TSTO systems are calculated on the basis of landing weights.
- Thermal protection system weight of the reentry vehicle is estimated on the assumption that C/C is on its nose and leading edges of the wings, and that ceramic tiles, which amount to 30 mm thick, are on the other part of the body.
- Propellant tanks are made of aluminum alloy and composed of dome parts and cylinder parts. Tank thickness is computed from tank pressure by membrane theory to estimate total tank weight.

There is a constraint condition that the total gross weight, which is one of the design variables, is equal to the total gross weight derived from the HASA program. To compute the center of gravity, the components are arranged inside the body that has full or empty of propellant, and the center of gravity in cases of full or empty propellant is within the location limits given by the aerodynamic analysis.

Trajectory Analysis

Flight trajectory depends on the number of stages and the takeoff style. The vehicle takes off on Aeon Field in Christmas Island, and flies for east. In case of the horizontal takeoff, takeoff velocity is supposed to be 100 m/sec. The vehicle equipped with the ABEs accelerates and climbs with the ABEs first. Maximum Mach number of ABE is 6. The time when the ABEs are cut off and the second stage vehicle is separated is optimized. During the flight, path constraints consist of dynamic pressure limit, axial acceleration limit, normal acceleration limit, ABE thrust limit, angle of attack limit, and RE throttle limit. The vehicle cuts the RE temporarily above an altitude of 120 km. After that, the vehicle continues to climb with no thrust, and, at an altitude of 200 km, it is put into LEO by an apogee kick. The trajectory is computed until the RE cutoff, and the apogee kick is approximated with impulse thrust. The vehicle reenters the atmosphere and returns to the launch site after the end of missions in the orbit. It is assumed that the analytic drag control guidance low which is employed by Space Shuttle [5] is applied to the trajectory analysis in the reentry flight, and heating rate limit, load factor limit, and dynamic pressure limit are considered.

In this study, the three-degree-of-freedom analysis is implemented. State variables are altitude, longitude, latitude, velocity, flight path angle, heading angle, and mass. Control variables are angle of attack, bank angle, and thrust throttle [6]. One of characteristics of the problem definition in this paper is to optimize the flight trajectories simultaneously. These variables are, however, functions of time. In addition, the constraint conditions satisfied by these variables are also functions of time and different equations, which are different from the others. Thus, these variables and constraint conditions are discretized in the manner of a block diagonal Hessian (BDH) method [7], and the optimized variables and the constraint functions are defined.

Performance Index

In the RLV design process, it is advisable that we design as small vehicles as possible. Thus, the gross weight of the vehicle is defined as a minimized performance index in the optimization problem. While the payload weight and volume of the TSTO vehicles are fixed to be 4 Mg and 40 m^3, respectively, total gross weights of the boosters and orbiters are minimized.

As for the SSTO system, however, it is impossible to obtain the vehicles of which the gross weights are with reality. The fact makes the assumption that the vehicle has no payload and the gross weight is fixed to be 300 Mg. A required dry weight is solved by subtracting the propellant weight from the gross weight, 300 Mg, while a net dry weight is given by the weight analysis. The latter gross weight is larger than the former, and we cannot make both the weight equal in this paper. Therefore, the required dry weight divided by the net dry weight is defined as the maximized performance index to aim for 1, which is called a weight reduction factor.

OPTIMAL SOLUTIONS

SSTO Systems

Figure 5 illustrates optimal vehicle shapes of three SSTO systems. Table 1 itemizes weights for each vehicle. In each system name, HT and VT stand for horizontal takeoff and vertical takeoff, respectively, and they are followed by the number of the engines. From these results, if the gross weights are fixed to be 300 Mg, the weight reduction factors are less than 1, which means that SSTO system cannot be realized by present technology.

Figure 5 demonstrates the SSTO vehicle with the ABE is larger than the vehicles with the only RE. In Table 1, its weight reduction factor is 0.39, which is by far the smallest of all. Compared with the SSTO vehicles equipped with the only RE, the SSTO vehicles with the ABE are difficult to be realized, because the ABE is heavy. In a development study of the airbreathing engines, we should strive improving thrust-to-weight ratio.

