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Experimental Study on Restart Control of A Supersonic Air-Breathing Engine

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To study the dynamic response of a supersonic airbreathing engine and establish control logic for intake unstart, restart control tests were conducted at Mach 3 using a subscale engine model consisting of an axisymmetric intake (inlet) and a turbojet. Assuming that the combustion flame is blown out by intake unstart, restart control follows a sequence. First, after a flow is started the turbojet engine is ignited. Second, the intake is started while the rotational speed and the combustion gas temperature of the core engine are controlled. Third, the intake spike position and the terminal shock position are controlled, and the intake total pressure recovery achieves the design value (60%). The tests were successful, and engine thrust was recovered at approximately 30–40 s after engine start-up. A sudden increase in combustion gas temperature and rotational speed occurred after intake unstart. To reduce the sudden increase in the gas temperature, a new sequence that involved closing a fuel control valve after detection of intake unstart was implemented, and the increase in gas temperature was reduced. To avoid intake buzz, buzz margin control using a bypass door was successfully implemented.

Nomenclature

A_{by} = area of bypass door
A_{pl} = area of back pressure control plug
A_1 = imaginary throat area with intake exit conditions
F_{in} = momentum of airflow into intake
F_{noz} = ideal thrust for an imaginary nozzle
I = moment of inertia
ISP_{net} = specific impulse estimated using $Fnoz\text{-}Fin$
ISP_{noz} = specific impulse estimated using $Fnoz$
MCR = intake mass capture ratio, $= m_1/m_0$
MCR_B = intake mass capture ratio where buzz initiates
$M0$ = freestream Mach number
m_0 = airflow rate through cowl inlet area in freestream
m_1 = airflow rate captured by intake
N = engine rotational speed
Pt_0 = freestream total pressure
Pt_1 = total pressure at intake exit
Q_{cmd} = fuel flow control valve command
Tc = combustion gas temperature
TPR = intake total pressure recovery, $= Pt_1/Pt_0$
TPR_B = intake total pressure recovery where buzz initiates
W_c = compressor power
W_t = turbine power
Xsp = spike position

I. Introduction

MANY studies of hypersonic airbreathing engines have been completed for both high-speed transports and spaceplanes.[1–3] The mission of conventional air transport is to cruise between airports, whereas the mission of the spaceplane is to accelerate. Therefore, airbreathing engines for the spaceplane have three characteristics: 1) engine parameters related to weight, such as specific impulse or thrust/weight ratio, are more important than parameters related to distance, such as specific range; 2) maximum thrust is always required for acceleration; and 3) freestream and engine conditions are constantly changing, so that an engine/vehicle design Mach number does not exist.

The most obvious difference between the intake (inlet) of a hypersonic airbreathing engine and the intake of the supersonic airbreathing engine is flight-speed range. Because the maximum flight speed of the hypersonic airbreathing engine is much higher, the contraction ratio of the intake A_{throat}/A_0 must be larger. Therefore, the decrease in both total pressure recovery and mass capture ratio of the intake caused by an intake unstart is immense. For hypersonic airbreathing engines, intake unstart causes a large drop of both engine thrust and specific impulse, so that intake unstart might cause catastrophic damage during hypersonic flight.

Furthermore, from the viewpoint of the engine control system, disturbances are introduced into the engine control system by accelerations that are several times larger than those of a transport. Also, quick intake restart is required because the loss of engine thrust caused by intake unstart results in a deceleration of the spaceplane and could lead to mission failure.[3–5]

As a candidate for the propulsion system of the fly-back booster of a two-stage-to-orbit spaceplane, an air-turboramjet engine with an expander cycle (ATREX) has been developed.[6] The ATREX engine is a combined-cycle airbreathing propulsion system and is able to give effective thrust from sea level to an altitude of approximately 30 km with a flight Mach number of 6. The development of the intake for the ATREX engine began in 1993, and the experimental development of the engine control for stable operation of the intake and engine system has been underway since 1998 (Refs. 6–8).

In this paper, an experimental study of the control system for a hypersonic airbreathing engine, like the ATREX engine, is reported. The study is focused on effective restart of the intake. To establish this effective restart sequence for a hypersonic engine, the dynamic response of the intake and engine during unstart must first be studied.

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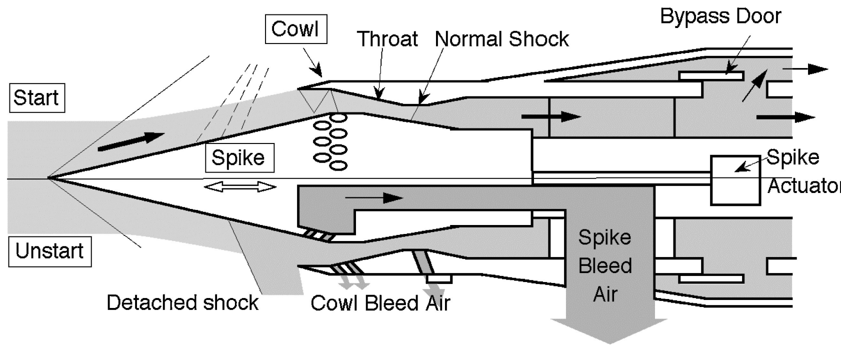

Fig. 1 Mixed compression variable geometry axisymmetric intake (inlet).

