Integration of the Engine Control into the Optimal Trajectory Determination for a Spaceplane

Kensuke MATSUNAGA
Department of Aeronautical and Astronautical Engineering, University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan
matsunaga@pub.isas.ac.jp

Nobuhiro TANATSUGU, Tetsuya SATO, Hiroaki KOBAYASHI, Yoriji OKABE
Japan Aerospace Exploration Agency

Keywords : Engine Control, Trajectory, Optimization, Spaceplane

Abstract

In this paper are presented TSTO system analysis including some controlled variables on the engine operation such as a fuel flow rate and a pressure ratio of compressor, as well as variables on the trajectory. TSTO studied here is accelerated up to Mach 6 by a fly-back booster powered by air breathing engines. Three different types of engine cycle were treated for propulsion system of the booster, such as a turbo ramjet, a precooled turbojet and an EXpander cycle Air Turbo Ramjet (ATREX). The history of the controlled variables on the engine operation was optimized by Sequential Quadratic Programming (SQP) to accomplish the minimum fuel consumption. The trajectory was also optimized simultaneously. The results showed that the turbo ramjet gave the best fuel consumption. The optimal trajectory was almost the same except in the transonic range and just before reaching to Mach 6. The history of the pressure ratio of compressor considerably depended on the engine type. It is concluded that simultaneous optimization for engine control and trajectory is effective especially for a high-speed airplane propelled by turbojets like the TSTO booster.

Introduction

Many concepts of future space transportation system have been proposed in the world. It is desirable to be safe, reliable, economical and ecological. Fully reusable TSTO spaceplane is one of the promising candidates for future space transportation system. In Japan, development studies of TSTO have been made aiming at realization of TSTO in 2010's.

A TSTO vehicle consists of a fly-back booster powered by air breathing engines and a winged orbiter by rocket engines. The booster carrying the orbiter takes off horizontally at a launch site, and accelerates with air breathing engines. After sufficient speed is obtained, the orbiter is separated from the booster., which flies back to the launch site. The orbiter continues its ascent further to an orbit around the earth with the rocket engines. After the mission on the orbit, the orbiter reenters the atmosphere, returns to the launch site and carries out level landing. TSTO has many strong points, such as high payload weight ratio and abortability.

Many studies of optimization of the TSTO system have been made[1-3]. However, most were merely for design and trajectory, and few treated the engine behavior. Since the air breathing engines of the booster operate over the wide range of Mach number and keep acceleration of the vehicle all the way in the ascent phase, it is important to examine how engines should be controlled. In this study, engine control is integrated into trajectory control, and simultaneous optimization is implemented.

Propulsion

The TSTO vehicle is propelled by air breathing engines of the booster. Air breathing engines derive large specific impulse because of utilizing oxygen in the air as oxidizer. However, at high Mach number, aerodynamic heating influences the engine performance. This is a serious problem especially for engines with turbo machinery. Therefore, it is necessary to control engines including the heat protection system properly.

Engine Cycle

In this paper, three different engine cycle are treated as candidates for the propulsion system of the booster, such as Turbo RamJet (TRJ), PreCooled TurboJet (PCTJ), and EXpander cycle Air Turbo Ramjet (ATREX). These cycles are defined below and the schematic of each cycle is shown in Fig.1.

(1) TRJ : At low Mach number, this engine operates as the turbojet. The turbine is driven by main combustion gas. Thrust can be augmented by utilizing an afterburner. At high Mach number, the engine no longer works as the turbojet because of thermal limit of the turbo machinery. The engine cycle shifts from the turbojet to the ramjet by shutting the door to stop the air flow entering the compressor.

(2) PCTJ : A precooler is equipped upstream of compressor to protect turbo machinery thermally. Hydrogen is used as a coolant. By precooling air, thrust and specific impulse are increased. The turbine is driven by main combustion gas. An afterburner is also dispensable to augment thrust like TRJ.

(3) ATREX : A precooler is installed also in this engine. The turbine is driven by the fuel which is pressurized by a turbo pump and is heated up by heat exchange with combustion gas. Therefore this engine can generate large thrust without an afterburner. On the other hand, since low turbine efficiency prevents the compressor from achieving high pressure ratio, engine power is lower than TRJ and PCTJ at low Mach number.

Engine Components

In this study the characteristics of primary components which have been analytically or experimentally developed by ISAS and NAL are applied4). These characteristics are described in the subsequent paragraph.

