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Thrust, Lift, and Pitching Moment of a Scramjet Engine

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Combustion tests of a scramjet engine were conducted to obtain thrust, lift, and pitching moment essential for evaluation of the engine's basic performance and for determination of the requirements to control the system of integrated engine and body. The engine was a side-compression type with a swept-back angle of 45 deg, and the inlet was open on the cowl side. Thrust, lift, and pitching moment were measured safely by a force measuring system under Mach 4, 6, and 8 simulated flight conditions including engine unstart. Measurements changed with transition of combustion conditions. Thrust decreased and lift increased suddenly when the engine fell into unstart conditions in the M6 and M8 tests although the change was gradual in the M4 tests. Effects of engine configurations were also investigated. Installation of a full-height strut improved combustion performance but increased drag more than thrust.

Introduction

A SCRAMJET engine to be used for future space planes has been tested under Mach 4, 6, and 8 flight conditions at the National Aerospace Laboratory Japan, Kakuda Research Center.[1–6] Knowledge of thrust, lift, and pitching moment is essential for evaluation of the engine's basic performance and for determination of the requirements to control the system of integrated engine and body. However, open literature reporting measured forces and moments of hypersonic engines are few. Even in the reported cases,[7,8] axis value is missing.

The scramjet engine tested in the present study is a side-compression type with a swept-back angle of 45 deg. To improve starting performance, the leading edge of the engine cowl is set rearward from the entrance of the intake by opening the cowl side passage of the intake. Hence, even when there is no change in attack angle, lift and pitching moment, as well as thrust of the engine, are expected to be affected by changes in the engine operating conditions. Especially, when the engine falls into conditions of unstart, pressure distribution in the engine changes drastically, causing rapid changes in thrust, lift, and pitching moment.

In the present study the effects of flight Mach number, fuel flow rate, and engine configuration on thrust, lift, and pitching moment of the scramjet engine were investigated by means of a force measuring system (FMS). Pressure distributions on the engine walls were used to analyze the causes of measured force variations.

Before the engine combustion tests, static load transmission tests and dynamic response tests of the FMS lock system were conducted to ensure safe combustion tests. After confirmation that the estimated peak loads were within the maximum load cell capacity, measurement by the unlocked FMS was conducted.

Test Facility and Test Article

Tests of the scramjet engine were carried out in a ramjet engine test facility[9] (RJTF). Three types of nozzles—M3.4, M5.3 and M6.7 (corresponding to M4, M6, and M8 flight conditions)—were used in the RJTF. Test conditions for each Mach number are shown in Ref. 9. The exits of the nozzles of the RJTF were square (510×510 mm). Figure 1 shows the test section of the RJTF. The scramjet engine was installed on an FMS. The blockage ratio of the scramjet engine including side-wall fairing and cowl thickness was about 25%. The test section was evacuated by steam ejectors.

After confirming the start of intake, the fuel flow rate of gaseous hydrogen was changed discretely. Fuel was injected and increased until unstable oscillating phenomena appeared. The flow rate was either increased, decreased, or alternately increased and decreased in order to investigate the hysteresis phenomenon.

Figure 2 shows an outline of the three-component force and moment measurement system. Two load cells in the front and a load cell in the rear were installed vertically, and one more load cell was installed horizontally. With these four load cells thrust (FT), lift (FL), and pitching moment (MP) were measured. Because the engine was installed upside down on the FMS as shown in Fig. 1, counterclockwise motion is nose up. Nose-up pitching moment was defined to be positive as shown in Fig. 2. The FMS was calibrated by an internal calibration system in every test series.

It is usual for a fluctuating load that is several times larger than steady load to be imposed on the load cells of an FMS by starting loads or engine unstart loads.[10,11] Therefore, initially, combustion tests were conducted under locked conditions of the FMS for safety. The amplitude of the large fluctuating loads was estimated before unlocked tests by using the test results under locked conditions and the force transmission rate of the FMS lock system.

