# CONTROL OF SUPERSONIC INLET WITH VARIABLE RAMP

**Yasushi WATANABE, Akira MURAKAMI**
**Aviation Program Group, Japan Aerospace Exploration Agency**

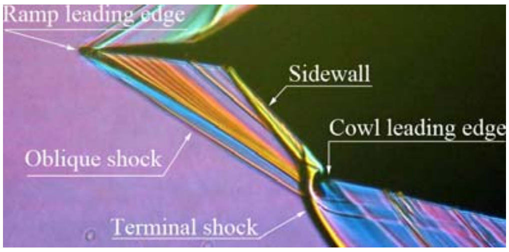
**Keywords**: *Propulsion, Inlet, Control, Wind Tunnel Testing*

## Abstract

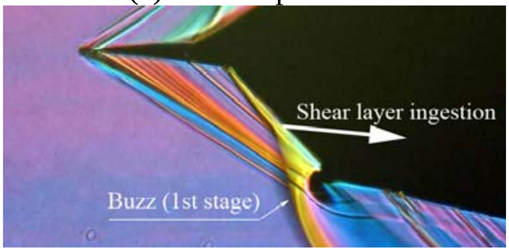
*The wind tunnel testing for the control test of a supersonic inlet was carried out. The inlet, which is two-dimensional external-compression type with variable ramp, was mounted on the airframe being designed as a next generation supersonic transport. The concept of the control to avoid unsteady phenomena known as "buzz" especially in the process of engine deceleration was successfully validated. Due to the function installed to the experimental model, which is able to emulate actual behavior of the engine or the actuator, the requirement to engine operation was made clear.*

## 1 Introduction

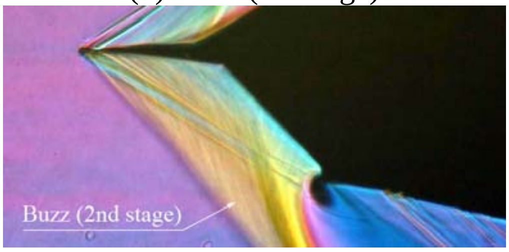
A supersonic inlet is one of the important components of a supersonic transport. In order to be the net thrust of a propulsion system higher, it should be considered the inlet to be with higher inlet pressure ratio and lower external drag in its design process. As design Mach number of the inlet become higher, the requirement to the variable ramp system would be considerable because the optimum turning angle of the supersonic diffuser would increase with flight Mach number. In this point of view, the variable ramp system has a role to keep the Mach number in front of the terminal shock nearly constant against varying flight Mach number. There is another serious problem being considered in the design of the supersonic inlet. That is stability for the engine operation. A supersonic inlet is characterized by occurring unsteady aerodynamic phenomena below a certain value of its mass flow rate, which is known as buzz. It is caused by the ingestion of the shear layer originated by the interaction of shock system [1] as shown in fig. 1b. By further reducing mass flow rate, this unsteady phenomenon would shift to another stage where the oscillation of the shock wave becomes considerable [2] (fig.1c). The focal point of the oblique shock system should be set far from the cowl leading edge to make the shear layer unlikely to be ingested; however, this design philosophy means the external drag of the inlet being large. As a solution to meet higher net thrust with wider stable operation range of the



(a) Stable operation



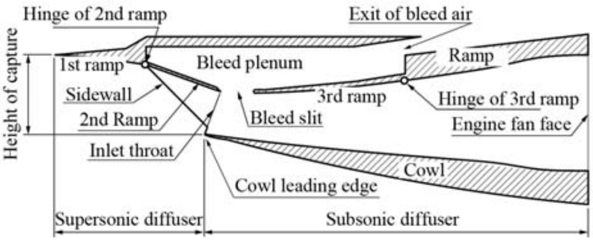
(b) Buzz (1st stage)



