Advanced Engineering Technology and Application
An International Journal

http://dx.doi.org/10.18576/aeta/080301

Optimization of Gas Generator Liquid Rocket Engine using an Advanced Mass Model

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Received: 24 Mar. 2018, Revised: 23 Jul. 2018, Accepted: 12 Nov. 2018
Published online: 1 Sep. 2019

Abstract: The conceptual design of Liquid rocket engine includes both performance and weight estimate considering mission requirements and constraints. In this study a design optimization strategy has been employed to obtain a suitable design for liquid rocket engine with gas generator cycles. Multi-objective optimization technique was used to maximize specific impulse and thrust to weight ratio by varying O/F and expansion ratio for a given chamber pressure. First the performance parameters are calculated followed by its mass estimation. In next step, FMINCON optimization technique is employed to get the best design. Two different mass estimation techniques are used in this study to find one which is more suitable for this purpose. First technique is based on an Empirical relation whereas second technique involves detailed calculation for every element with respect to a reference engine.
Results obtained show the compromise between the engine performance and thrust to weight requirements. The methodology developed in this article is beneficial in preliminary phase of system design to meet optimized performance and thrust to weight requirements.

Keywords: LPRE; Multi-objective optimization; FMINCON; mass estimation techniques

1 Introduction

The preliminary stage Liquid Propellant Rocket Engine (LPRE) design is a complex process, which includes not only maximizing performance along with its reliability but also minimizing cost and weight variables. These are all, however contradictory requirements which require deep insight into the design process. Optimization process to evaluate different candidate designs and compromises is therefore employed by the design engineers to select the best possible design. These variables may include chamber Pressure, nozzle contraction ratio, expansion ratio and oxidizer to fuel (O/F) ratio of propellants. Multidisciplinary Design Optimization techniques are increasingly being used for design optimization of space launch vehicle [1]. Different multi-objective methods have been employed to optimize the system parameters for gas-generator cycle engines [2,3]. Use of Genetic Algorithm [4,5] and particle swarm methods[6] have also been studied. Liquid Bi-Propellant Rocket Engine Design, Analysis and Optimization using different LPRE cycles has also been studied [7].Several mass estimation techniques are studied for initial design [8]. Based on historical data of engines, several empirical engine mass estimation relations for both pressure fed and pump fed engines have been investigated [9,10]. In this study two different mass models are investigated to optimize the design for gas-generator cycle engines using FMINCON optimization technique. The optimal solutions are identified using pareto frontiers to find impact of mass models used. The methodology used is discussed in detail in following section.

2 Method

The overall methodology consists of performance analysis of LPRE using thermodynamic and chemical equilibrium, mass estimation using two different weight models and finally applying design optimization technique.

3 Performance analysis

The chemical equilibrium analysis which calculates the thermodynamic properties of combustion products including specific heats, gas constant and temperatures is done using a legacy program [6]. The input is the

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combustion chamber pressure, Ambient Pressure at design altitude, Mixture ratio, Reactants, Expansion and Contraction Ratio. Based on these, LPRE performance is calculated which comprises of Specific Impulse, thrust coefficient and characteristic velocity.

4 Mass Model

Mass of system is a very important design constraint in optimization and must be calculated using some suitable method. Two strategies have been used in this regard. One is direct estimation of the engine mass as a whole and second is estimation of each of its elements. Both types of strategies are used in this study. For first case (case-1), an empirical method is employed to estimate engine mass as a whole [7]. For this case one relation for turbo pump system using cryogenic fuel is used which is as follows.

$$M = 0.06F^{0.858}Pc^{0.117}(Ae/At)^{0.034} \quad (1)$$

Here F, is the vacuum thrust in Newton, Pc the chamber pressure in bar and (Ae/At) is the nozzle area expansion ratio. This, however, does not directly include the effects in variation of mass flows and mixture ratios. A newly developed mass model [11] is engaged for detailed mass estimation to be used in design optimization (case-2). This model calculates mass of each element of engine as a function of different parameters with reference to an existing engine. In this was dimensionless coefficients can be used. Engine mass is the sum of all subcomponents

$$m_{engine} = \sum_{i=1}^{n}[m_i] \quad (2)$$

The overall model can be represented as

$$m_{engine}/m^0_{engine} = \sum_{i=1}^{n}\alpha_i[\prod_{j=1}^{m}(P_j/P^0_j)^{a_ij}] \quad (3)$$

The value of α distribute the components mass in the total engine mass and depend on the reference engine while $alpha_{ij}$ are the exponents which define influence of each parameter on each element mass. The third required constant is the mass of the reference engine. HM60 [12] is selected as the reference engine for this study using LOX-LH2 as propellants.

$$alpha_i = m^0_i/m^0_{engine} \quad (4)$$

The technique permits use of exponents in two ways. First is based on historical data obtained by mathematical adjustment and second by the use of design techniques in which the exponents of the expressions are fixed by the design rules. Former technique was used in this study with the assumption that same materials and manufacturing techniques will be used. As a consequence, material densities, strengths and factor of safety are all considered to be same. Reference engine was selected to have same propellants so the effects of different propellants on mass are not present. The parameters changed will be
I. Chamber Pressure
II. Throat radius
III. Area Ratio
IV. Mtotal
V. Mixture Ratio

