2009-a-04

Visualization and Optimization of LE-X Engine System Margin

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The LE-X is a new cryogenic booster engine with high performance, high reliability and low cost, designed for the next-generation Japanese launch vehicle, called H-X. It will be the first booster engine in the world with an expander cycle. In the LE-X engine design process, Taguchi method using L27 orthogonal array is applied to visualize quantitatively the margin and the correlation of engine system / components performance, reliability, and cost, and to determine the robust and optimum engine configuration. First, we extract the evaluation functions which affect the engine system performance, reliability and cost, and the control parameters which have a large impact on the evaluation parameters. Next, each control parameter is changed by three levels, and assigned to the orthogonal array L27. The margins of the evaluation functions and the sensitivities between the evaluation functions and the control parameters are calculated and visualized by engine system analysis for each case. Using the 27 engines in this L27 orthogonal array, the margins of the engine system and components will be visualized, and the control parameters which make the engine system be robust and match the system requirement of performance, reliability, and cost will be determined.

Key Words: LE-X, expander bleed, Taguchi method

1. Introduction

JAXA is under study for the next booster rocket engine with higher reliability and significantly reduced cost, called LE-X. The LE-X will be applied to the next flagship Japanese launch vehicle. Last year, JAXA determined the LE-X engine cycle from the requirement of the reference next flagship launch vehicle and the trade study with respect to the performance, reliability, cost, and development risk. The next step of the LE-X engine design is to optimize the design parameters for adequate margins against the requirements of performance, reliability, and cost.

Liquid rocket engine is huge and complex system with many components, such as combustion chamber, fuel/oxidizer injection elements, turbopumps, valves, pipelines and so on. They interact with each other in severe environment. For example, the life time of combustion chamber, turbine energy output and the total engine weight are strongly correlated in a expander cycle engine. Therefore it is important for liquid rocket engine designers to keep enough margins against the requirements in order to determine the robust and optimum engine configuration in the early phase of the development. In this paper, this systems engineering approach which is applied to the LE-X engine design is introduced.

2. Reference launch vehicle

Fig. 1 shows an image of the reference launch vehicle, H-X. JAXA initiated the early-stage feasibility study of the H-X rocket. A version of the H-X candidates for the light payload without solid rocket booster (H-X200) will require the throttling capability of first stage engine to avoid the excessive acceleration in the flight envelope. The requirement of the reference first stage engine is shown in Table 1.

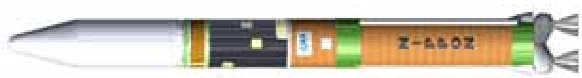

Fig. 1. A version of the H-X

Table 1 Reference 1st stage engine specification

Performance	More than 3 ton payload to SSO
Propellants	Liquid Oxygen /Liquid Hydrogen
Thrust Throttling Level	60-100%
1st stage propellant mass	111.1 ton
Engine O/F	5.9

3. LE-X engine cycle

One of the features of the LE-X engine is its engine cycle. The engine cycle schematic of the LE-X is shown in Fig. 2. The expander bleed cycle will be applied to the LE-X engine, and the LE-X will be the first booster engine in the world with an expander cycle. In this cycle, hydrogen pumped by the fuel turbopump is partly directed to the main combustion chamber cooling channels and then used to drive the turbines. The turbine drive hydrogen is injected into the main combustion flow at nozzle extension. This cycle has following advantages compared to the staged combustion cycle adopted in the LE-7A:

A) Simple engine configuration
B) Reduced maximum system pressure and temperature
C) Reduced heat impact to the turbines of turbopump
D) Robustness to failure events

In the expander bleed cycle engine, a main technical challenge is how to extract turbine power. Turbine drive gas of the expander bleed cycle is regenerative heated hydrogen, therefore, the energy of turbine drive gas depends on combustion chamber heat load, while they are independent in the staged combustion cycle and the gas generator cycle which use combustion energy. In order to increase the turbine energy output, the combustion chamber of the LE-X will be longer than that of the LE-7A. A longer chamber brings heavier engine weight. A smaller pressure loss though the regenerative coolant channel is preferred from the view of engine performance, which might result in a excessive high temperature at combustion chamber wall. As above, in order to determine properly the system and component specification, it is important to evaluate the whole engine system..

