HiSST: International Conference on
High-Speed Vehicle Science Technology
26–29 November 2018, Moscow, Russia

Effects of the lift-to-drag ratio on climbing characteristics of reusable launch vehicles

CUI Kai, [1,2], XU Yingzhou [1,2], Li Guangli*, [1,2], XIAO Yao[1,2], WANG Haoxiang[1,2]*

Abstract

This study aims at climbing characteristics investigation of the first-stage reusable launch vehicle in small Two-Stage-To-Orbit (TSTO) systems adopting ground boosting, horizontal take-off strategy. On the basis of the two-dimensional, three degree of freedom ballistic equations, the impact of the lift-to-drag ratio of the vehicle on some key performance parameters, which include the velocity gain, the height gain, the trajectory inclination angle, the dynamic pressure, and the maximal overload, etc are systematically analyzed under different thrust-weight ratios. The results clearly show that a high lift-to-drag ratio is not only propitious to elevate the height of separation, but also conducive to reduce the dynamic pressure as well as the maximal overload, especially in small thrust-weight ratio conditions. The adjustment range of the trajectory inclination angle is significantly extended due to a high lift-to-drag value simultaneously. Finally, some critical requirements of aerodynamic configuration design are proposed.

Keywords: *Reusable launch vehicle (RLV), horizontal take-off, two-stage-to-orbit, trajectory analysis, lift-to-drag ratio*

Nomenclature

Latin
C_d – Aerodynamic drag coefficient
C_l – Aerodynamic lift coefficient
D – Aerodynamic drag
D/m – Drag to mass ratio
g – Gravitational acceleration
H – Altitude
Isp – Specific impulse
L – Aerodynamic lift
L/D – Lift to drag ratio
m – Mass
P – Thrust
P/m – Thrust to mass ratio
TWR – Thrust to weight ratio
V – Velocity
x – Horizonal position

Greek
α – Flight angle of attack
θ – Trajectory inclination angle
ρ – Atmospheric density

Subscripts
0 – Initial parameters
f – Fuel

1. Introduction

Reusable launch vehicles (RLV) had been of much concern in recent decades. Generally, the launching mode can be divided into two categories, i.e., the vertical launching mode and the horizonal takeoff mode. The theoretical foundation of the former mode is the famous Tsiolkovsky rocket equation. Although the vertical launching mode had been widely used to send up various satellites, but most of the launching vehicles are expendable, that is to say, they are not reusable. However, by using stage supersonic retro-propulsion (SRP) technique, Space-X corporation had successfully completed several demonstrations to reuse the first stage on multiple flights [1]. The Falcon-9 rocket is no doubt an important milestone of the development of reusable vertical launch vehicles.

[1] *LHD of Institute of Mechanics, Chinese Academy of Sciences, Beijing, 100190, China*
[2] *School of Engineering Science, University of Chinese Academy of Sciences, Beijing 100049, China*

By comparison, the horizonal takeoff mode is still at the exploratory stage at present. Pioneered by the X-30 aerospace plane program [2] of the USA and the HOTOL program [3] of the UK in 1980's, a large number of plans and concepts had been proposed. In recent years, two-stage-to-orbit (TSTO) vehicles have become a research hotspot. Various system level schemes had boomed, some typically concepts include the Hypersonic Space and Global Transportation System (HSGTS) [4], TSTO conceptual vehicle using the SABRE Engine [5], RBCC engine-powered launch vehicles [6], etc.

The primary advantage of the horizonal takeoff launch vehicles is that they are wing vehicles. Thus they can directly fly back to the launch site and prepare for the next journey if the values of their Lift to drag ratio (L/D) are high enough. However, if a high L/D is negatively affect the operation performance of the launch vehicle in the climbing stage, the advantage may fade, even nothingness. Therefore, it is important to investigate the effects of the L/D on climbing characteristics of reusable launch vehicles. This problem motivates our work. In this paper, a primary study based on two-dimensional, three degree of freedom ballistic equations is carried out to aim at the above problems.

