Response Evaluation of Scramjet Engine System Using Dynamic Simulator

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論 文 内 容 要 旨

Research on transportation systems equipped with scramjet engines has been further accelerated in recent years. The scramjet engine, whose research began in World War II, has been successfully flight-tested in real-world conditions since the beginning of 2000 with the X-43A and X-51A engines. The fuel for the X-51A was jet fuel. The flight demonstration test using inexpensive and easily manageable fuel has brought us much closer to the practical application of a transport plane equipped with a scramjet engine. In Japan, ground tests have been conducted at the Kakuda Space Center of the Japan Aerospace Exploration Agency (JAXA) using a wind tunnel facility for high-enthalpy flow. Furthermore, the launch experiment of S-520-RD1 was conducted on July 24, 2022. During the descent, the vehicle was accelerated to a flight Mach number of 5.5, and supersonic combustion using ethylene was conducted under realistic conditions. The launch experiment was successful. The results of this experiment will accelerate research and development in the practical application of the scramjet engine.

Among the future steps toward the commercialization of the scramjet engine is a demonstration test of a scramjet engine with an engine cycle system. However, there are high hurdles to overcome before a demonstration test can be conducted. One of them is to understand the dynamic characteristics of the scramjet engine with the engine system. Understanding the dynamics in the system during startup, shutdown, and fuel flow control is very important for the development of control laws for fueling systems. However, repeated ground tests to establish control laws for the fuel supply system under transient conditions are very costly and time consuming. In addition, ground tests cannot simulate changes in flight conditions. Therefore, it is necessary to reproduce the state changes of the entire engine system in order to construct a control law for non-stationary conditions. In this study, a dynamic simulator was developed to understand the dynamic characteristics of the entire engine system of a scramjet engine. The developed dynamic simulator was then tested in two ground tests

to verify the dynamic characteristics of the fuel in the fuel supply system. Then, using the validated dynamic simulator, the state of fuel in the fuel delivery system was analyzed for a scramjet engine modeled after the X-51A in accordance with the flight profile. As a question that arose from this analysis, it was necessary to investigate the combustion characteristics during system startup.

In Chapter 3, Hypersonic Engine Dynamic Simulator (HEDS) is developed as a dynamic simulator for scramjet engines in previous studies. The volume junction method was introduced to calculate the fuel physics inside fuel supply system using multiple CPUs. A system had been established to output calculation results in a short period of time. After the explanation of the dynamic simulator, fuel supply system simulating an engine system was constructed to confirm the reproducibility of the HEDS. Two types of tests were conducted using the system including a cooling panel. In the first test, no-heated fuel flowed into the cooling panel and high enthalpy flow flowed into the combustor. During the first test, the fuel flow rate was controlled by a valve to vary the fuel temperature after passing through the cooling panel. In the second test, the heated fuel flowed into the cooling panel and injected into the combustor through the injection port and was burned by forced ignition with a torch. The two experiments were compared with the results of the dynamic simulator analysis. Comparison between the analytical results of the dynamic simulator and the measured data enables us to reproduce the condition of the fuel after passing through the cooling panel. Therefore, the heat fluxes received by the cooling panels from the combustion gas and the heat fluxes received by the fuel passing through the cooling panels could be estimated.

In Chapter 4, a dynamic analysis of a hydrocarbon-fueled scramjet engine is conducted using the X-51A as a model. HEDS was modified to adopt the X-51A flight profile. In order to predict the flow state after the passage of the inlet, a model using the shock wave relation in two dimensions is introduced. Then, a combustion efficiency model with hydrocarbon fuels was applied to the quasi-one-dimensional analysis in the combustor. In the analysis, two cases were compared: one in which the fuel flow rate is controlled by changing the pump speed and the valve opening degree, and the other in which no control is applied. The results show that the identification of engine system failure events and changes in fuel conditions affect the system control.

In Chapter 5, a method to sustain stable combustion during engine system startup was investigated for the flight demonstration test of the scramjet engine. In the experiments, two air flow conditions were selected from the range of flight Mach number from 4.5 to 5.0. With reference to the X-51A mission configuration, Mach 4.5, which is the flight Mach number during system startup, and Mach 5.0, which is the flight Mach number during acceleration, were adopted. Dodecane, the surrogate fuel of Jet-A, was used as the fuel. Parameters such as fuel

temperature, pilot fuel, and fuel equivalent ratio were varied and comprehensively investigated flame holding of dodecane. From the test results, it was found that it was necessary to heat the dodecane and vaporize the injected dodecane to sustain combustion in case without pilot fuel. Dodecane at room temperature was injected simultaneously with the pilot fuel to maintain sustained combustion. As a suggestion for the engine system startup method, how to heat dodecane before moving to the acceleration phase was discussed.