In the takeoff styles of the SSTO vehicles powered by the only RE, the weight reduction factor of the vertical takeoff vehicle is larger than that of the horizontal takeoff vehicle, which means that the vertical takeoff vehicle is nearer to be realized. It is due to large difference of landing gear weight. The landing gears of the vertical takeoff vehicles are designed on the basis of the landing weight that includes empty propellant. The rocket engine of the vertical takeoff vehicle is heavy, because large thrust is required when the vehicle takes off. The influence of the rocket engine weight is smaller than that of the landing gear weight. This makes the dry weight of the vertical takeoff vehicle light.

TSTO Systems

Figure 6 illustrates optimal vehicle shapes of four TSTO systems. Table 2 itemizes weights for each vehicle. In each system name, HT and VT stand for the takeoff style, and they are followed by the number of the boosters' engines.

First, let us compare the TSTO vehicle whose booster has the only ABE, "HT–4 ABEs", with the vehicles of which the boosters also have the RE, "HT–4 ABEs / 2 REs". Table 2 shows the total gross weights of the latter are smaller. Though the booster in which the RE is installed is indeed heavy, it has large acceleration capability, as shown in Fig. 7, and the orbiter is small size.

Second, let us compare the horizontal takeoff TSTO vehicle with the only REs "HT–2 REs" with the vehicles in which the ABEs are installed ("HT–4 ABEs" and " HT–4 ABEs / 2 REs"). Figure 6 and Table 2 show that the vehicle "HT–2 REs" is much smaller size and the total gross weight of “HT–2 REs” vehicle is almost as large. As for the dry weight, “HT–2 REs” vehicle is smaller. There is the same reason that is described in the results of the SSTO system, that is, the ABE is heavy. We have to make the thrust-to-weight ratio higher.

Finally, we make a comparison in the TSTO systems composed of the booster with the only RE. Table 2 shows that the total gross weight of the vertical takeoff TSTO vehicle “VT–2 REs” is smaller than that of the horizontal takeoff vehicle “HT–2 REs”, because of the difference of the landing gear. By the way, both the flight trajectories are in good agreement, as shown in Fig. 8.

From these results, in this study, the vertical takeoff TSTO vehicle with the only rocket engines is the smallest in the vehicle size, total gross weight, and dry weight, and has the best possibility to be realized. Of course, for final choice of the system in the near future, we should consider more details, operation, cost and so on.

CONCLUSIONS

The multidisciplinary optimization technique was applied into the conceptual designs of the future reusable launch vehicles. First, analysis tools were provided: the surface mesh generator, the simple aerodynamic analysis method, the engine analysis, the weight estimation method, and the trajectory analysis. Second, these analyzed models were integrated functionally and incorporated into an optimization method. The gross weight and the weight reduction factor were defined as an objective function of the optimization problem to find the best vehicle configurations and flight trajectories. The solutions show as follows. It is difficult to realize the SSTO vehicles by present technology, and component weight reduction, more than 30 %, is required. The TSTO vehicles with the boosters powered by the only rocket engines are smaller than the vehicles of which the boosters have the air-breathing engines. Future studies should reconfirm the weight of the air-breathing engines. The vertical takeoff vehicles surpass the horizontal vehicles in the total gross weight and the vehicle size. In addition, through this study, it was confirmed that the proposed multidisciplinary optimization method was effective.