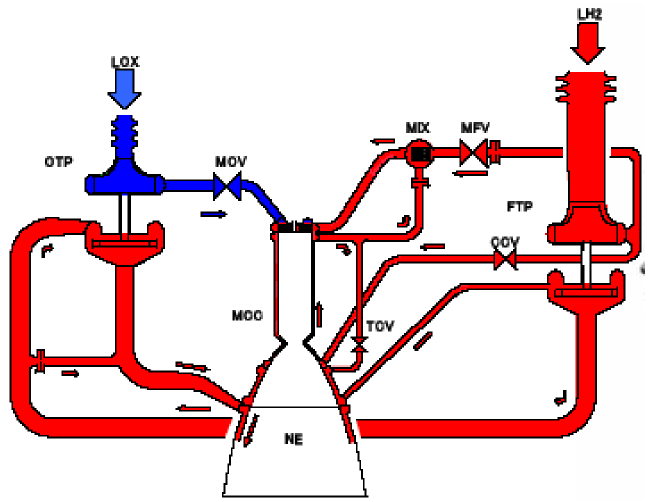

Fig. 2 LE-X engine cycle

4. Design process

4.0 Overview

Taguchi method, which is the statistical method for the improvement of the manufacture quality, is applied to the LE-X engine design. Fig. 3 shows the design process of the optimization. First, baseline configuration is set as a reference engine. Based on this baseline configuration, evaluation functions which affect the LE-X engine performance, cost and reliability are extracted. Control parameters which have a large impact on each evaluation function are also chosen. Considering the cycle calculation loading, L27 orthogonal array are applied to this design process. 13 control parameters with 3 levels can be allocated to L27 orthogonal array. Using the 27 engines in this L27 orthogonal array, the margins against the evaluation functions and the sensitivities between the evaluation functions and the control parameters are calculated and visualized. This analysis leads to the optimization of the design parameters of each component along with the requirement from the launch vehicle system.

This process is ongoing under collaborating among JAXA, MHI and IHI. In this paper, the results from "1. Baseline configuration" to "5. L27 cycle calculation" are described.

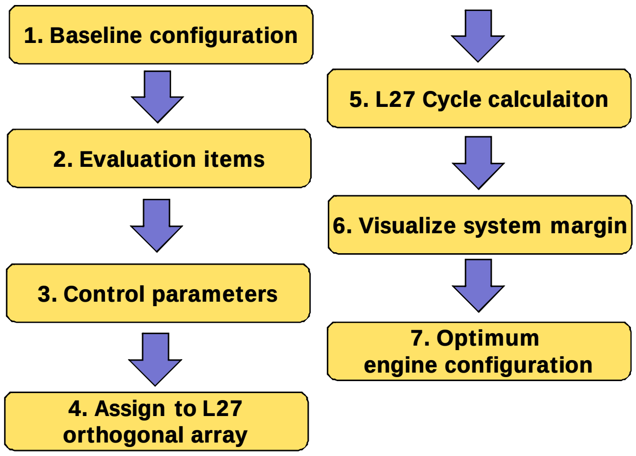

Fig. 3 Design process of optimization

4.1 Baseline configuration

Based on the reference 1st stage specification (Table 1) and the LE-X engine cycle (Fig. 2), LE-X 'baseline' configuration including turbopump inducer, impeller and turbine types is determined by the general engine cycle estimation. The principal specification of the LE-X baseline configuration is shown in Table 2, and the 3D layout model of the LE-X engine is shown in Fig.4. The 100% vacuum thrust of the LE-X engine is set to 1,448kN to maximize the payload transportation capability. The configuration of the FTP and the OTP are shown in Table 3. and Fig. 5. Single stage impeller with 2 stage inducer is applied to the FTP for high pump head with low cost.

Table 2. LE-X baseline configuration

	100% thrust	60% thrust
Combustion time (for SSO mission)	140 sec	60 sec
Engine thrust (vacuum)	1,448 kN	868 kN
Engine thrust (sea level)	1,217 kN	638 kN
Chamber O/F	6.9	6.7
ISP(vacuum)	432 sec	435 sec

Fig. 4 LE-X engine 3D layout model

Table 3. LE-X turbopump type

FTP	OTP
2 stage inducer	single stage inducer
single stage impeller	single stage impeller
2 stage impulse turbine	2 stage impulse turbine

4.2 Engine system evaluation functions

Optimization of the engine parameters is the goal of this process. The evaluation functions which represent the LE-X system performance, cost and reliability are described as follows.