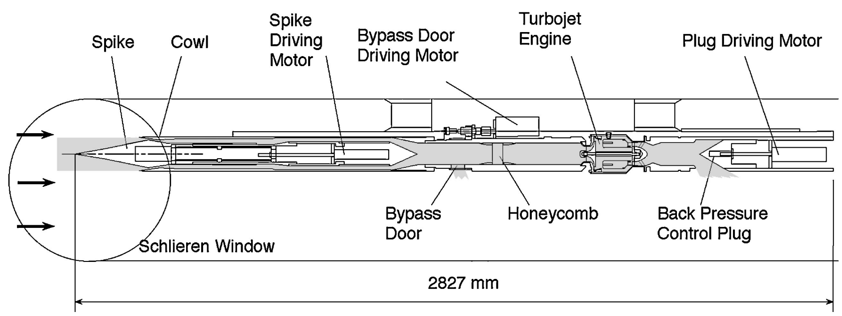

Fig. 2 Sketch of test model.

Because phenomena that are caused by intake unstart are unsteady, it is difficult to study the dynamic response of the hypersonic airbreathing engine numerically. Therefore, a subscale airbreathing engine model that consists of an axisymmetric intake and a turbojet engine was assembled, and intake restart control tests were done at the Institute of Space and Astronautical Science (ISAS) supersonic wind tunnel at Mach 3.

II. Axisymmetric Intake

Because the oblique shock angle becomes smaller with higher flight Mach number, the diameter and length of an intake designed for Mach 6 are much larger than those of an intake that is designed for Mach 2. As a result, the intake weight as a fraction of total engine weight becomes bigger. Hence, intake weight reduction is a key issue in the development of an engine system. Therefore, an axisymmetric intake configuration is employed in the ATREX engine because it can be lighter than a two-dimensional configuration. A schematic drawing of a mixed-compression variable-geometry axisymmetric intake is shown in Fig. 1. The shock pattern shown in the upper half of the figure shows the intake started condition, and the shock pattern shown in the lower half of the figure shows the intake unstart condition. The intake consists of two components; the spike (center body) and the cowl. The spike translates backward and forward in order to change the supersonic diffuser configuration and the intake contraction ratio so as to adapt to the changing freestream conditions.

When the freestream is supersonic and the intake is started, the airflow rate entering the cowl is defined without core engine conditions because all characteristic lines have turned forward the inside of the cowl. On the other hand, if the freestream Mach number is subsonic or transonic the intake spike position is controlled to make the intake throat area larger to provide more airflow. Therefore, it is almost impossible to design an intake whose airflow rate always matches the demands of the core engine. As a result, the intake always breathes slightly more air than the engine demands, and the excess flow is dumped through the bypass doors (or bleed system) while the freestream Mach number is supersonic and the intake is started. Now, if the control of this excess flow ratio fails then the intake will unstart. When unstart of the intake occurs, a detached

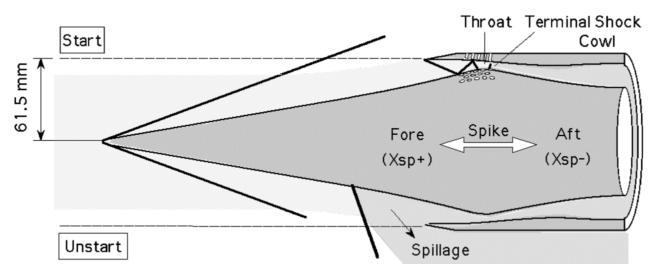

Fig. 3 Intake test model.

shock is formed in front of the cowl. This strong detached shock generates a large total pressure loss, and therefore the airflow that can pass through the throat of the intake is limited. Therefore, if the intake unstarts large decreases of both total pressure recovery and mass capture ratio are caused, and a large decrease of engine thrust results. It is then necessary to restart the intake as quickly as possible. The goal of a supersonic intake control system is thus to prevent occurrence of inlet unstart and, in the event of unstart, to restart the intake quickly. To restart the intake, the spike moves forward, and the contraction ratio of the intake is lowered. The contraction ratio where the intake unstarts and the contraction ratio that allows the unstarted intake to restart are not the same; unstart-restart phenomena have hysterisis.[7,8]

III. Test Model

A sketch of the whole test model is shown in Fig. 2. The test model consists of an axisymmetric intake, a bypass door, a turbojet engine, and an exhaust plug. Each component is described in the following subsections.