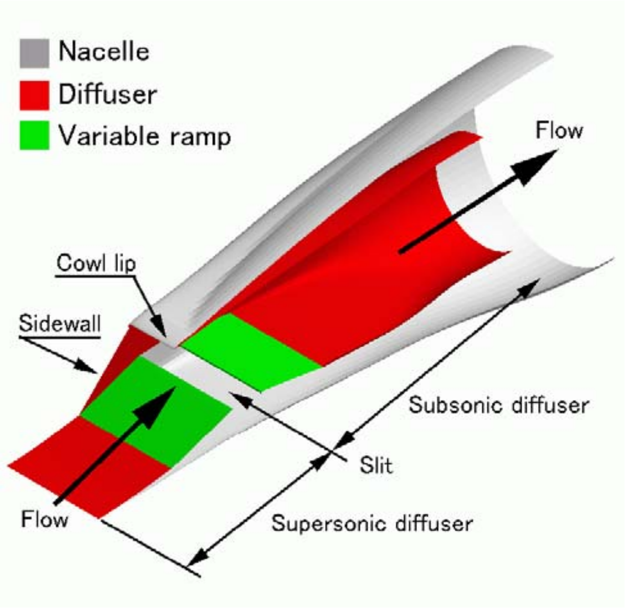
(c) Buzz (2nd stage)

Fig.1 Shock patterns in sub-critical conditions inlet, certain mechanisms would be needed to adjust mass flow rate of the inlet against varying flight conditions or engine throttling. In this point of view, the variable ramp would be anticipated to adjust the mass flow rate of the inlet.

In this study, our aim was focused on the development of the concept to control the inlet with the variable ramp. Aerodynamic design and conceptual design of the control law was done for the inlet of jet-powered experimental air plane which had been developed in JAXA [3], [4], [5] (Japan Aerospace Exploration Agency). Wind tunnel testing was carried out to proof the conceptual design of the inlet control for avoiding buzz especially in the decelerating process of the engine at design Mach number of 2.0. Making clear the requirement to the operation of the engine was also important objective in order to apply the present control technology to actual design of the inlet.



(a) Names of each part of inlet



(b) Schematic of inlet

Fig.2 Supersonic inlet with variable ramp

## 2 Inlet control concept with variable ramp

### 2.1 Aerodynamic design of supersonic inlet

The inlet designed in this study is two-dimensional and external compression type of which design Mach number is 2.0. Figure 2 shows the schematic of the inlet. The inlet has three-shock system; first ramp is fixed geometry with its turning angle of 8 degrees. Second ramp is able to vary its turning angle from 0 to 18 degrees for first ramp. Third ramp is also variable geometry, and the position of its leading edge is determined by the position of second ramp. Relative positions of the leading edge of first ramp and the corner of second ramp to the cowl leading edge were designed to focus the shock waves at the cowl leading edge at Mach number of 2.3. This implies the inlet has a certain margin for stability in subcritical operation at design Mach number. The total length and height of capture area are 4.57 times and 0.687 times to the diameter of the engine fan face, respectively, while the width of the inlet is constant along the flow direction at diameter of the engine fan face. The sidewall covering downstream corner of second ramp was designed its configuration to minimize the effect of side slip and pressure loss in the subsonic diffuser. There is a slit for boundary layer bleeding between the second ramp and third ramp, and bleed air is ejected to outside through the bleed plenum. The length of subsonic diffuser, which area ratio is about 2.0, is determined 3.3 times to the diameter of the engine fan face based on the database in order to avoid the separation inside it. The area distribution of the subsonic diffuser is also determined according to the database based on CFD analysis.

### 2.2 Conceptual design of inlet control

Control of the inlet is keeping its operating condition constant against to varying flight conditions or engine operating conditions. In the example shown in fig.3 indicates that occurring buzz could be avoidable by changing the