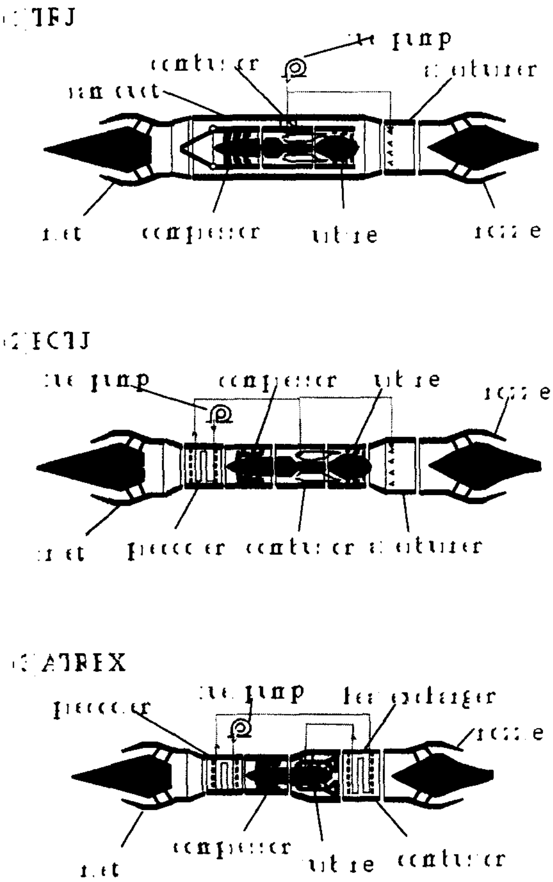

Fig 1 Engine schematic

the inlet is evaluated mainly by total pressure recovery and mass capture ratio. The former is normalized by ambient total pressure, and the latter by the air flow rate through cowl inlet area. These are shown in Fig.2 with bleed mass ratio. Coefficient of spillage drag, which is normalized by the cowl inlet area, is shown in Fig.3 with nozzle thrust coefficient.

The compressor for FJR710/20 is employed as a compressor model. Its performance map is shown in Fig.4. It is one of the characteristics of this study that pressure ratio is allowed to take any value in the domain surrounded by the outside line of Fig.4. In the case of ATREX, pressure ratio in Fig.4 is modified to decrease by 80% with no change of the corrected flow rate as if the performance map shrank in the direction of the vertical axis because of its lower pressure ratio as mentioned above. The surplus air flow which cannot enter the compressor is bled after the inlet. Turbine efficiency is a function of speed ratio.

The precooler is modeled as a fully counter flows heat exchanger. Thermal efficiency and pressure drop are estimated by using Zukauskas's formulas.

Pump efficiency and head coefficient are modeled referring to the characteristics of the LE-5 fuel pump.