5 Multi Objective Optimization

Multi-objective optimization searches for an optimum design that involves the minimization (or maximization) of more than one objective functions, which can be sometimes contradicting. So it is difficult to optimize all the objectives simultaneously. Another issue is that different objectives in multi-objective optimization usually have different measurement units and magnitudes. In the engine system parameters optimization, various techniques including changing weight method, e-constraint method [13], and the Neighborhood Cultivation Genetic Algorithm (NCGA) [14] have been adopted, for maximization of the engine specific impulse and the thrust to weight ratio. In this study, weighted sum method is used to maximize the specific impulse and the thrust to weight ratio using the following equation.

$$Obj = \alpha Isp/400 + (1-\alpha)F_{engine}/W/600 \quad (5)$$

alpha is used here to define weights and its value changes from 0.1 to 1. For lower value of alpha, the priority is to maximize thrust to weight ratio, while for 1,
priority changes to maximize Specific Impulse only. In between the two values, a compromise is made on both depending on the weight. Defining Objective function in this way, a gradient-based constrained optimization is performed using Matlab. One of its standard optimization tools, fmincon [15] is employed. This function minimizes a constrained nonlinear multivariable problem. The case selected is one on which particle swarm optimization has already been applied [6]. The conditions and design variables are shown in Table 1

Table 1: Optimization Case Definition

Parameter	Type	Value/Rang
Pc Chamber Pressure	Constant	10e6 Pa
Pa Ambient Pressure	Constant	50e3 Pa
Ac Contraction Ratio	Constant	3.5
Thrust	Constant	1025e3 N
Mixture Ratio	Design Variable	3.5 - 7.5
Expansion Ratio	Design Variable	5-70

Above stated problem with contraction ratio ranging from 1.5 – 3.5 as design variable, was optimized for Specific impulse only and results are given in table 2.

Table 2: Reference Results

Mixture Ratio	Expansion Ratio	Contraction ratio	Specific Impulse
4.46379	18.22399	3.5	416.83759

In this case only specific impulse was maximized. This study augments said optimization problem by including thrust to weight ratio as objective. Contraction ratio was kept constant as it tends to maximize in stated conditions

6 Results

the value of α, optimization is done and results obtained for both the cases are shown as pareto frontiers. Since a single optimum solution cannot be obtained, using these results the designer can select the optimal design according to his own requirements. The resulting pareto frontiers are shown in Fig1 and Fig2 for both the optimization cases. The results in tabular form are given in Table 3.

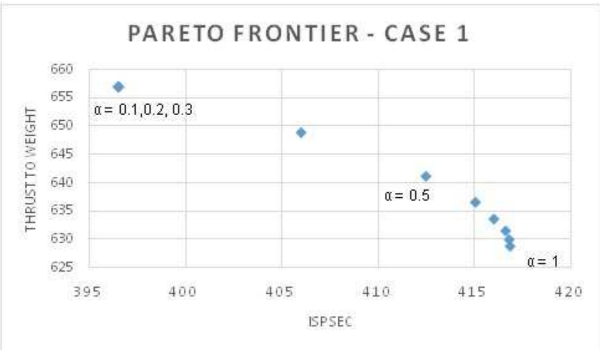

Fig. 1: A picture of Pareto frontier case1.

Case 1: It is seen that varying alpha from 01 to 0.3 doesn't affect the design much because it only considers expansion ratio for weight calculation. While O/F and expansion ratio both effect Isp.

Case 2: In addition to expansion ratio, mass flows and Mixture ratio also effect engine mass, so this model giver slightly different results at low Alpha value. At higher alpha values, behavior of both models is similar.

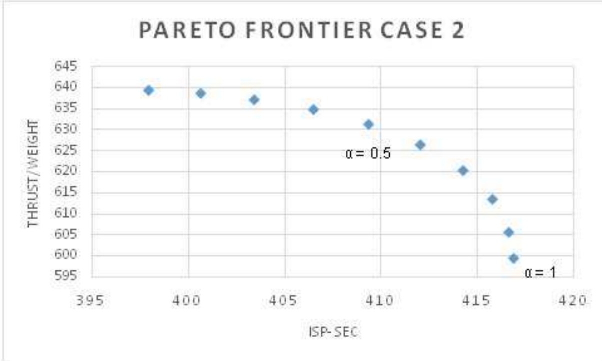

Fig. 2: A picture of Pareto frontier case2.

Table 3: Reference Results

Case	Alpha	Alpha=0.1	Alpha=0.5	Alpha=1
1	ISP	396.54	412.48	416.84
1	T/M	657	641.19	628.818
1	Mixture Ratio	3.8	4.144	4.457
1	Exp Rato	5	10.2612	18.205
2	ISP	397.92	409.32	416.83
2	T/M	639.92	631.42	599.32
2	Mixture Ratio	7.499	6.379	4.4575
2	Exp Rato	16.37	17.411	18.203

7 Conclusion

A code has been developed for findings/investigations of best solution for liquid rocket engine. Two type of mass models have been employed along with multi objective optimization strategy. Result is obtained in form of Pareto frontiers. System design of an already model optimized for Isp only was taken as case study and solved for multi objective scenario. The case-2 was found to be more effective for intermediate values of Alpha. Additional study with multiple mass models can be conducted to ascertain design parameters.

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