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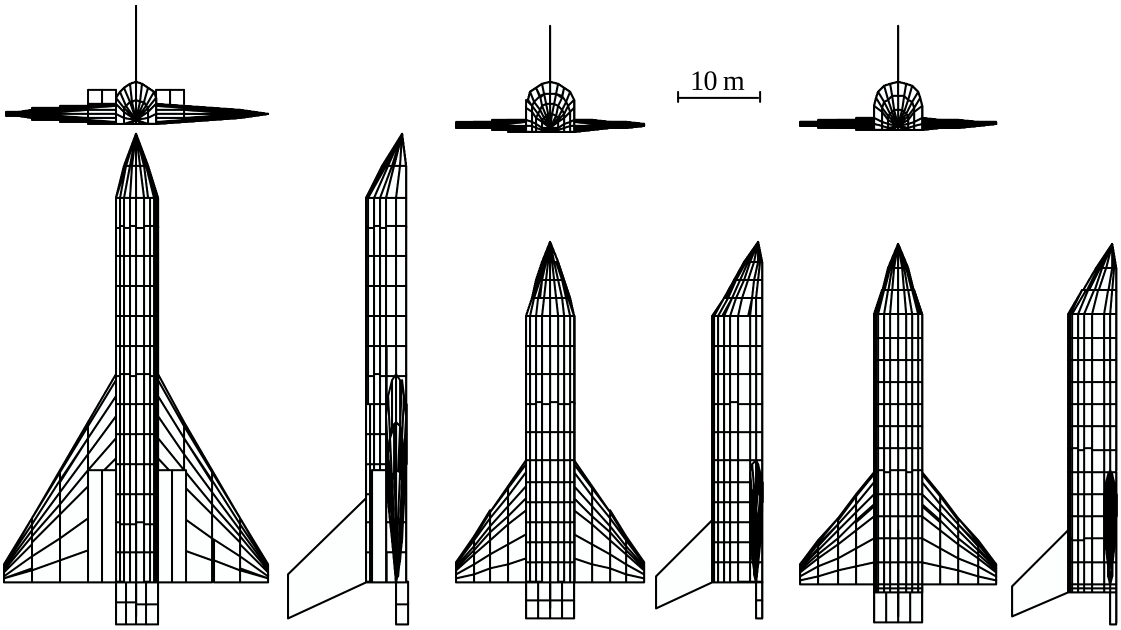
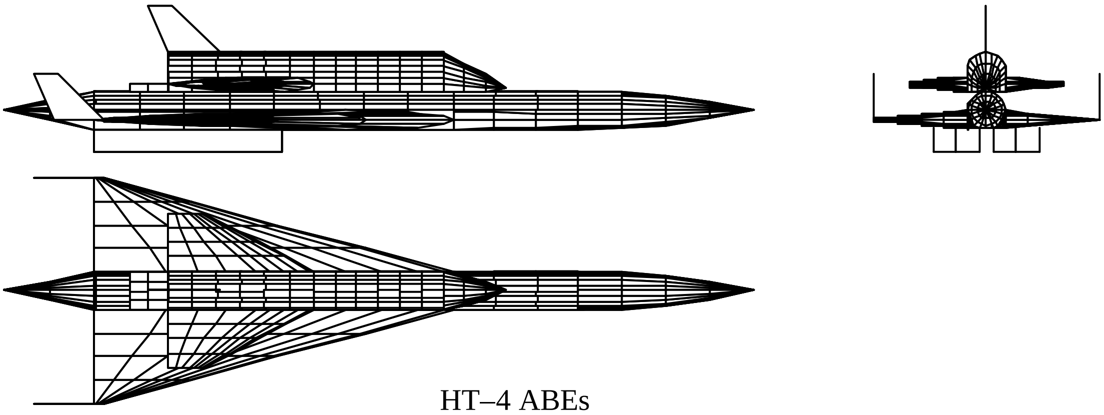


HT–4 ABEs/3 REs HT–3 REs VT–3 REs

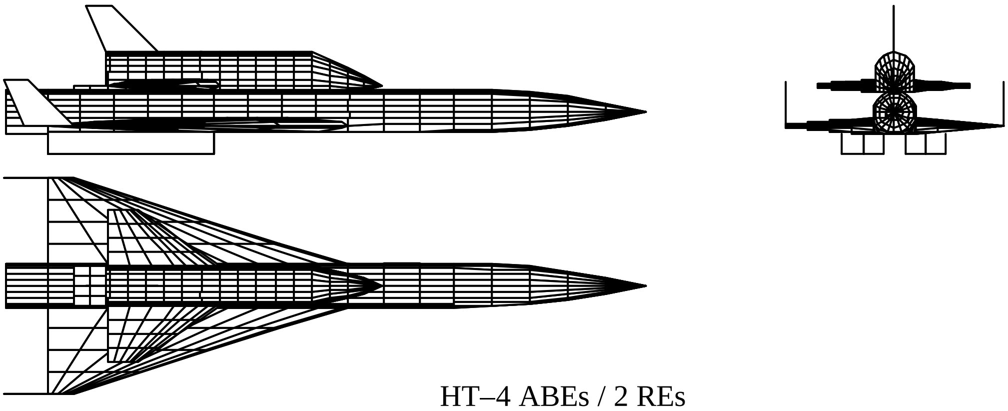
Fig. 5 Optimal shapes of the SSTO vehicles

Table 1 Component weights of the SSTO vehicles (Unit is Mg.)