The lock system was comprised of conical pins on the grounding frame and mating plates on the floating frame. The conical pins were actuated by hydraulic actuators to mate with the mating plates. The lock system transmitted the force imposed on the engine rather linearly to the load cells as will be shown later.

Figure 3 shows the scramjet engine tested. Its overall length was 2100 mm. The width of the entrance was 200 mm. The height of the entrance was 250 mm. The exit width and height were the same as those of the entrance. The engine was composed of four components; inlet, isolator, combustor, and nozzle. The inlet was a side-wall compression type with a six-deg half-wedge angle and a contraction ratio of 2.9. The leading edge of the inlet was swept back 45 deg to deflect the airstream for suitable spillage required for starting at low Mach numbers. Hydrogen fuel was injected by four injectors: main parallel, main vertical, pilot side-wall, and pilot top-wall injectors. In this report only the test results of the vertical injection are presented. Two plasma torch igniters of 2.5 kW were used for ignition at the top wall. To obtain better performance, strut height and thickness were changed according to the test Mach numbers. Isolator length was extended from 100 to 200 mm to improve the engine unstart limit in the cases of M4 and M6.

Test Results and Discussion

Force Transmission Coefficient of the Lock System

Before the combustion tests of the engine under unlocked conditions of the FMS, static load transmission tests and dynamic

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Table 1 Test conditions and test results without fuel injection

Mach number	Configuration	Thrust coefficient	Lift coefficient	Pitching-moment coefficient
4	Without strut	-0.324 ± 0.008	0.0289 ± 0.005	0.0226 ± 0.0007
6	$\frac{1}{5}$-height strut	-0.198 ± 0.001	0.0058 ± 0.0001	0.0084 ± 0.0001
6	30-mm-thick full-height strut	-0.256	0.0178	0.0027
8	30-mm-thick full-height strut	-0.248 ± 0.011	0.0121 ± 0.0014	0.0035 ± 0.0006
8	46-mm-thick full-height strut	-0.312 ± 0.008	0.0176 ± 0.0012	0.0020 ± 0.0004

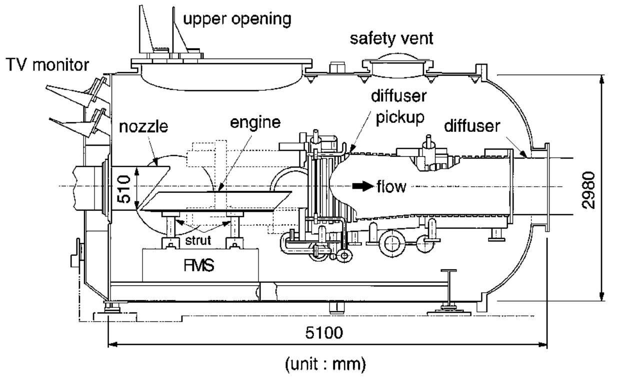

Fig. 1 Test section of the RJTF.

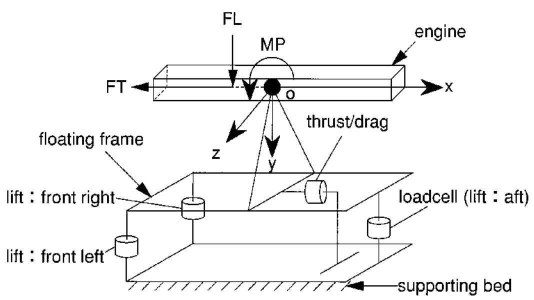

Fig. 2 Force measurement system.