A. Intake

A schematic drawing of the axisymmetric intake model[7–10] is shown in Fig. 3. Specific details of the intake design are shown in Table 1. The intake cowl inlet radius is 61.5 mm. In this paper, the position of the spike *Xsp* is defined to be zero at a freestream Mach number of 3.5 (design Mach number). The spike position

Table 1 Intake test model specifications

Item	Intake specifications
Intake type	Variable geometry Axisymmetric
Design Mach number	*M*3.5
Shock on cowl lip Mach number	*M*5.3
Cowl inlet radius	61.5, mm
Spike tip-cowl inlet distance	241.7, mm (at design Mach number M3.5)
Cowl inlet-throat distance	49.2 mm (at design Mach number M3.5)

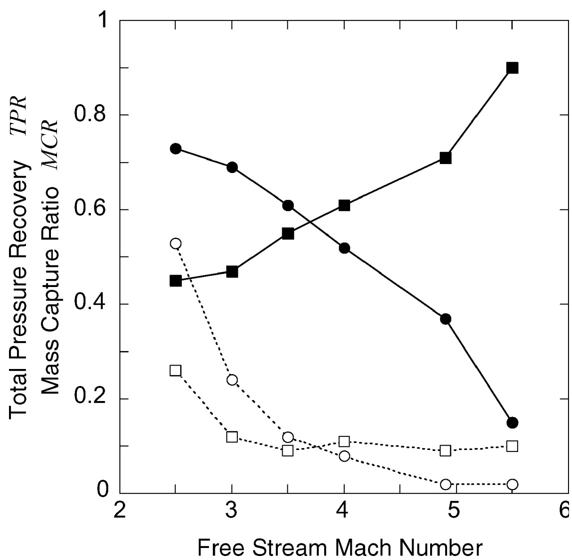

Fig. 4 Intake performance: ●, *TPR*, start; ■, *MCR*, start; ○, *TPR*, unstart; and □, *MCR*, unstart.

is considered to be positive when the spike moves in the forward (upstream) direction. The supersonic diffuser is designed with two conditions. First, the distance between the spike tip and the cowl lip is set at the maximum Mach number of 5.3. (The maximum Mach number is set as Mach 5.3 because of the precompression effect of the fuselage.[11]) Second, the supersonic diffuser is designed using a computer program that employs the method of characteristics at the design Mach number of 3.5. On the spike and the cowl surface around the intake throat, bleed holes of 1 mm diam have been drilled. By moving the spike, the supersonic diffuser configuration and the intake throat area are controlled, such that the Mach number at the intake throat is fixed at about 1.3. A terminal shock, which reduces the flow velocity to subsonic, is located downstream of the intake throat and moves upstream and downstream in response to change in the backpressure.

There are two conditions that can cause intake unstart: reduction of the intake throat area to the point that the supersonic flow chokes and increase in the intake backpressure to the point that the terminal shock moves upstream of the intake throat. Total pressure recovery and mass capture ratio of the intake vs Mach number are shown in Fig. 4. The decrease of both total pressure recovery and mass capture ratio are much more critical at higher Mach numbers.

B. Bypass Door

As mentioned before, the intake always breathes slightly more air than the engine demands. The excess flow is dumped through the bypass door. When the intake is started, the area of the bypass door is varied to control the normal shock position and to prevent intake unstart. When the intake is unstarted, the bypass door is operated to decrease the backpressure of the intake so as to restart the intake. A schematic drawing of the bypass door is shown in Fig. 5. Three semicircular bypass doors are arranged around the circumference. The area of the bypass door is varied from fully closed to

Table 2 AMT olympus engine specifications

Item	Engine specifications
Outer diameter	130 mm
Total length	270 mm
Thrust	170 N (max.) 7 N (Idle)
Compressor	Centrifugal one stage
Turbine	Axial one-stage reaction
Pressure ratio	4
Airflow rate	0.36 kg/s (max.) 0.08 kg/s (Idle)
Rotational speed	105,000 rpm (max.) 26,000 rpm (Idle)
Exhaust gas temperature	950 K
Fuel	Jet A − 1 (specific gravity = 0.81)
Fuel flow rate	6.1 g/s (max.) 2.1 g/s (Idle)
Theoritical fuel/air ratio	0.07
Ignition plug	Glow plug
Combustor	Annular
Fuel injection	Vaporizer
Startup method	Propane gas ignition

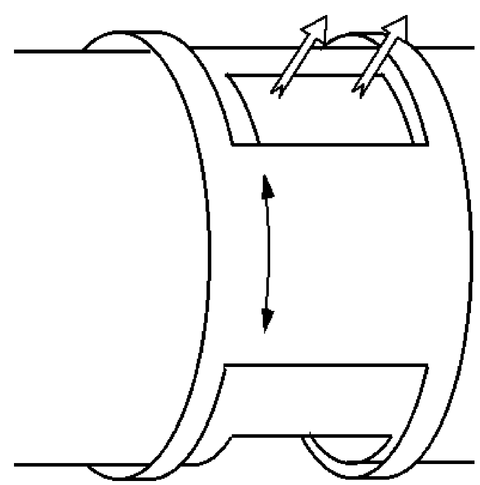

Fig. 5 Bypass door.