2. Equations and parameters

The two-dimensional, three degree of freedom ballistic equations using in this paper is as follows,

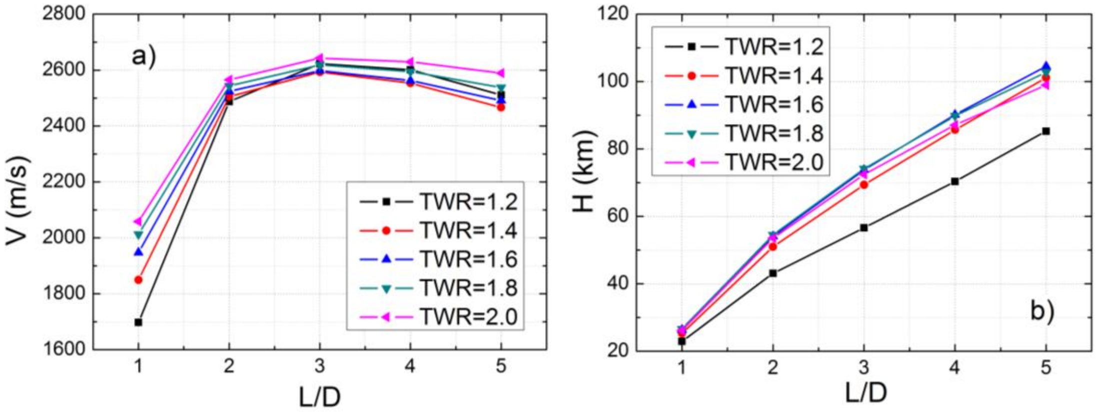
$$\begin{cases} \dfrac{dV}{dt} = \dfrac{P}{m} - \dfrac{D}{m} - g\sin\theta \\ \dfrac{d\theta}{dt} = \dfrac{L}{D}\cdot\dfrac{D}{m}\cdot\dfrac{1}{V} - \dfrac{g\cos\theta}{V} \\ \dfrac{dx}{dt} = V\cos\theta \\ \dfrac{dH}{dt} = V\sin\theta \\ \dfrac{dm}{dt} = -\dfrac{P}{gI_{sp}} \end{cases} \tag{1}$$

In order to simplify the analysis, some assumptions are made as follows. First, the flight angle of attack of the vehicle remains a constant value. Next, suppose the takeoff speed of the vehicle is in the supersonic regime. On the basis of the above assumption, the value of the L/D can be roughly regards as a constant in the calculation. In addition, the thrust of the engine, expressed by the thrust-to-weight ratio (TWR), is also assumed to a constant. The values of some key parameters are listed in table 1. Besides, the reference area for calculation the aerodynamic force is given 8 m^2.

Table 1. values of some key parameters

TWR	C_l	C_d	m_0 (kg)	m_f (kg)	V_0 (m/s)	θ_0 (deg)	x_0 (m)	H_0 (m)
[1.2-2.0]	[0.03-0.15]	0.03	10000.0	6000.0	400.0	0.0	0.0	0.0