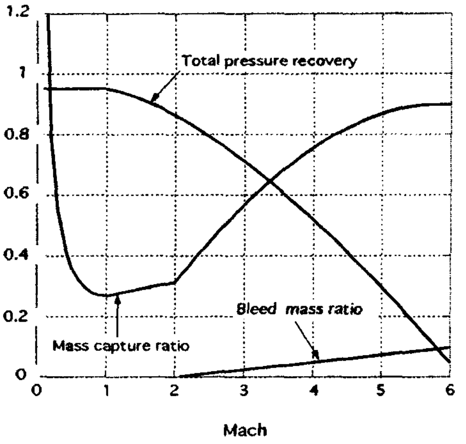

Fig 2 Inlet characteristics

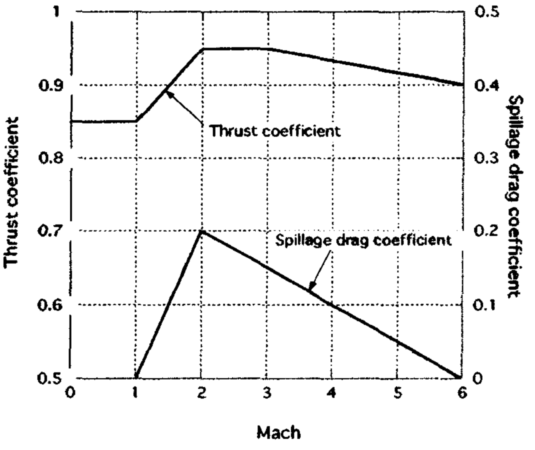

Fig 3 Thrust characteristics

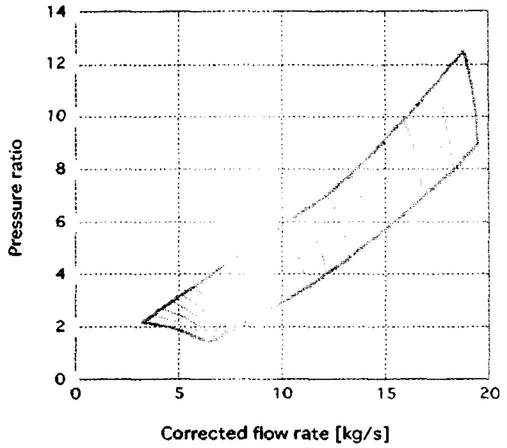

Fig 4 Compressor performance map

TRAJECTORY

Trajectory optimization with minimum propellant consumption is essential to design the flight path of TSTO. In this paper, the booster ascent phase from take off to Mach 6 is treated. The TSTO vehicle is assumed as a mass point. The motion of TSTO is restricted to the two-dimensional equatorial plane. the variables are altitude h, longitude θ, flight path angle γ, and velocity V. Motion equations of TSTO are as follows.

$$\frac{dh}{dt} = V\sin \tag{1}$$

$$\frac{d}{dt} = \frac{V\cos}{r} \tag{2}$$

$$\frac{d}{dt} = \frac{T\sin \; + L}{mV} \quad \cos \quad \frac{g}{V} \quad \frac{V}{r} \tag{3}$$

$$\frac{dV}{dt} = \frac{T\cos \quad D}{m} \quad g\sin \tag{4}$$

where α : angle of attack, m : mass, g : gravity acceleration at altitude h, r : distance from the Earth center, T : thrust, L : lift, and D : drag. Aerodynamic characteristics of the TSTO vehicle are based on NAL 0th configuration. U.S. Standard Atmosphere is applied for atmospheric condition.

Optimization Problem

The flight condition with the air breathing engines, such as TRJ, PCTJ, and ATREX, is investigated with the optimization of the TSTO vehicle from take off to Mach 6. Common configurations are described.

- gross take off weight	300 [Mg]
- wing area	500 [m2]
- number of engines	8 [-]
- cowl inlet area	4.33 [m2]

As the optimization method, Sequential Quadratic Programming (SQP) is applied here. The SQP is regarded as one of the most effective method to solve a nonlinear programming problem. Variables to be optimized are listed as follows.

(1) trajectory
  state variables
    - altitude
    - longitude
    - flight path angle,
    - velocity
  a control variable
    - angle of attack
(2) engine operation
  control variables
    - fuel flow rate of combustor
    - fuel flow rate of afterburner
    - pressure ratio of compressor
    - rotational speed of fuel pump

In a practical point of view, it is difficult to control pressure ratio of compressor directly. Therefore, it should be controlled by adjusting nozzle area ratio on the assumption that the flow is choked.

The following constraints are defined.

(1) trajectory	
initial conditions	
- Mach number	0.3 [-]
- flight path angle	0.1 [rad]
path constraints	
- maximum dynamic pressure	50 [kPa]
- maximum attack angle	0.32 [rad]
a terminal condition	
- Mach number	6.0 [-]
(2) engine operation	
precooler	
- coolant temperature limit	900 [K]
compressor	
- gas temperature limit	720 [K]
- tip speed limit	
(mechanical)	350 [m/s]
(corrected)	400 [m/s]
turbine	
- gas temperature limit	1700 [K]
heat exchanger	
- coolant temperature limit	1200[K]

Results

Under the above assumption, the simultaneous optimization for trajectory and engine control was implemented.

Fig.5 and Fig.6 show the cumulative fuel consumption and the history of the equivalent ratio, respectively. In the subsonic range, TRJ and PCTJ operated without afterburning for high specific impulse. ATREX worked at overstoichiometric operation to provide the turbine with driving power. Once the vehicle began the supersonic flight, TRJ ran at stoichiometric operation to the last. On the other hand, at high Mach number PCTJ and ATREX demanded much fuel for the thermal protection. The fuel was used mainly to cool the compressor over M4.2 in the case of PCTJ, and the precooler over M4.5 in the case of ATREX. As a result, at low Mach number ATREX consumed fuel in large quantities, and at M4.5 or more the fuel consumption of PCTJ and ATREX increased considerably. TRJ gave the least cumulative fuel consumption.