6800 mm^2, that is, more than twice the area of the compressor inlet, by rotation of 50 deg. To reduce distortion of the compressor inlet flow, a honeycomb is installed between the bypass door and the core engine.

C. Core Engine[12–15*]

An AMT Olympus engine (Netherlands) is used as the core engine. The Olympus engine is manufactured for use in model airplanes. A sketch of the Olympus engine is shown in Fig. 6. Detailed design parameters for the Olympus engine are given in Table 2.

D. Backpressure Control Plug

A variable geometry plug controls the engine exhaust pressure. For the engine control tests, the plug plays the same roll as a convergent-divergent nozzle because the flow is always choked at the plug.

IV. Control Logic

Feedback control loops for the supersonic airbreathing engine model are shown in Fig. 7. When the intake is started, four engine conditions are measured, that is, intake throat Mach number, terminal shock position, engine rotational speed, and combustion gas temperature. The controller outputs four control orders, that is, intake spike translation command, bypass door translation command,

*Data for AMT Netherlands available online at http://www.amtjets.com.

fuel flow control valve command, and plug translation command. Therefore, a four-input-four-output controller was designed. In this study, this feedback loop is divided into three feedback loops that are named as follows: intake control loop, bypass door control loop, and core engine control loop.

Each feedback controller consists of a proportional element and an integral element. Controller gain is determined by performing dynamic engine simulation. The dynamic simulation program is run under the following assumptions: 1) all aerodynamic and thermodynamic conditions are always balanced except the rotational speed 2) the rotational speed changes by the difference between compressor power and turbine power, as shown in the following equation:

$$W_t - W_c \equiv I \frac{d}{dt}(N^2) \tag{1}$$

A rotor's moment of inertia I is estimated by measuring the response of the rotational speed to step changes of the fuel flow rate under sea level (SL) static condition. As a result of the step response, a time constant was fixed to 1.33 s. 3) Static characteristics of each component were determined by preliminary tests. Intake aerodynamic characteristics, such as intake total pressure recovery and mass capture ratio vs intake spike position and backpressure were determined through wind-tunnel tests of the intake.[8–10] The turbojet engine was operated to obtain characteristics of the engine components, such as characteristic curve of the compressor and the turbine and combustion efficiency under the SL-static condition.

Each control loop is described in the following subsections.

A. Intake Control

When the intake is started, the spike position controls the intake throat Mach number. Because the test model is subscale and the throat area is thus small, the bow shock, which would be generated in front of a pitot tube used to measure the throat Mach number, would cause a large decrease in intake total pressure recovery. To avoid this pressure loss, the intake throat Mach number was not measured in this test. Furthermore, the spike position is controlled because the throat Mach number is a direct function of the spike position when the freestream Mach number is constant. When the intake unstarts, the spike moves forward to reduce the intake contraction ratio until the intake restarts.

Both mass capture ratio and total pressure recovery of the intake are measured by four pitot tubes installed around the circumference of the intake exit.

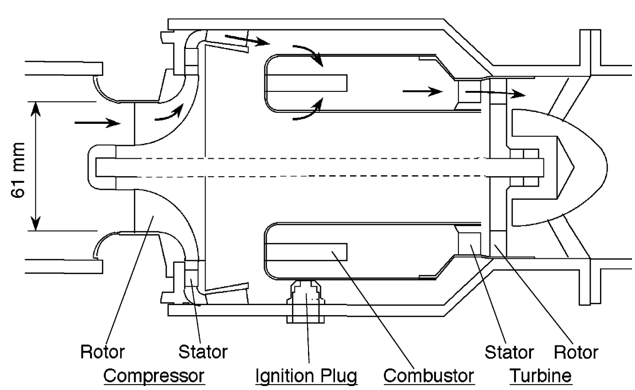

Fig. 6 AMT Olympus engine.

B. Bypass Door Control

When the intake is started, the bypass door controls the terminal shock position to prevent intake unstart and to maximize total pressure recovery. Total pressure recovery is used as the controlled variable because the normal shock position is a function of total pressure recovery. When the intake is unstarted, the bypass door normally opens until the intake restarts. Furthermore, a buzz margin control technique using the bypass door was tried and will be described in the section that describes the avoidance of intake buzz (Sec. VI.C).

C. Core Engine Control

The core engine controller monitors the engine rotational speed and the combustion gas temperature, which is measured at the turbine nozzle inlet temperature, and outputs a fuel flow control valve command and an exhaust plug motor command. The compressor airflow rate is measured using the pitot tubes installed between the honeycomb and the compressor.

V. Test Sequence

The engine control tests were conducted at the ISAS supersonic wind tunnel. Freestream conditions were fixed as follows: Mach number = 3, total pressure = 4.5 ± 0.03 kg/cm^2, total temperature = 293 ± 5 K, and test duration = 90 ± 1 s. The following sequence was used to simulate the restart of the intake during supersonic flight with the combustion flame blown out: 1) the wind tunnel starts while the intake is unstarted; 2) after wind-tunnel startup, the engine is ignited using propane gas; 3) after the engine is warmed up, jet fuel is supplied to the engine, and the intake is restarted while the engine rotational speed and combustion gas temperature are controlled; and 4) after intake restart is confirmed, the intake spike position, the bypass door, the fuel flow rate, and the plug are controlled to maximize the intake total pressure recovery, the engine rotational speed, and combustion gas temperature.