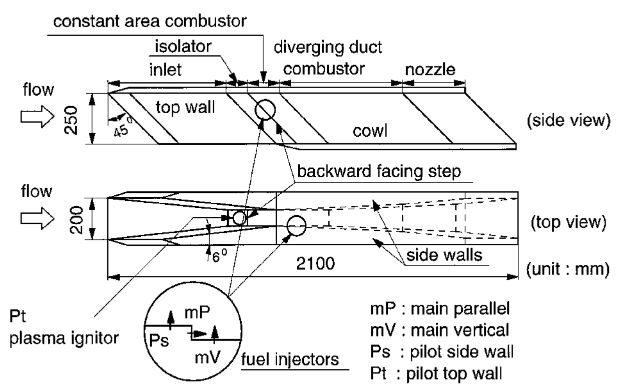

Fig. 3 Scramjet engine.

response tests of the FMS lock system were conducted. Figure 4 shows the static load transmission test results. Static load was imposed on the engine in the thrust direction by a jack through a load calibrator. Uncertainty of the FMS was ±20N. The force imposed on the engine transmitted rather linearly to the load cells. The load transmission rate of the lock system of the FMS was determined to be 0.37.

The frequency response function of the FMS was also investigated by an impulse hammering test. Its resonant frequency was 14 Hz, and the gain at this frequency was 16.3 under unlocked conditions. When the FMS was locked, the resonant frequency increased to 20 Hz, and the gain at this frequency decreased to 5.6. Peak gain was reduced to 34% of unlocked conditions by the lock system.

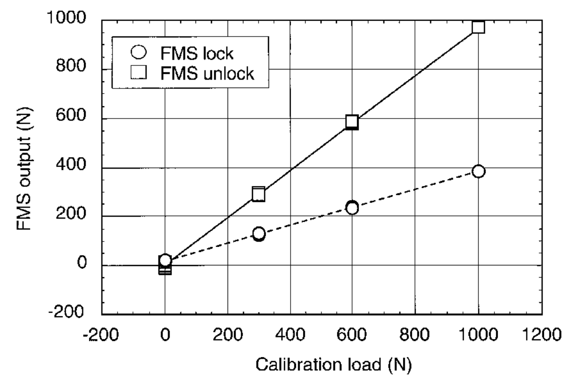

Fig. 4 Force transmission coefficient of the FMS lock system.

Test Results of No Fuel Injection

Table 1 shows Mach numbers and engine configurations of the tests carried out in the RJTF. Thrust, lift, and pitching-moment coefficient under test conditions without fuel injection are also shown in Table 1. The standard deviation is indicated after the ± symbol in the cases in which there was more than one sample. Thrust coefficient is defined as the thrust divided by the dynamic pressure of the freestream and inlet cross-sectional area (200 × 250 mm). Lift coefficient is defined as the lift divided by the dynamic pressure of the freestream and the engine planform area (200 × 2100 mm). Pitching-moment coefficient was defined as the pitching moment divided by the dynamic pressure, the engine planform area, and engine total length (2100 mm). Pitching moment was measured around the z axis in Fig. 2. The location of the z axis was 741 mm from the leading edge of the engine top wall in the x direction and −136 mm from the top wall in the y direction (i.e., almost the centerline of the cross section of the inlet exit).

Thrust coefficient was greatly decreased by installation of the tall strut or the thick strut. In the M6 case the thrust coefficient decreased 29% from −0.198 to −0.256 when the $\frac{1}{5}$-height (50-mm) strut was replaced by the full-height (250-mm) strut. When the thickness of the strut was increased from 30 mm (contraction ratio of 5.0) to 46 mm (contraction ratio of 8.3) to improve combustion performance by increasing combustion pressure in the M8 tests, the thrust coefficient decreased 26% from −0.248 to −0.312. Because the thrust coefficient is decreased by installation of the tall strut or the thick strut, it is necessary to optimize the configuration of the strut to obtain a compromise between the improvement in combustion efficiency and performance deterioration caused by drag increase.

In the M4 tests the thrust coefficient was less than obtained in the M6 and M8 tests although a strut was not installed in the case of the M4 tests.

The lift coefficient increased from 0.0058 to 0.0178 when the strut height was increased from the $\frac{1}{5}$ height to the full height of the inlet flow passage at Mach 6. The lift coefficient of the test result with a strut of 30 mm thickness, 0.0121, changed to 0.0176 when the strut thickness was increased to 46 mm at Mach 8.