3. Results



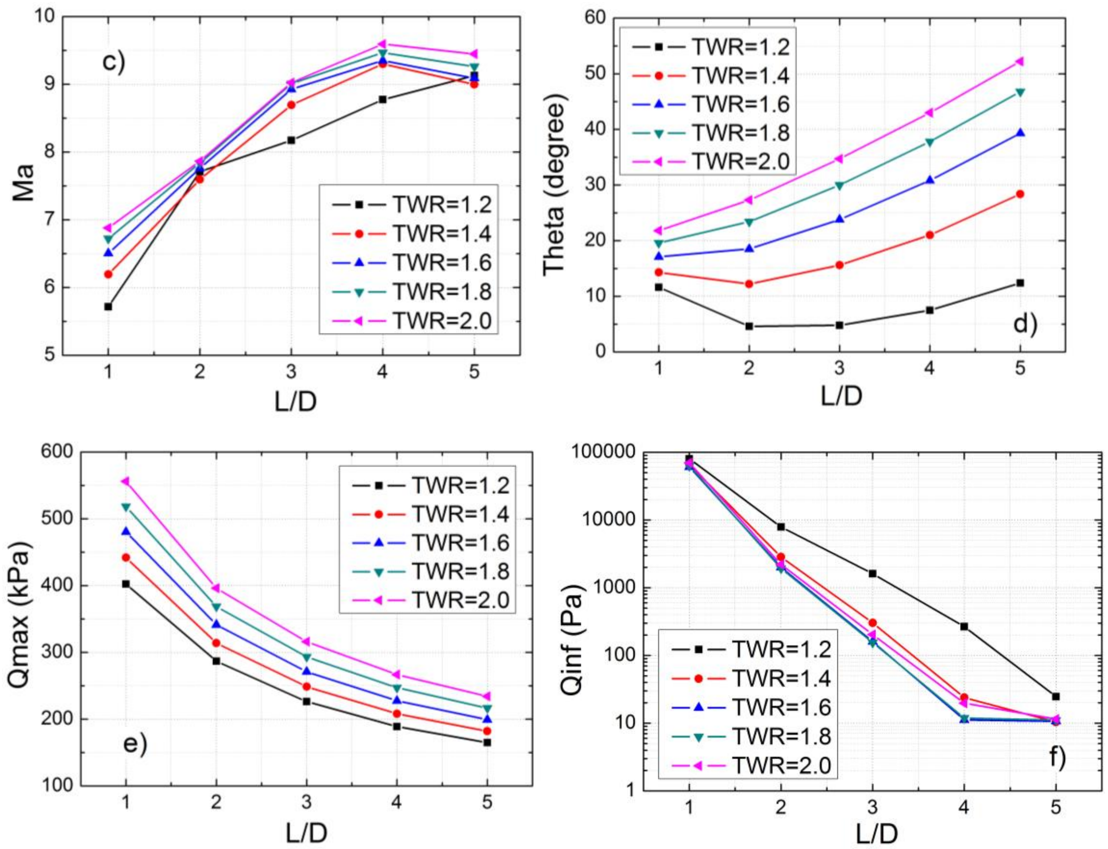


Fig 1. Main performance parameters versus the L/D

Curves of some main performance parameters vary with the L/D are plotted in Fig. 1, where V represents the velocity, H represents the flight height, Ma is the Mach number, Theta is the trajectory inclination angle, Qmax is the maximal dynamic pressure, Qinf is the dynamic pressure at the ending point of the launch vehicle.

4. Conclusions

The above results clearly show that a high value of the L/D is benefit to the climbing performances of RLVs. Although the increment of the velocity is not sensitive to the L/D (Fig. 1-a), but the increment of the height is proportional to the L/D (Fig. 1-b). In addition, the trajectory inclination angle may get a large adjustment range due to a high L/D (Fig. 1-d). Moreover, both the maximal dynamic pressure and the dynamic pressure at the ending point of the launch vehicle are inverse proportional to the L/D, which is helpful to reduce the structure weight because the aerodynamic force load decreases (Fig. 1-e and Fig. 1-f). Finally, because a RLV general need a large volume to contain fuel and oxidant, it should be noted that a high value of the L/D is difficult to obtain under the requirement of large volumetric efficiency. Some new concepts, such as the High-pressure capturing wing configurations [7, 8], may resolve this problem.

Acknowledgement

This work was supported by the National Natural Science Foundation of China (Grant Nos. 11572333 and 11372324) and the State Key Laboratory of High Temperature Gas Dynamics, Institute of Mechanics, Chinese Academy of Sciences (Grant Nos. LHD2017TC01, LHD2017MS04, and LHD2017QN03).

References

1. Edquist, K.T., Korzun, A.M., Bibb, K.L., et al: Comparison of navier-stokes flow solvers to falcon 9 supersonic retropropulsion flight data. AIAA Paper 2017-5296 (2017)
2. Johnson, D., Hill, C., Brown, S., et al: Natural environment application for NASP-X-30 design and mission planning. AIAA Paper 1993-851 (1993)
3. Conchie, P.: The HOTOL space transportation system. AIAA Paper 1986-786 (1986)
4. Bowcutt, K.G., Smith, T.R., Kothari A.P., et al: The Hypersonic Space and Global Transportation System: A Concept for Routine and Affordable Access to Space. AIAA Paper 2011-2295 (2011)
5. Hellman, B.M., Bradford, J., St.Germain, B., et al: Two stage to orbit conceptual vehicle designs using the SABRE engine. AIAA Paper 2016-5320 (2016)
6. Gong, C.L., Chen, B., Gu, L.X. et al: The Airframe/Propulsion Integrated Design, Analysis and Ground Test for RBCC launch vehicle. AIAA Paper 2017-2318 (2017)
7. Cui, K., Xiao, Y., Xu, Y.Z, et al: Hypersonic I-shaped aerodynamic configurations. SCIENCE CHINA Physics, Mechanics & Astronomy 61(2), 024722 (2018)
8. Cui, K., Li, G.L., Xiao, Y., et al: High-Pressure Capturing Wing Configurations，AIAA Journal, 55: 1909-1919 (2017)