Because a vaporizer is used as the fuel supply system, a small amount of propane gas is supplied to warm up the vaporizer during startup. To ignite the propane gas, conditions in the combustion

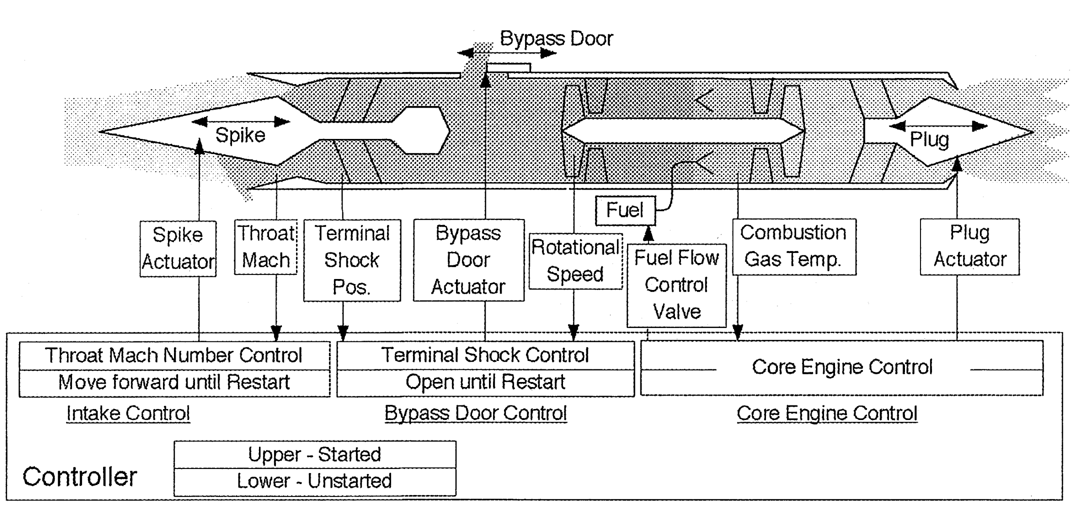

Fig. 7 Control logic.

chamber must be the same as they would be for ignition at SL-static condition. Therefore, the propane gas is ignited while the backpressure control plug is only slightly open, so that only a very small quantity of air is supplied into the combustion chamber. The wind-tunnel engine test startup sequence is more complicated than the sequence for restarting an engine during supersonic flight, when the combustor is warm.

VI. Test Results

A. Intake Restart Test Results

The typical results of the intake restart control test are shown in Figs. 8–11. In Fig. 8, the equivalence ratio (*ER*) is estimated using the compressor inlet airflow rate and fuel flow rate. In Fig. 11, ideal nozzle thrust $Fnoz$ and ideal nozzle specific impulse ISP_{noz} are estimated using turbine outlet static pressure, total temperature, and flow rate measured by the pitot tubes at the compressor inlet and a fuel flow rate sensor, assuming that an ideal nozzle is installed in exchange for the backpressure control plug. Net specific impulse ISP_{net} is estimated using net thrust (ideal nozzle thrust $Fnoz$ and momentum into intake Fin). When the intake is started, the spillage drag of the intake is negligible (1/10 of Fin) (Ref. 9). Therefore, the engine net thrust is almost the same as $Fnoz$ - Fin. The engine control sequence is divided into three phases, that is, an engine start phase, an intake unstart phase, and an intake start phase, as shown in Fig. 8. The test sequence is as follows. Propane gas is supplied to warm up the engine (at 5 ± 1 s). After the vaporizer is warmed up,

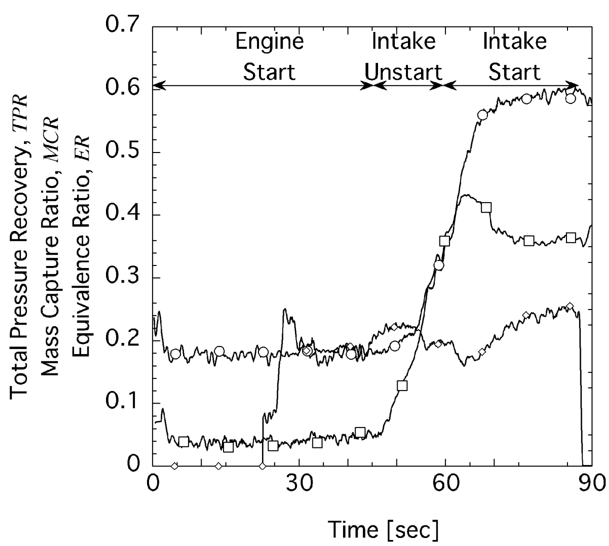

Fig. 8 Restart control test results (intake, combustor): ○, *TPR*; □, *MCR*; and ◇ *ER*.