The pitching-moment coefficient was less than 0.01 in the tests of M6 and M8. In the M4 test the pitching-moment coefficient was 0.0226. This value was larger than those of the M6 and M8 tests because of the higher level of pressure in the inlet.

Computational fluid dynamics results and thrust coefficient measured in $\frac{1}{5}$-scale model cold-flow tests in a small wind tunnel are presented in Ref. 12.

Combustion Test Results of Thrust, Lift, and Pitching Moment

M4 Tests

Figure 5 shows variation of thrust, lift, and pitching-moment coefficient at M4 conditions for various fuel flow rate conditions with no strut.[1] The stoichiometric flow rate of gaseous hydrogen is 193 g/s for an air capture ratio of 0.72 (Ref. 13).

Uncertainty of H2 flow rate was ±0.8%. Uncertainties caused by force measurement error were ±0.007 for the thrust coefficient, ±0.0006 for the lift coefficient, and ±0.0009 for the pitching-moment coefficient.

Three-component force and moment changed greatly when the fuel flow rate was increased to more than 50 g/s. At less than 50 g/s, weak combustion near the top wall was observed by examining the pressure temperature distributions. However, at rates greater than 50 g/s, intensive combustion was achieved; the resulting plume spread over the whole exit area of the engine. As a result, combustion pressure rose extensively. The former combustion mode is called weak, and the latter is termed intensive.[2]

Figure 6 shows the change of pressure distribution on the top wall of the engine when the fuel flow rate was increased under M4 conditions. Part of the plotted data corresponds to the data shown in Fig. 5. The pressure distribution of the zero flow rate corresponds to that of the M4 case of Table 1.

With the increase in fuel flow rate in the intensive combustion mode, thrust decreased gradually as shown in Fig. 5. In this condition the high-pressure region gradually moved upstream into the inlet. Oscillating pressure measured by wide-band pressure sensors in the inlet showed that the values of pressure in the inlet oscillated between the values of start and unstart conditions.

Extension of isolator length from 100 to 200 mm was effective to suppress unstarted conditions although it was not enough.[1]

With a further increase in fuel flow rate, the thrust coefficient increased from −0.132 at 86 g/s to −0.066 at 100 g/s. When this change occurred, the thrust coefficient determined by wall pressure integration did not increase, but continued to decrease. For this case pressure in the base region of the fairing, which covered the engine supporting strut, increased and caused an increase of the thrust measured by the FMS. Therefore, it was concluded that the thrust generated by the engine continued to decrease with the increase of the fuel flow rate.

When the combustion mode changed from weak to intensive, the lift coefficient decreased from 0.0126 at 42 g/s to 0.0056 at 54 g/s as a result of the increase in combustion pressure in the cowl side region. The pressure increase in the cowl side region caused the lift component to increase in negative direction. With a further increase of the fuel flow rate, the lift coefficient increased. This was caused by the increase of pressure in the inlet because of the gradual growth of engine unstart strength brought about by the increase of the fuel flow rate. The pressure increase in the inlet directly caused an increase of lift because the cowl side was open in this engine.

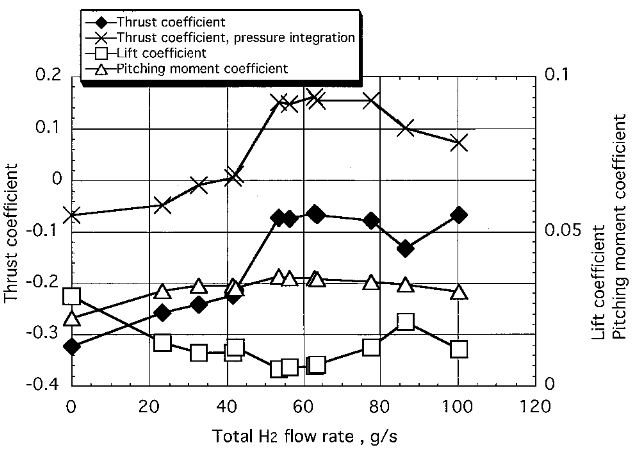

Fig. 5 Thrust, lift, and pitching moment of the M4 test.