In Fig.7 the optimal trajectory is shown. Regardless of the engine cycle, the TSTO vehicle flew along the dynamic pressure limit of 50 kPa, except in the transonic range and just before reaching to M6. In the transonic range, the vehicle with the lower thrust engine took the higher trajectory. The reason is as follows. In the transonic range, the drag coefficient is large. The flight at a high altitude reduces the drag force because the density of air is low. This makes the flight of the vehicle with the low thrust engine efficient. Just before reaching to M6, the vehicle dived in all cases. The vehicle with PCTJ and ATREX began its ascent for the dive earlier than that with TRJ. This is because the flight at higher altitude reduced the air mass flow captured by the engines, and quantity of the fuel required to cool the air was also correspondingly decreased for PCTJ and ATREX.

Fig.8-10 show the histories on the performance map for TRJ, PCTJ and ATREX, respectively. In the case of TRJ, the compressor operating line was quite smooth. The diverging point of engine cycle, having shifted from the turbojet to the ramjet, was at M2.21. The mechanical tip speed of the compressor took the maximum value between M2 and M2.21. In the case of PCTJ, the compressor operating line was along the surge line under M2. The pressure ratio became lower as the ram compression became more effective. Between M3 and M5.5 the operating line was along the stall line. After the flight path was higher than the trajectory of the constant dynamic pressure around M5 (Fig.7), the operating line separated from the boundary line. The mechanical tip speed between M2.8 and M4.2 and the gas temperature of the compressor over M4.2 reached the maximum limits, respectively. In the case of ATREX, the large variation of the compressor pressure ratio made the operating line complex in the subsonic and transonic range, unlike TRJ and PCTJ. This is because the flow rate of fuel driving the turbine in ATREX was controlled so that fuel consumption might be minimum. Thereafter, the operating line was along the stall line. The mechanical tip speed reached the maximum limits between M3 and M4.5 and over M5.8. As shown above, the operating lines of PCTJ and ATREX whose compressors run all the time in the flight were complicated. It is considered that the operating condition was influenced by many elements, such as the mechanical tip speed and the gas temperature of the compressor.