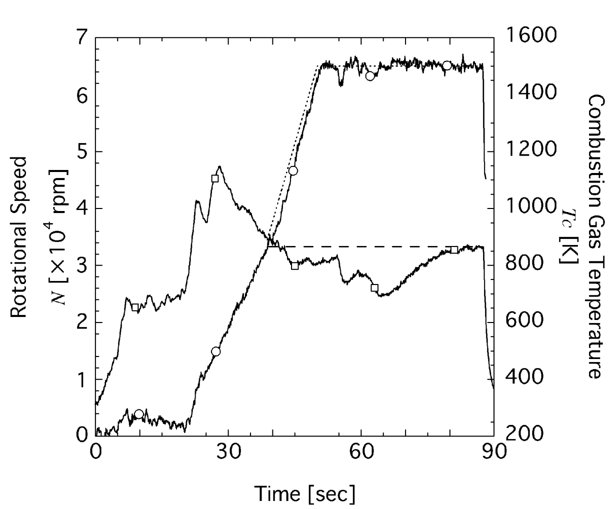

Fig. 9 Restart control test results (core engine): ○, *N*; □, *Tc*; - - - -, *N* (target); and – – –, *Tc* (target).

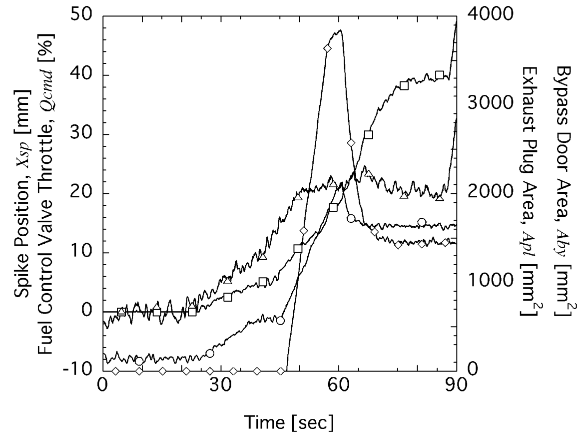

Fig. 10 Restart control test results (position, throttle): ○, *Xsp*; □, Q_{cmd}; ◇, A_{by}; and △, A_{pl}.

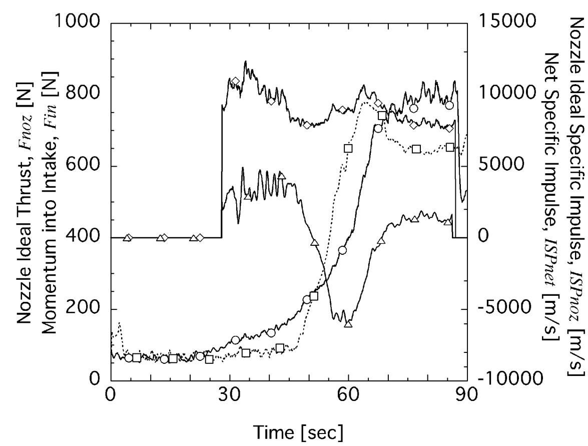

Fig. 11 Restart control test results (thrust, *ISP*): ○, *Fnoz*; □, *Fin*; ◇, ISP_{noz}; and △, ISP_{net}.

the fuel supply (ER in Fig. 8) starts to increase rotational speed (at 21 ± 3 s). In the meantime, the spike is fixed (in the unstart position), the bypass door is fully closed, and the plug is slightly opened to provide a small amount of air to the combustor (Fig. 10). After the rotational speed reaches 32,500 rpm, the engine start phase finishes, and the intake unstart phase starts (at 42 ± 3 s). The spike moves forward (*Xsp* increases), and the bypass door opens to restart the intake (see Fig. 10) while the core engine rotational speed N and the combustion gas temperature Tc are controlled to 65,000 rpm and 865 K, respectively (see Fig. 9). When the spike position and the bypass door area reach predetermined values ($Xsp = 22$ mm and $Aby = 3600$ mm^2 in the case shown in Fig. 10), the intake unstart phase finishes, and the intake start phase starts (60 ± 5 s). During the intake start phase, the spike position is controlled and moves back (*Xsp* decreases). The bypass door closes to control the normal shock position. Then the total pressure recovery increases almost to the design value (60% in Fig. 8), and all controlled variables are stabilized (85 ± 5 s). After the intake restart test is successfully performed, the spike is moved slightly backward, and the intake is forced to unstart in order to determine the engine response immediately after intake unstart (see Sec. VI.B).

