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Simplified procedure for controlling pressure distribution of a scramjet combustor

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Abstract Scramjet engines are used at extreme temperatures and velocity. New control problems involving distributed parameter control have been found concerning investigations of the control of scramjet engines whose physical states are spatially interacted. Succeeding the existing theoretical studies on the distributed parameter control for scramjet engines, this paper puts forward a simplified distributed parameter control approach for scramjet engines aimed at engineering application. The simplified control procedure uses the classical proportional-integral (PI) compensation to control the target pressure distribution of scramjet engines, which is effective and applicable for practical implements. Simulation results show the validation of the simplified distributed parameter control procedure.

1. Introduction

Recent breakthrough in the hypersonic flight experiments of scramjet engines has greatly provided the motivation for research on engine control technologies. To achieve hypersonic flight test objectives of accelerating the scramjet engines under controlled autonomous free flight, automatic control of the engines should be required. As the development of scramjet system is quite complex and it involves a number of technological challenges, many principles and methods have been put forward and applied to solving the key problems related to the mixture of very high speed air with fuel, achieving stable ignition and flame holding in addition to ensuring efficient combustion within the practical length of the combustor.[1] Correspondingly, some problems and methods have also been proposed in studying the control of scramjet engines. In terms of inlet control of scramjet engines, Voland et al.[2] presented the control problems in the CIAM/NASA Mach 6.5 scramjet flight test, in which the engine control system made error identification on inlet operation mode, which resulted in the part failure of flight test. Rodriguez[3] numerically interpreted the reasons about the error identification of inlet operation mode, and presented nonlinearity problem involving in the control of inlet operation mode. Jones and Baumann[4] evaluated the performance of the inlet controller for the scramjet engines by Monte Carlo technology, and the Monte Carlo data

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obtained from simulations predicts that utilizing the unstart protection logic significantly reduces the risk of unstart by keeping the isolator margin at or above its desired value. In terms of combustion control of scramjet engines, as scramjet engines are used with wide range of Mach numbers, the combustion control system must inject the fuel so that its heat release profile will produce the required combustor pressure distribution at each Mach number. The critical problems of matching heat release profile to combustor pressure distribution over a wide speed range have early been proposed when Ferri[5] created the concepts that tailor the aerothermodynamics of fuel injection, mixing and diffusive combustion to the desired engineering features of the fixed geometry scramjet engines. However, Voland presented that the combustion control goal was not achieved in the CIAM/NASA Mach 6.5 scramjet flight test even though pretest predictions by both CIAM and NASA indicated supersonic combustion mode would be achieved. This means there are difficulties in the control of the complex supersonic combustion system.

Modern aeronautical propulsion systems, such as turbojet and ramjet engines, being multivariable in nature require more complicated control mechanisms and better control strategies for enhanced control over the variables to ensure the improved performance of the plant.[6–8] Hence, new control techniques like linear feedback, optimal control, fuzzy control and sliding mode control etc., are being investigated in literature. These control technologies are still in the frame of lumped parameter control, in which the characteristic variables can be found and chosen to represent the distributed parameter nature of the system by ordinary differential equations instead of partial differential equations. However, it is not certain for scramjet engines if lumped parameter control can achieve the designate performance for the complex spatial interaction of the supersonic flow and supersonic combustion where the spatial effects cannot be neglected,[9] because scramjet engines are such systems with obviously distributed parameter properties characterized by complex scramjet combustion and inlet-combustor interactions along the flow field. The flow field in a scramjet engine is transitional over a wide range of speed, and in this range engine performance is characterized by complex transitional fluid dynamics, supersonic/subsonic flows with the corresponding shock fields,[10] coupled heat release/shock generation, combustion thermodynamics and chemical reactions.[11] So there are benefits from thinking scramjet engines in terms of continuum mechanics with distributed parameter control. To help solve the problems existing in the combustion control of scramjet engines, Daren et al.[12] and Tao et al.[13] made some suggestions from a viewpoint of applying distributed parameter control technologies to the control of scramjet engines, and the studies have provided an initial proof of the validity of distributed parameter control for scramjet engines. However, from a viewpoint of engineering application, the proposed distributed parameter control arithmetic is in need of computation of the sensitivity function to provide the gradients of the objective function, and is computationally expensive and complex. It is for these reasons that the methods cannot be directly used for engineering application. Based on this consideration, this paper makes an effort to find simplified ways for engineering application of the control idea. As a result, the simulation results have shown the validities of the simplification.

2. Simplified distributed parameter control arithmetic

The schematic illustration of the previous shape control procedure for scramjet engines may be shown in Fig. 1.[13]
where x is the axial coordinate, $M_t(x)$ is the target shape, $M(x)$ is the feedback shape, T denotes the sampling switch, τ is stagnation temperature rise ratio, $D(z)$ is the digital controller, $S(x)$ is the sensitive function, and L is the time constant of the actuator.

The control problem is to minimize the objective function defined as the squared difference of displacements between the desired and the actual shape, that is

$$J(\tau) = \frac{1}{2}\int_{x_1}^{x_2} (M(x,\tau) - M_t(x))^2 \mathrm{d}x \tag{1}$$

where $M(x,\tau)$ is the feedback shape, x_1 and x_2 denote the entrance and exit of the combustor respectively. Shape control problem can be formulated as finding an optimal control variable τ^* to minimize this objective function

$$J(\tau^*) \leqslant J(\tau) = \frac{1}{2}\int_{x_1}^{x_2} (M(x,\tau) - M_t(x))^2 \mathrm{d}x \tag{2}$$

In order to further develop the distributed parameter control idea for scramjet engines, this paper attempts to make some simplification on the control arithmetic to make it possible for engineering application. As shown in Eq. (1), although the control objective is to approach the target parameter distribution, the objective function is just a norm that describes the distance between the feedback parameter distribution and the target parameter distribution. The norm, in a sense, is a lumped parameter. If the mathematic relations can be directly constructed between the control variable and the norm, we can transform the distributed parameter control problem into a lumped parameter control problem. Thereby the classical lumped parameter control methods may be applied to this problem, and the control arithmetic may thus be greatly simplified. Starting from this point, we make a transformation of the control procedure in Fig. 1 into the simplified control procedure as shown in Fig. 2, in which the function relations are constructed between the equivalence ratio Φ (control variable) and the output parameter R. To be measurable, we select the wall pressure distribution $P_w(x)$ as the state parameters. Then the output parameter R may be defined as the difference of displacements between the desired and the actual pressure distribution, that is

$$R(\Phi) = \int_{x_1}^{x_2} (P(x,\Phi) - P_t(x))\ \mathrm{d}x \tag{3}$$

where $P(x,\Phi)$ is the feedback pressure distribution, and $P_t(x)$ is the target pressure distribution.

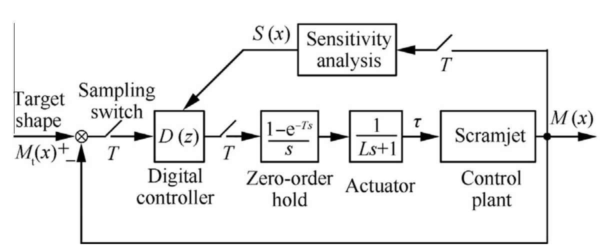

Fig. 1 Schematic illustration of shape control arithmetic for scramjet engines.