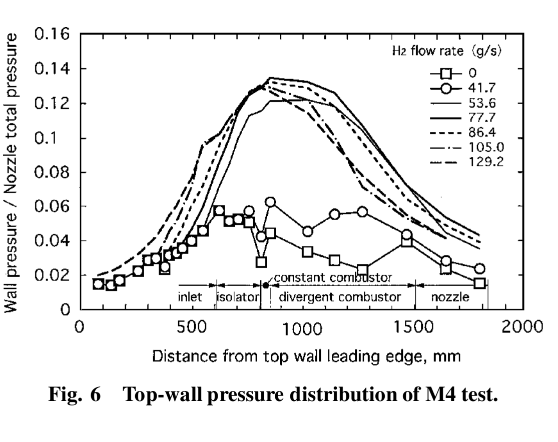

Fig. 6 Top-wall pressure distribution of M4 test.

M6 Tests

Figure 7 shows variations of thrust, lift, and pitching-moment coefficient for various fuel flow rates under M6 conditions. A $\frac{1}{5}$-height strut was installed in the engine.[3] The stoichiometric flow rate of gaseous hydrogen is 153 g/s for an air capture ratio of 0.87 (Ref. 13).

Uncertainty of H2 flow rate was ±0.8%. Uncertainties caused by force measurement error were ±0.003 for the thrust coefficient, ±0.0004 for the lift coefficient, and ±0.0006 for the pitching-moment coefficient.

When the fuel flow rate was increased, the combustion mode changed from weak to intensive at a fuel flow rate of 100 g/s. At this flow rate the thrust increased steeply, and a positive value of the thrust coefficient, 0.075, was achieved. With a further increase of the fuel flow rate, the engine suddenly fell into unstart conditions, and the thrust had a value close to the value with no fuel injection.

When the fuel flow rate was decreased from 100 g/s, combustion was unstable near 100 g/s, but the intensive combustion mode was reestablished steadily from 92 g/s down to 50 g/s, and a maximum thrust coefficient of 0.09 was obtained at 92 g/s. This hysteresis phenomenon and the sudden unstart characteristic were not observed under M4 conditions.[1,3] Therefore, in the case of M6 conditions, control necessary to cope with the change of forces and moments is more difficult than under M4 conditions.

The tendency of decrease in lift coefficient with the change of combustion mode from weak to intensive was the same as that in the M4 conditions. The pitching-moment coefficient increased with the change of the combustion mode from weak to intensive.

Consider the change of pitching moment together with the change of lift: in the case of started conditions, pressure distribution in the inlet remained constant. Pitching moment generated in the combustor and internal nozzle increased because combustion pressure in the cowl side region increased, and it increased the lift component in the negative direction as in the case of M4.

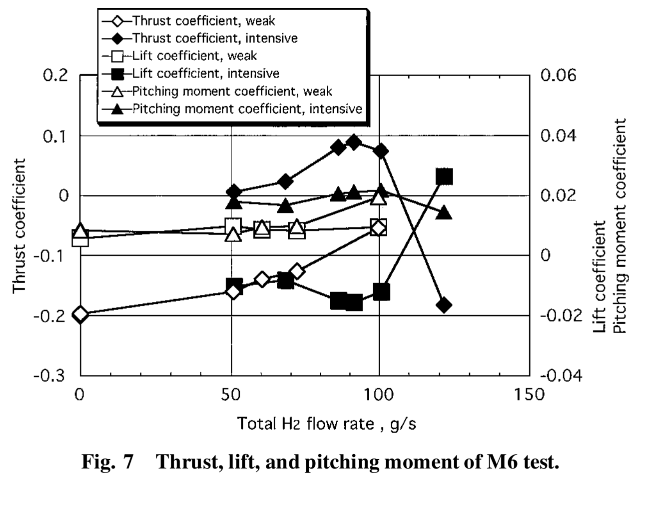

Fig. 7 Thrust, lift, and pitching moment of M6 test.