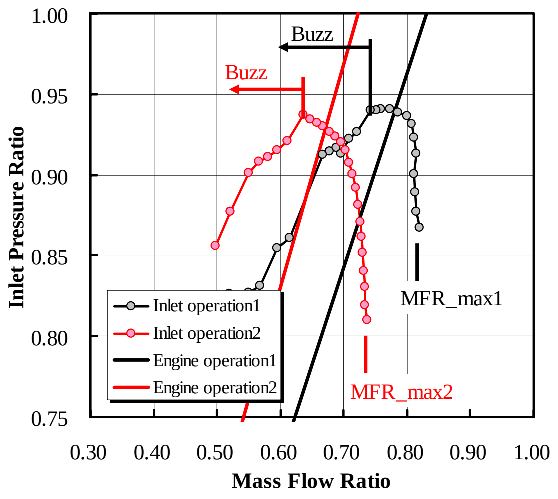
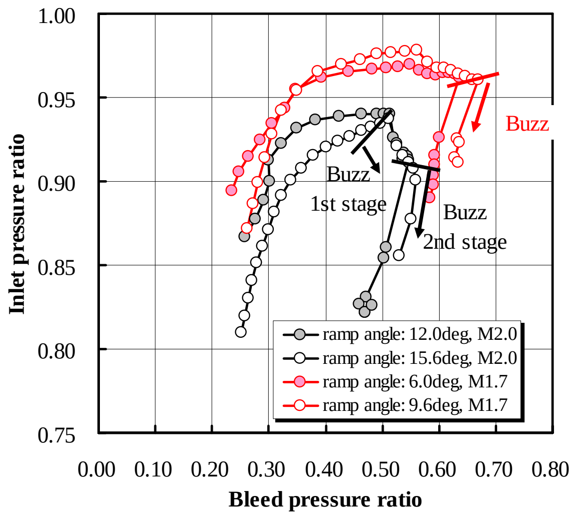
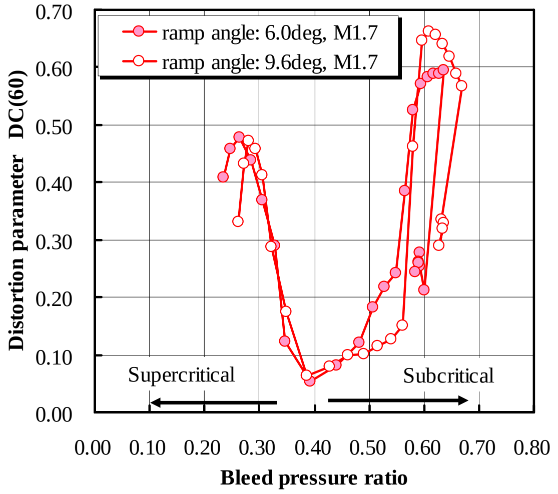


Fig.3 Matching of engine and inlet



(a) Inlet pressure ratio



(b) Distortion parameter

Fig.4 Relation of inlet condition to bleed pressure ratio

operating condition of the inlet correspond to the change in engine operating condition. Changing the inlet operation is related to changing maximum mass flow ratio of the inlet. Although there are several methods to change maximum mass flow ratio of the inlet such as a variable bleed system or a spill door, a variable ramp system was adopted as a view of simplifying the whole system of the inlet.

A variable ramp works as a manipulated value in the control system. The value which is able to express the operating condition of the inlet is necessary, and the control of the intake could be possible by using that parameter as a controlled value. The bleed pressure ratio, which is the value of the pressure in the bleed plenum normalized by the total pressure of the free stream, was used as a controlled value in this study. The controlled value describe the operating condition well regardless of the angle of second ramp, which is a manipulated value of the control concept, under conditions for constant Mach number and constant angle of attitude as shown in fig.4. Thus the condition of the inlet could be kept constant by keeping the bleed pressure ratio constant. However, since the relation of the operating condition and the bleed pressure ratio is different for the different Mach number (fig.4a), control maps for the different Mach number is necessary as well as those for different angle of attitude. When the inlet is controlled by using the value of bleed pressure ratio, it should be made attention that two conditions, stable condition and buzz, is possible for one value of the bleed pressure ratio (fig.4a).

## 3 Wind tunnel testing

### 3.1 Experimental model of inlet

Figure 5 shows the schematic of experimental model. It was a 15% scale model of fuselage, inboard wing and nacelle for jet-powered experimental airplane developed in JAXA. The nacelle mounted on the starboard was fixed geometry used to measure flow conditions just upstream of the inlet. The nacelle mounted on portside wing, the detail of which is shown in fig.6, was used for measurement of the performance and validation of the present control concept. Variable ramp system consists of the actuator mounted inside fuselage, two variable ramps and the linkage connecting actuator and both ramps. The bleed pressure ratio was measured on the back of the second ramp surface. The aerodynamic performance was obtained by measuring spatial pressure distribution at the exit of the inlet where 41 pitot probes and 5 pressure transducers were set. Straight duct, in which the mass flow meter of veturi type is installed, was connected downstream the inlet. Inlet mass flow was regulated by means of the inlet flow plug mounted at the exit of the straight duct. Bleed air ingested at the slit was issued regulating by the bleed flow plug.