Although it took about 42 s to start up the engine in these tests, an actual engine ignition process of flight engine would occur in a few seconds because gaseous fuel would be supplied to the combustor and ignitability of the fuel would be much higher. In the restart control test, the intake restart process starts at 42 s, and the effective thrust is recovered after approximately 75 s (see $Fnoz$ and ISP_{net} in Fig. 11). Therefore, engine thrust is recovered 33 s after engine ignition. Hence, the restart control test results proved that the engine thrust recovery could be completed in about 30–40 s

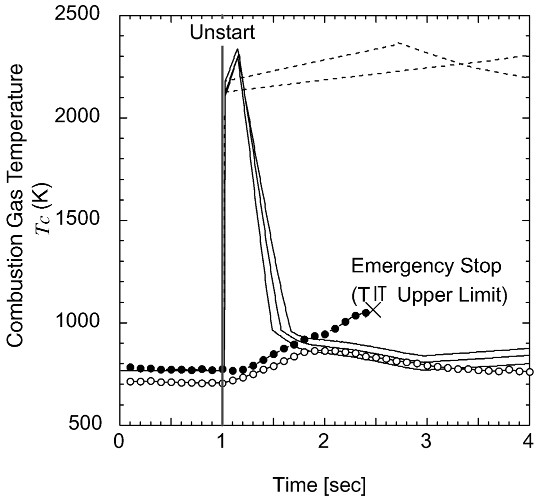

Fig. 12 Combustion gas temperature response: ——, simulation with fuel shutoff; - - - -, simulation without fuel shutoff; ○, experiment with fuel shutoff; and ●, experiment without fuel shutoff.

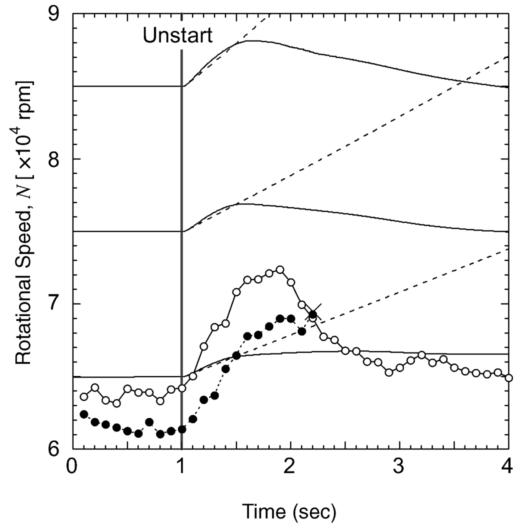

Fig. 13 Rotational speed response: ——, simulation with fuel shutoff; - - - -, simulation without fuel shutoff; ○, experiment with fuel shutoff; and ●, experiment without fuel shutoff.

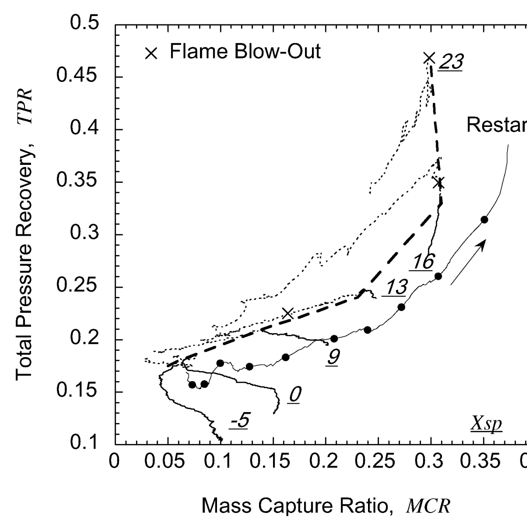

Fig. 14 Performance characteristics of the intake (unstart): ——, unstart; - - - -, buzz line; – – –, buzz; and ●, test result.

after intake unstart. This timeframe is too long for a spaceplane, which is accelerated from liftoff to Mach 6 in 10 min (Refs. 1–3). The thrust recovery time could be shortened, however, because the control gains of every controller could be made much higher by changing the fuel supply system and increasing the controllability of the combustion gas temperature.

B. Engine Behavior Immediately After Intake Unstart

After the restart control is stabilized, the intake is forcibly unstarted. The combustion gas temperature after the intake unstart is shown in Fig. 12. The unstart of the intake occurs at 1 s. After the intake unstart, the sudden decrease in the mass capture ratio causes an increase in combustor equivalence ratio. Normally, the air/fuel equivalence ratio of a turbojet combustor (gas generator) is about 0.2~0.3. This sudden increase of the equivalence ratio causes an increase in the combustion temperature. If a turbojet cycle is used as a core engine for a supersonic airbreathing engine, then this sudden increase in turbine inlet temperature caused by the intake unstart is inevitable. The lines without symbols show the results of the dynamic simulation. A sudden increase (from 800–2400 K) in the temperature is seen because the combustion efficiency in the simulation is 100%. The lines with symbols show the results of the experimented tests. The temperature increase rate is about 200 K per second because of the effects of combustion efficiency and thermocouple delay. The thermocouple measuring the combustion gas temperature, which has the diameter of 1.6 mm, requires 0.9 ± 0.2 s to reach 90% of the step change in real temperature. Because the gain of the combustion gas temperature controller was low, this sudden increase in the temperature could not be controlled. When the temperature increased to the turbine inlet temperature limit, an emergency stop ended the test (2.4 s, 1073 K).