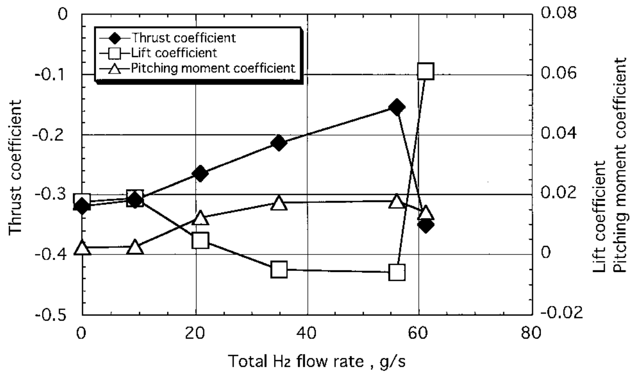

Fig. 8 Thrust, lift, and pitching moment of M8 test.

When the engine fell into unstarted conditions, pitching moment and lift increased as a result of the pressure rise in the inlet. However, at the same time combustion pressure in the cowl side region decreased, and pitching moment generated in the combustor and internal nozzle decreased. Therefore, the change of pitching moment caused by engine unstart conditions was considerably mitigated. On the other hand, lift changed greatly because it increased with pressure reduction on the cowl side in the combustor and internal nozzle in addition to the lift increase in the inlet.

The range of variation of the lift and moment coefficients, respectively, with the change in operating conditions for the weak and intensive combustion modes and unstart was from −0.0157 to 0.0265 and 0.0072 to 0.0217.

M8 Tests

Figure 8 shows variations of thrust, lift, and pitching-moment coefficient for various fuel flow rate conditions for the M8 conditions.[5] A full-height strut with a thickness of 46 mm was used for the scramjet engine. In the case of a full-height strut with a thickness of 30 mm, intensive combustion was not achieved.[6] The stoichiometric flow rate of gaseous hydrogen is 51 g/s for an air capture ratio of 0.91 (Ref. 13).

Uncertainty of H2 flow rate was ±0.8%. Uncertainties caused by force measurement error were ±0.022 for the thrust coefficient, ±0.0011 for the lift coefficient, and ±0.0010 for the pitching-moment coefficient. In the case of M8 tests, the engine was cooled by water although it was not cooled in the case of M4 and M6 tests. Plumbing of the coolant increased the error of the force and moment measurement.

With the increase in fuel flow rate, thrust increased linearly. This result was different from the test results of M4 and M6 conditions. In the case of the M4 and M6 conditions, thrust increased suddenly when the combustion mode changed to the intensive mode from the weak mode.

The engine fell into unstarted conditions more suddenly than for M6 case. When the engine fell into unstart conditions at the fuel flow rate of 61 g/s, the thrust coefficient decreased to −0.35, which was lower than the value for no fuel injection.

With the increase in fuel flow rate, the lift coefficient decreased. This tendency was similar to the test results of M4 and M6. It was caused by the increase of the combustion pressure in the cowl side region similar to the cases of M4 and M6. Lift coefficient suddenly increased to 0.061 from −0.006 (because of engine unstart) when the fuel flow rate was changed from 56 to 61 g/s. The change of lift coefficient under M8 conditions was larger than that under M4 and M6 conditions because of stronger shock generation caused by unstart.

The tendency of a slight increase in pitching-moment coefficient with the increase of combustion pressure was similar to that found in M4 and M6 tests. The pitching-moment coefficient did not change as much as the thrust coefficient and lift coefficient when the engine fell into unstart conditions. This is explained by noting the fact that a part of the increase of pitching moment in the inlet caused by unstart was cancelled by the decrease of pitching moment in the combustor. The decrease of combustion pressure in the cowl side region decreased the pitching moment generated in the combustor.