i. Performance

Engine performance is estimated by the payload transportation capability to the sun-synchronous orbit (SSO). The capability is function of the engine thrust, weight and specific impulse, defined by a sensitivity analysis of the H-X launch vehicle orbit computation considering the ground radar station, upper-level wind, and so on.

ii. Cost

Cost is estimated by each component cost model. For example, cost is influenced by the chamber length, impeller diameter, and so on.

iii. Reliability

In the LE-X engine design, quantitative reliability of the LE-X engine system will be estimated using failure mode effect analysis (FMEA) list which includes every failure mode of the LE-X system and components. Using the FMEA, functions which affect the LE-X engine reliability are extracted. Each function concerning reliability is estimated by distance from design criteria of each component. However, estimation of all of the functions leads to somewhat pointless effort. For example, thickness of the pipeline could be independently designed with little system balance impacts. Therefore, the functions which have the large effect to the engine system balance and cannot be changed independently, are extracted. The reason of the function selection of each component is described as follows.

A) Combustion Chamber (MCC)

The LE-X combustion chamber consists of large size copper alloy inner liner and steel based superalloy outer shell. Pratt & Whitney Rocketdyne (PWR)'s hot isostatic pressure (HIP) bonding technology will be applied to fabricate the combustion chamber with significantly low cost. To enlarge the energy of the turbine drive gas, the combustion chamber (MCC) is divided into two part, upper chamber, which includes chamber throat and injector interface, and lower chamber. Fig. 5 shows the image of the chamber. The upper chamber inner liner has high temperature part, and the creep and fatigue damage of this part is the most critical for the chamber life.

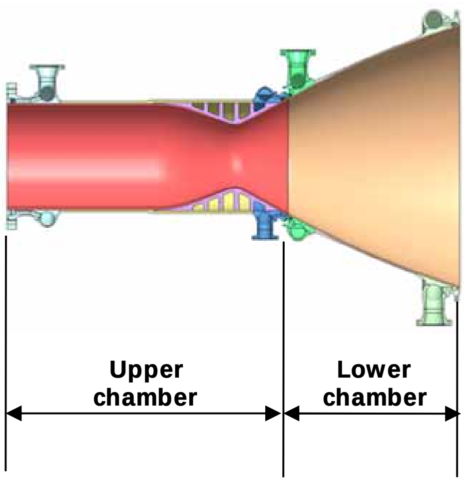

Fig. 5 LE-X combustion chamber

B) Injector (INJ)

The injector design affects combustion efficiency and combustion stability, which is one of the technical issues for the LE-X. Especially, combustion instability should be avoided at the baseline design phase.

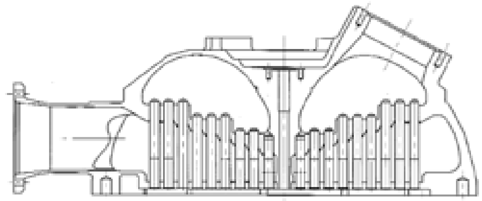

Fig. 6 LE-X injector

C) Nozzle skirt (NSA)

The nozzle skirt is cooled by the turbine drive gas and the gas should be choked at the nozzle skirt exit to

stabilize the turbine back pressure.
Critical failure mode of NSA is buckling. The temperature of nozzle wall and the pressuere of combustion gas should be controlled by the engine system.

Fig. 7　LE-X nozzle skirt

D) Main valves (MOV/MFV/TCV/CCV)
Eccentric ball valve (Fig. 8) with excellent flow characteristics, shut off capability and light weight, is applied to the LE-X as main valves, which are main oxidizer valve (MOV), main fuel valve (MFV), thrust control valve (TCV), and chamber coolant valve (CCV). Each main valve is driven by electric actuator, and has shaft seals and bearings. Controlling the environment of the shaft seals and bearings is important.

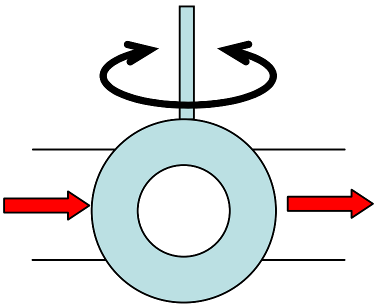

Fig. 8　Eccentric ball valve

E) Fuel turbopump (FTP)
Major criteria for the FTP are as follows;

- Suction limitation
- Rotor dynamics
- Bearing life time
- Impeller and turbine centrifugal force
- Turbine hydrodynamic force
- Turbine disk thermal impulse

The FTP runs in high rotational speed (more than 40,000rpm), impeller and turbine centrifugal force is critical. In addition, high temperature turbine drive gas flows into the FTP turbine when the engine starts, and the turbine disk might have cracks by the thermal shock.