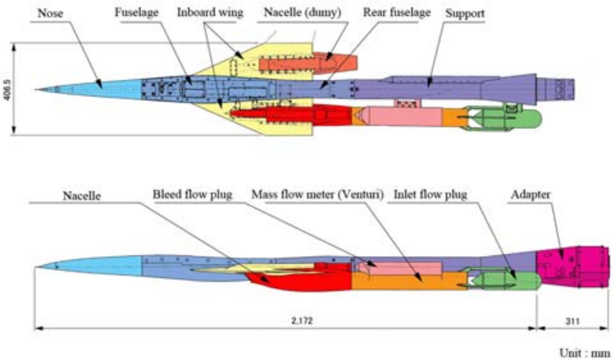


Fig.5 Schematic of experimental model

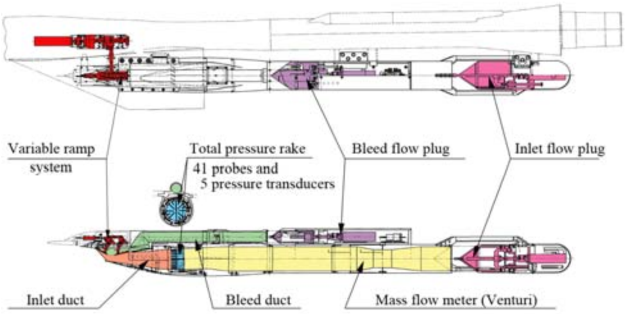


Fig.6 Detail of supersonic inlet

### 3.2 Emulators for actual system

Actuators used for the experimental model has much quicker response than those for actual system. One of our objectives of wind tunnel testing was to validate the control technology of the inlet for an actual propulsion system. In order to achieve that, it would be important that the experimental system should be adapted its response to that of the actual system. Thus the special function was installed into the control device of the experimental model to emulate the behavior of the actuator to the behavior of the actual system such as the engine. The verified result of the function of emulator is shown in fig.7. Result shows the behavior of the actuator for the inlet flow plug, having a role to simulate engine throttling, after applying the function of the emulator. The condition of the engine throttling was translated to the position of the plug, and it was inputted as a step function. The input command shown here is the signal varying from the plug position corresponds to the engine rotating number of maximum to that of 80%. Experimentally obtained result agrees well with the result of the simulation of the control law. This result ensured that the validation of the control technique for actual system would be possible.

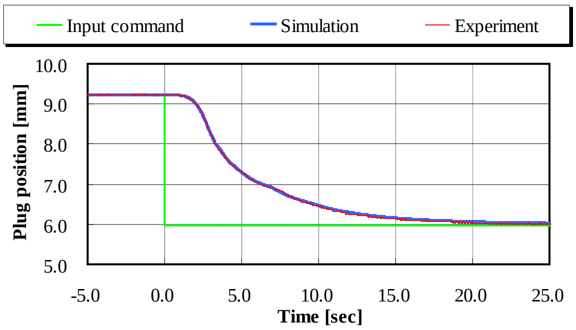


Fig.7 Function to emulate behavior of engine

### 3.3 Control law of inlet

Figure 8 shows the example of the control map. The horizontal axis of the map represents the movement distance of the actuator by changing the angle of the variable ramp system. The operating condition of the inlet, expressed by the bleed pressure ratio in the control map, varies as the change in the angle of the variable ramp, rotating number of the engine, altitude and the condition of atmosphere. Thus many lines for combination of various conditions make the region of the engine operation. There are four boundaries in the control map, limitation of buzz, limitation of spatial distortion, maximum ramp angle and minimum ramp angle. Former two boundaries were determined by the performance of the inlet. On the other hand, latter two boundaries were determined by the mechanical limitation together with considering the performance of the inlet. The inlet could be controlled appropriately by setting the control line to across all engine operation lines within the boundaries. Various settings of control line make various types of the operation of the inlet possible, such as keeping maximum thrust of the propulsion system during cruise or keeping the operating condition of the inlet far from occurring buzz in the process of engine deceleration and so on. A number of maps were prepared for the various conditions of flight Mach number and the angle of attitude.