To address this issue, a new control logic to shut off the fuel control valve after the detection of intake unstart was incorporated into the system. The results of this new control logic are shown by the open-circle symbols in Fig. 12. By closing the fuel flow control valve quickly after the detection of intake unstart, the sudden increase of flame temperature was limited to 200 K.

The engine rotational speed after intake unstart is shown in Fig. 13. A sudden increase in turbine power causes an increase in rotational speed. As a result, the possibility of a compressor surge increases. The phenomenon of an increase in combustion flame temperature along with a possible simultaneous increase in compressor surge after intake unstart is a unique characteristic of a supersonic airbreathing engine that has a turbojet engine as a core engine.

C. Avoidance of Intake Buzz

The relationship between intake total pressure recovery and mass capture ratio during intake unstart is shown in Fig 14. The underlined numbers indicate the spike position. At each spike position, by fixing the plug area and decreasing the bypass door area slowly the flow condition is changed from unstart (narrow solid line) to buzz (dash line). Schlieren pictures taken during intake buzz are shown in Fig. 15. Once intake buzz initiates, the incoming flow oscillates strongly, and sometimes the combustion flame extinguishes (cross mark in Fig. 14). Here intake buzz must be avoided, and the intake must be operated in the lower right domain of the buzz line (heavy solid line in Fig. 14).

Whether intake buzz occurs depends on the intake exit choke area A_1 (the area that the flow chokes because of the intake exit conditions). Hence, the likelihood of intake buzz occurring can be determined by measuring the value MCR/TPR, which is in proportion to the intake exit choke area A_1.

$$A_1 = \frac{m_1}{P_{t1}}\sqrt{\frac{RT_{t1}}{\gamma}}\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \propto \frac{m_1}{P_{t1}} = \frac{m_0}{P_{t0}}\frac{MCR}{TPR} \qquad (2)$$

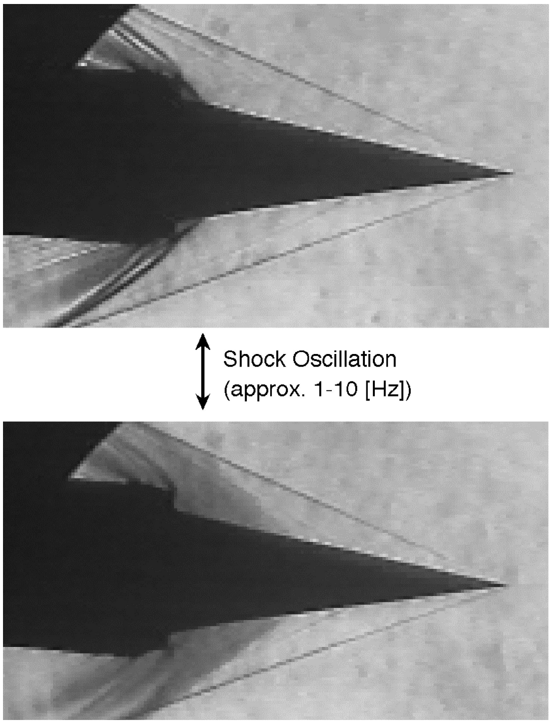

Fig. 15 Schlieren photograph of intake buzz.

Therefore, providing "intake buzz margin" by use of the bypass door is proposed to avoid intake buzz. A definition of intake buzz margin (*IBM*) is shown here:

$$IBM \equiv \frac{MCR}{TPR}\frac{TPR_B}{MCR_B} \tag{3}$$

where TPR_B and MCR_B are functions of the spike position Xsp. Therefore, TPR_B and MCR_B are always on the buzz line (see Fig. 14). If the *IBM* is 1.0, then buzz initiates.

$$TPR_B \equiv TPR_B(Xsp) \tag{4}$$

$$MCR_B \equiv MCR_B(Xsp) \tag{5}$$

By controlling the intake buzz margin, intake restart without buzz can be achieved (round mark in Fig. 14). The possibility of buzz initiation can be determined by monitoring the intake buzz margin, and the control of buzz occurrence through feedback becomes possible.

VII. Conclusions

Restart control tests of a supersonic airbreathing engine model, consisting of an axisymmetric air intake and a turbojet engine, were successfully performed. The test results proved that the engine thrust recovery could be completed in about 30~40 s after intake unstart. This duration could be shortened by increasing the controllability of the combustion gas temperature so that the control gains of each controller could be made much higher. After intake unstart, the sudden decrease in the intake mass capture ratio causes an increase in combustion temperature. If a turbojet cycle is used as a core engine for a supersonic airbreathing engine, then this sudden increase in turbine inlet temperature caused by the intake unstart is inevitable. To reduce the sudden increase in gas temperature, a new sequence of closing the fuel flow control valve quickly after a detection of intake unstart was combined with the temperature feedback control, and the increase in the gas temperature was reduced. To avoid intake buzz, intake buzz margin control using the bypass door was successfully used.

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