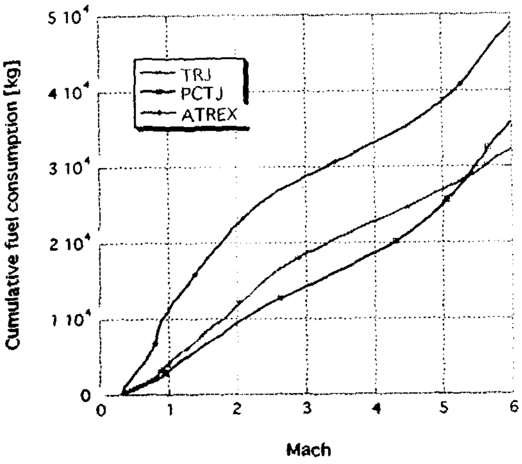

Fig 5 Cumulative fuel consumption

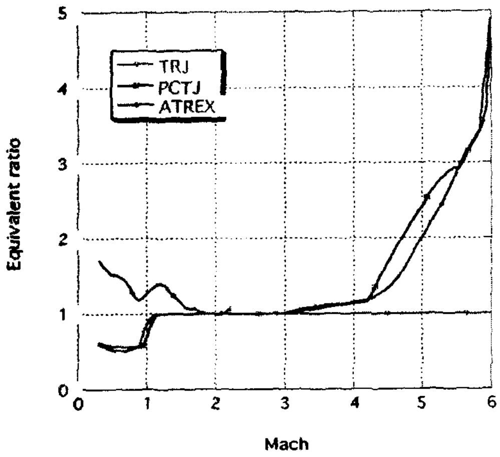

Fig 6 Equivalent ratio

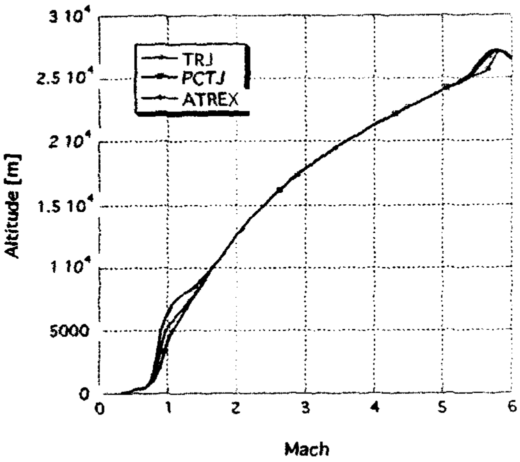

Fig 7 M-h trajectory

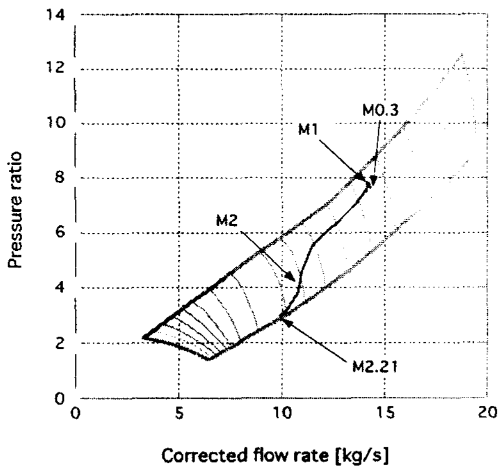

Fig 8 Performance map (TRJ)

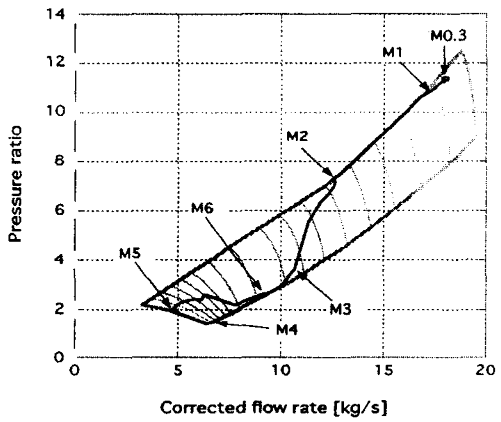

Fig 9 Performance map (PCTJ)

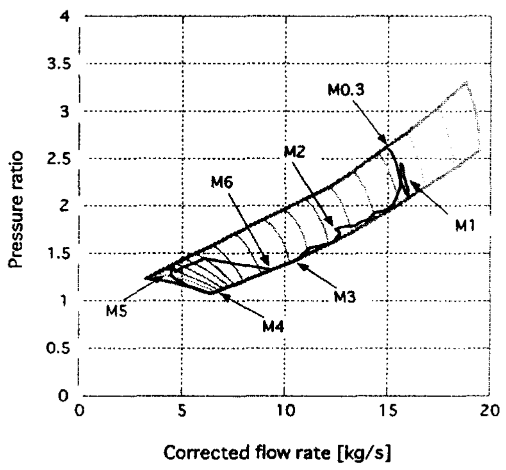

Fig 10 Performance map (ATREX)

Conclusion

In this study, we combined the engine control with the trajectory optimization of TSTO. The simultaneous optimization was carried out for three different engine cycles (TRJ, PCTJ and ATREX). From the numerical solutions, the operational characteristics of each engine were examined and compared. TRJ was the best from the viewpoint of fuel consumption. The every optimal trajectory was almost along the dynamic pressure limit. The difference arouse only in the transonic range and the dive. The compressor operating line on the performance map was smooth in TRJ. On the other hand, the operating lines were complicated in PCTJ and ATREX. It was confirmed that the engine control was effective especially for turbojets operating over the wide range of flight Mach number.

Acknowledgement

We would like to sincerely thank Mr. Tsugio Matsuda and Mr. Takeshi Tagashira of JAXA for providing the information on the compressor. We also wish to mention special thanks to Mr. Nobuhiro Yokoyama of University of Tokyo. His advice on the optimization problems has been much appreciated.

Reference

(1)Li, P. : Inverse Dynamics Approach to Trajectory Optimization for an aerospace plane, Journal of Guidance, Control, and Dynamics, Vol.16, No.4, pp726-732, 1993

(2)小林弘明 : 二段式スペースプレーンのシステム統合設計に関する研究, 東京大学博士論文, 2001

(3)Tsuchiya, T., Suzuki, S. : A Simultaneous Optimization Technique for Spaceplane Shape and Trajectory, AIAA-2001-1847, 2001

(4)棚次亘弘 : ATREX エンジンの開発研究, 宇宙研報告, 2003

(5)茨木俊秀, 福島雅夫 : Fortran 77 非線形最適化プログラミング, 岩波書店, 1991

(6)Betts, J. T., Frank, P. D. : A Sparse Nonlinear

Optimization Algorithm, Journal of Optimization Theory and Applications, Vol. 82, No. 3, pp519-541, 1994