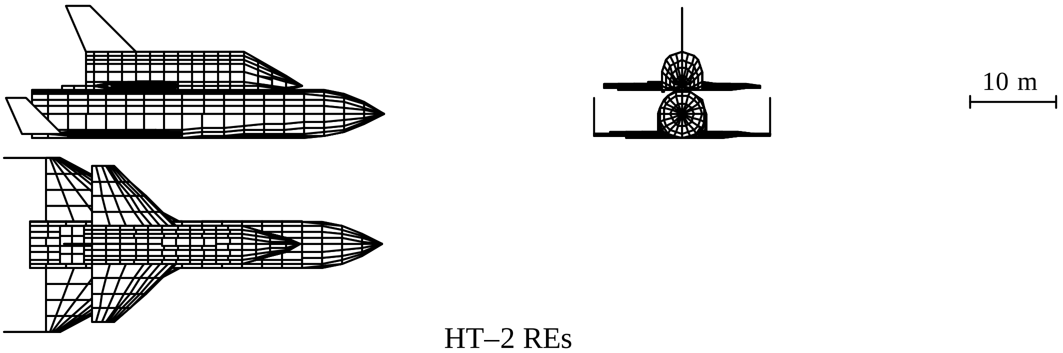
	HT–4 ABEs/3 REs	HT–3 REs	VT–3 REs
fuselage	13.61	10.67	10.96
wing	5.04	2.70	2.66
stabilizer	3.85	2.29	2.17
TPS	10.38	6.27	6.23
landing gear	14.47	14.47	1.21
tank	11.07	8.93	9.06
ABE	30.20	0.00	0.00
RE	7.26	5.85	7.25
payload	0.00	0.00	0.00
misc.	9.71	7.07	6.33
real dry weight	105.60	59.26	47.87
required dry weight	40.93	33.50	32.87
dry weight reduction factor	0.39	0.57	0.69
LH2	44.21	37.51	37.61
LOX	210.02	225.03	225.64
RCS propulsion	4.84	3.96	3.89
gross weight	300.00	300.00	300.00



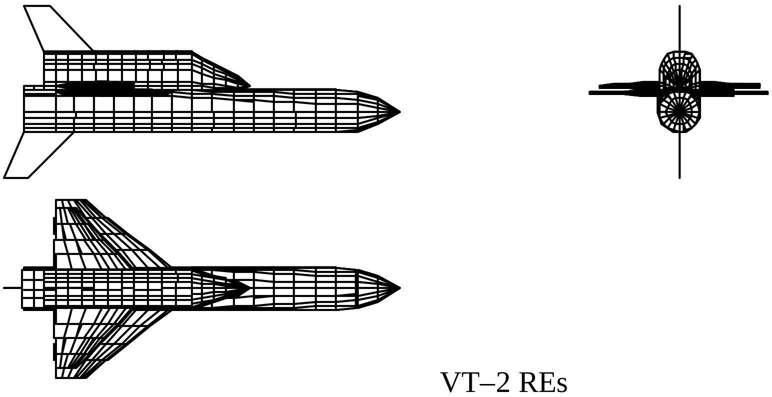
HT–4 ABEs



HT–4 ABEs / 2 REs



HT–2 REs



VT–2 REs

Fig. 6 Optimal shapes of the TSTO vehicles

Table 2 Component weights of the TSTO vehicles (Unit is Mg.)

	HT–4 ABEs		HT–4 ABEs / 2 REs		HT–2 REs		VT–2 REs	
	Booster	Orbiter	Booster	Orbiter	Booster	Orbiter	Booster	Orbiter
fuselage	16.91	6.77	17.98	5.11	10.18	3.80	9.78	3.49
wing	16.07	2.12	13.36	1.57	4.40	1.25	3.38	1.17
stabilizer	2.01	1.19	1.91	1.11	1.21	1.00	0.92	0.96
TPS	8.18	4.72	7.77	3.75	4.17	3.02	4.00	2.84
landing gear	17.98	1.27	16.78	0.97	16.90	0.75	1.64	0.70
tank	8.64	4.49	9.13	2.88	7.55	1.96	7.38	1.69
ABE	65.68	0.00	53.72	0.00	0.00	0.00	0.00	0.00
RE	0.00	3.07	6.74	2.09	8.41	1.29	8.92	1.08
payload		4.00		4.00		4.00		4.00
misc.	13.92	6.79	13.17	5.50	7.39	4.51	7.11	4.22
dry weight	149.39	34.42	140.56	26.98	60.21	21.59	43.13	20.15
LH2	53.70	17.46	54.11	11.25	29.81	7.32	27.19	6.08
LOX	0.00	104.76	38.51	67.49	178.85	43.93	163.13	36.49
RCS prolusion		4.07		3.19		2.56		2.38
gross weight	203.09	160.71	233.18	108.91	268.87	75.41	233.45	65.10
total gross weight	363.80		342.09		344.28		298.55	