F)Oxidizer turbopump (OTP)
Criteria for the OTP are same as th FTP's. The OTP is drived by the relatively low pressure hydrogen gas, therefore, large size turbine disk is necessary. Rotor dynamics and turbine hydrodynamic force is severe compared to the FTP.

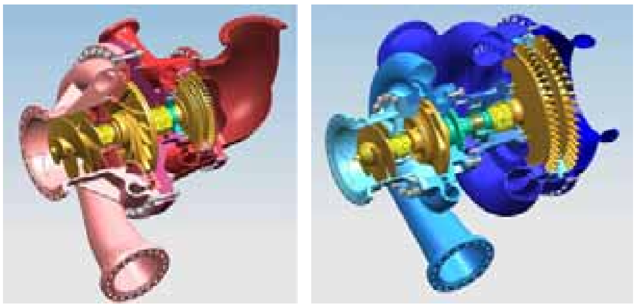

Fig. 9　LE-X engine turbopump (Left :FTP / Right :OTP)

4.3 Engine system control parameters

Considering these evaluation functions, 13 control design parameters which have a large impact on the evaluation functions are chosen;

- Combusiton chamber pressure
  Combustion chamber pressure is the factor of many evaluation functions, such as payload transportation capability (specific impulse, engine weight), FTP/OTP impeller centrifugal force and so on.
- FTP/OTP rotation speed
  Turbopump rotation speed controls the turbopump efficiency. High efficiency turbopump brings high specific impulse engine especially in case of expander bleed cycle.
- Wall temperature of combustiom chamber inner liner
  Generally, the life time of rocket engine is almost equal to the life time of combustion chamber inner liner. The wall temperature of the combustion chamber inner liner is the main factor of the life time of the chamber. In case of expander bleed cycle, the life time of the chamber contradicts the engine performance.
- Fuel injection temperature
- Contraction ratio　　　　etc...

4.4 L27 orthogonal array

Each control design parameter is changed by three levels, and assigned to the L27(3^{13}) orthogonal array. Three levels are set to be wide range as possible.

4.5.　Factor effect analysis

Relation between the evaluation functions and the control parameters are visualized by factor effect diagram. Fig. 10 shows thetypical factor effect of the LE-X engine specific impulse against the control parameters. It is shown that larger TCJF (fuel injection temperature) and TT1F (FTP turbine inlet flow temperature) leads to higher specific impulse.

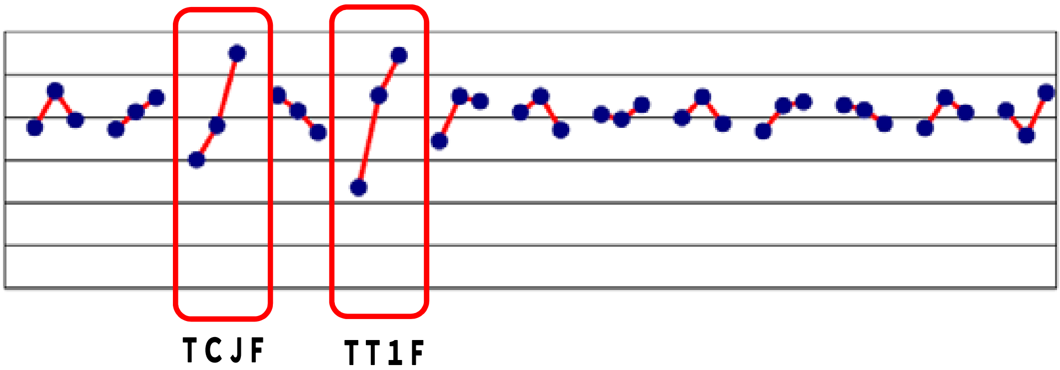

Fig. 10 Factor effect (ISP)

5. Future works

In the present study, variation of production, computation analysis are not considered. The margins of the evaluation functions and the sensitivities between the evaluation functions and the control parameters are calculated and visualized by engine system analysis for each case, and then the evaluation functions are optimized according to the system requirement.

6. Conclusion

The design process balancing engine performance, cost and reliability applied to the LE-X was planned. Factor effect analysis has conducted using L27 orthogonal array. And it is found that larger fuel injection temperature and FTP turbine inlet flow temperature leads to higher specific impulse.

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