Numerical Optimization of 2D Scramjet Inlets

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Introduction

A scramjet engine is viewed as a promising propulsion system for a spaceplane, and significant research is in progress worldwide on scramjet engine design and performance. Japan Aerospace Exploration Agency (JAXA) has been conducting scramjet engine research at the flight conditions of Mach 4, 6 and 8 by using the RamJet engine Test Facility (RJTF). A free-piston high-enthalpy shock tunnel (HIEST), the largest in the world, was completed in November 1997. Scramjet Engine Testing in the range of Mach 8 to 15 has been conducted.

The design of an efficient compression system for an airframe-integrated scramjet engine is essential for acceptable performance of a scramjet airbreathing vehicle. The goal in the design of a scramjet inlet is to define a minimum weight geometry that provides an efficient compression process, and provides these characteristics over a wide range of flight and engine operating conditions. The design of a scramjet inlet is complicated by the many constraints, both aerodynamic and mechanical, that are imposed on the inlet. Examples of aerodynamic constraints include starting limits, boundary layer separation limits, and constraints on combustor entrance flow profiles. Examples of mechanical constraints include variable geometry flexibility and cooling system limits. The design of scramjet inlets is influenced greatly by vehicle and flight constraints.

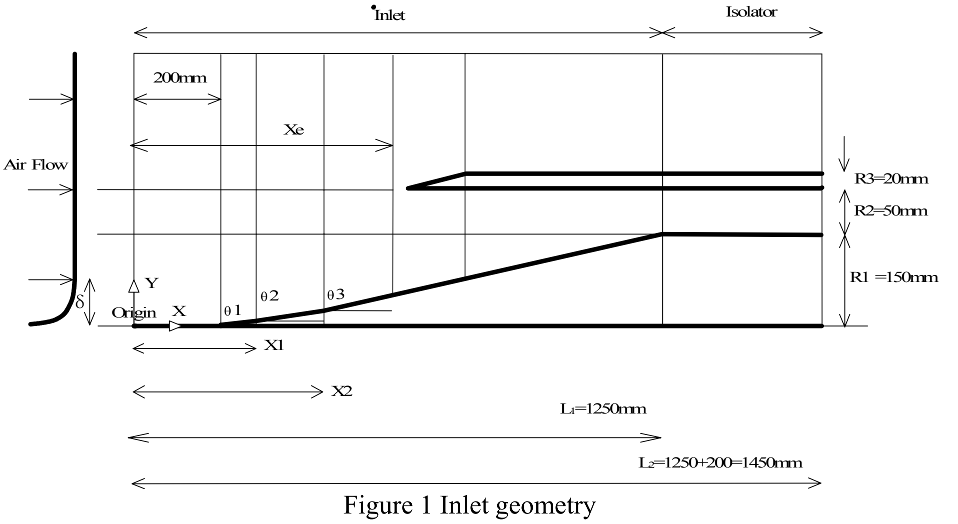

Figure 1 Inlet geometry

This paper focuses on the development and application of an efficient and powerful tool to optimize the aerodynamic performance of a 2D scramjet inlet. The 2D scramjet inlet configuration is presented in Fig.1. The scramjet inlet has three ramps. The computation of the flowfield inside the inlet is performed using the General Aerodynamic Simulation Program (GASPex). In our computations, the inviscid flux scheme is Roe's Method with third-order spatial accuracy restruction using the Min Mod limiter. Turbulence model is represented by the Wilcox k-omega model. A steady state solution is obtained by applying Gauss-Seidel relaxation scheme.

The flowfield inside the inlet is calculated numerically including all relevant flow features such as the interactions between shock waves and expansion waves. The calculated Mach number distribution is shown in Fig.2.

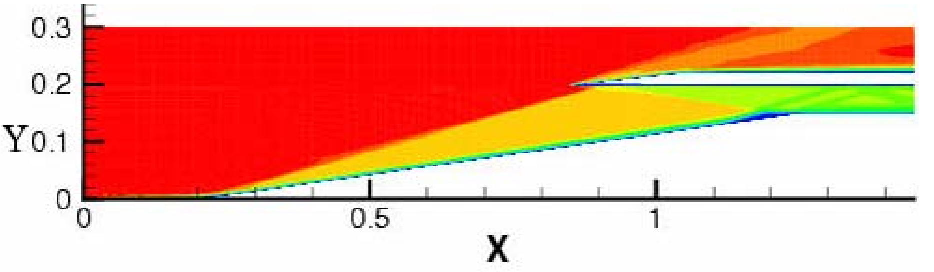

Figure 2 Calculated Mach number distribution

Optimization Algorithm

We consider the general nonlinear problem

$$\text{minimize } F(x) \text{ (or maximize } F(x) \text{) subject to } G(x) \leq 0$$

where x = $(x_1, x_2, \ldots, x_n)$ is the vector of design variables, F(x)is a scalar function and G (x) is a vector-valued set of nonlinear constraints. F(x) is the fitness function characterizing how much the shape suits the optimization problem. G(x) represents all the constraints of the problem. The design variables x_i are typically geometric parameters defining the inlet shape (*e.g.*, lengths and angles).

There are two families of optimization algorithms. One family is local algorithms such as gradient methods. Another family is constituted by global algorithms such as genetic algorithm (GA), and simulated annealing (SA). In our research, the optimization of the 2D scramjet inlet began to be performed by the gradient-based algorithms. From a basic shape, the gradient-based algorithms are able to quickly find an optimum. However, they have some drawbacks that make their use difficult for complex industrial problems. They can easily be trapped by local minima. The method used is C code for feasible sequential quadratic programming (CFSQP). CFSQP is a set of C functions for the minimization of the maximum of a set of smooth objective functions (possibly a single one) subject to nonlinear equality and inequality constraints, linear equality and inequality constraints, and simple bounds on the variables.

In this optimization program, the objective function is the total pressure recovery η. To maximize the total pressure recovery is as same as to maximize the kinetic energy efficiency. The geometrical constraints are linear inequality constraints, and a nonlinear equality constraint, which are shown in the following.

$$0 \le \theta_1 \le \theta_2 \le \theta_3 \text{ (radians)}, 0.2 \le X_1 \le X_2 \le 1.25 \text{ (m)}, 0.2 \le Xe \le 1.25 \text{ (m)}$$
$$(X_1 - 0.2)\tan(\theta_1) + (X_2 - X_1)\tan(\theta_2) + (1.25 - X_2)\tan(\theta_3) = 0.15 \quad \text{(m)}$$

Scramjet Inlet Optimization

To perform the scramjet inlet optimization, our first step was to optimize the inlet assuming uniform inflow condition. The initial total pressure recovery coefficient η is obtained as 0.545. Depending on the runs, from 5 to 13 line searches were performed during these optimizations. The maximum value obtained by these computations is η_{max} =0.599. The maximum value is higher than the initial value by 9.9%. Then, the optimization was performed in case that the inflow boundary layer δ is 61.7mm. The initial total pressure recovery η is 0.575, and the maximum value obtained by these computations is η_{max} =0.626. The maximum value is higher than the initial value by 8.9%. Further optimized results and discussion will be presented in the conference.