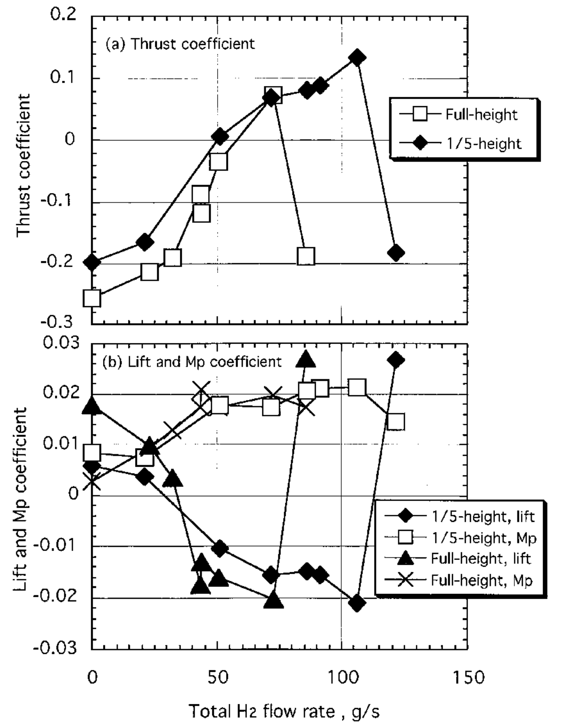

Fig. 9 Effects of strut height of M6 test.

Effects of Strut Configuration

Figure 9 shows a comparison between the $\frac{1}{5}$-height strut and the full-height strut for the M6 tests. In Fig. 9a, the thrust coefficient of the $\frac{1}{5}$-height strut with no fuel injection was larger than that of the full-height strut. The maximum thrust coefficient of the $\frac{1}{5}$-height strut was superior to the full-height strut. On the other hand, thrust coefficient with the full-height strut increased with fuel flow rate more rapidly than that of the $\frac{1}{5}$-height strut, and it decreased at a fuel flow rate lower than that of the $\frac{1}{5}$-height strut.

Distributions of equivalence ratio and combustion efficiency were measured at the exit of the engine.[3] The full-height strut was effective to improve fuel distribution and combustion efficiency. Thus, the full-height strut improved combustion performance and thrust, but increased drag more than thrust increase.

As shown in Fig. 9b, the lift coefficient of the full-height strut with no fuel injection was larger than that of the $\frac{1}{5}$-height strut. The lift coefficient of the full-height strut decreased with fuel flow rate more rapidly than that of the $\frac{1}{5}$-height strut; this corresponds to the rapid change of the thrust coefficient. The variation in lift and pitching-moment coefficient with thrust coefficient variation was similar for both $\frac{1}{5}$-height strut tests and full-height strut tests.

Conclusions

Combustion tests of the side-compression-type scramjet engine with a swept-back angle of 45 deg were conducted under Mach 4, 6, 8 simulated flight conditions. Conclusions are summarized as follows:

1) Peak loads of combustion tests could be predicted by determining the force transmission coefficient of the lock system of the FMS. Based on the results of the prediction, combustion tests of a scramjet engine were safely carried out.

2) Lift and pitching moment, in addition to thrust, changed with the transition of combustion conditions, including weak, intensive, and unstart modes.

3) Thrust decreased, and lift increased suddenly when the engine fell into unstart conditions in the M6 and M8 tests although the change was gradual in the M4 tests. Therefore, it is more difficult

to control the engine under M6 and M8 conditions than under the M4 conditions.

4) Pitching moment remained almost constant when the engine fell into unstart conditions because of the cancellation of the moments generated in the inlet and in the combustor and the nozzle.

5) Net thrust was achieved in M6 tests by installation of a strut. The full-height strut improved combustion performance compared with the $\frac{1}{5}$-height strut in the M6 tests but resulted in smaller maximum thrust coefficient because of higher drag and unstart limit deterioration.

6) The thick strut was necessary for intensive combustion although the drag of it was larger than that of the thin strut in the M8 tests.

Acknowledgments

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