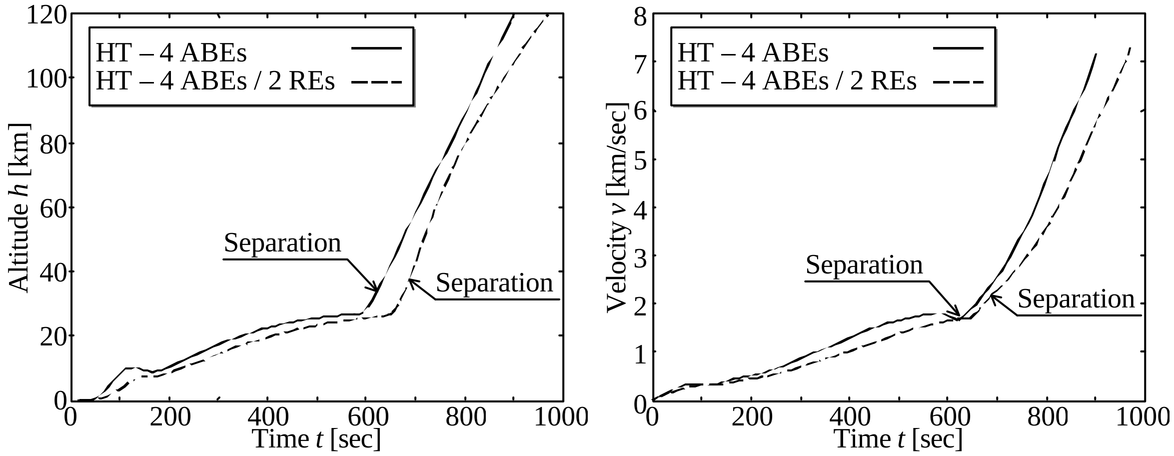


Fig. 7 Optimal flight trajectory of “HT–4 ABEs” and “HT–4 ABEs / 2 REs”

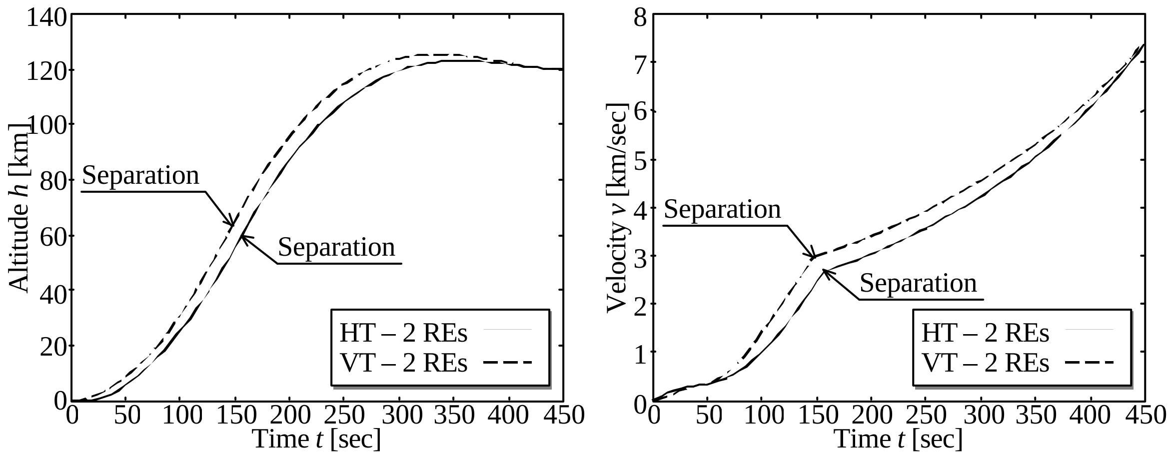


Fig. 8 Optimal flight trajectory of “HT–2 REs” and “VT–2 REs”