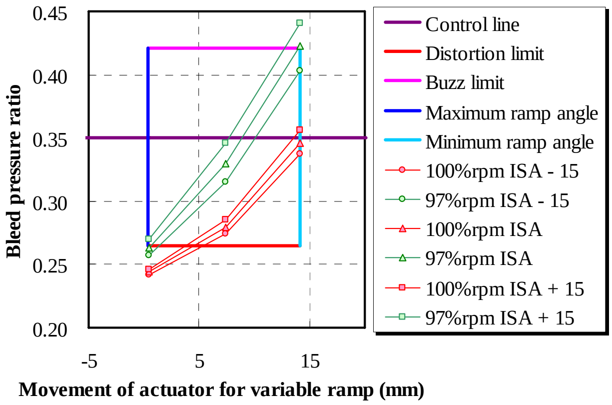


Fig.8 Example of control map

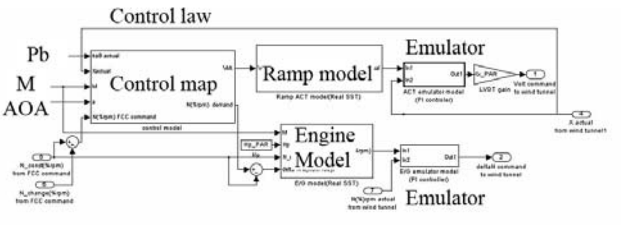


Fig.9 Control law of experimental model

Control law of the inlet used for the wind tunnel testing was based on the PI control law and the function of the emulator was added to the control law designed for the actual system as shown in fig.9. It is needed three inputs, Mach number, angle of attitude and the bleed pressure ratio. Two inputs, Mach number and angle of attitude, were used to select the appropriate control map, and then the bleed pressure ratio was controlled to follow the setting of the control lines.

### 3.4 Wind tunnel testing

Wind tunnel testing were performed at 2m×2m transonic wind tunnel in JAXA for Mach number below 1.4 and at S2MA wind tunnel in ONERA for Mach number above 1.5 up to 2.0 (fig.10). Experimental system shown in fig.11 is roughly classified into four systems, the experimental model, the measurement system for pressure and temperature, the measurement system for highly unsteady signals and the controller of the model. All systems were synchronized by the signal generated by the sequencer. The sequencer has also the function of making signal to control the inlet of which cycle is about 20 Hz. Flow conditions, such as total pressure, total temperature and so on, were

Fig.10 Experimental model in wind tunnel

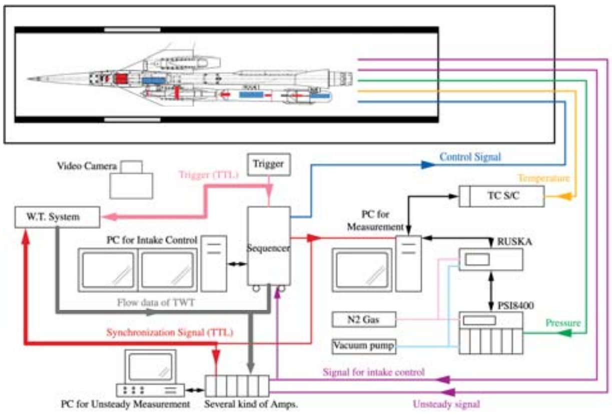


Fig.11 Measurement and control system

obtained by means of devices installed in the wind tunnel system.

Wind tunnel testing was categorized into three kinds. Firstly, verifying the functions of the experimental model was carried out at the transonic wind tunnel in JAXA. Functional test of the emulator was main objective in this category, the result of which is shown in fig.7. Further important information such as back rush of the gear or effects of the mechanical fitting of pins used for a linkage of variable ramp system were obtained. These data was reflected to the design of the control law. Secondly, acquisition of the aerodynamic performance was carried out. Experiments were performed under the conditions, Mach number range from 0.8 to 2.0, the range of angle of attitude from -4 to 8 degrees and the range of variable ramp from -2 to 18 degrees. Results obtained made boundaries in the control map shown in fig.8. Matching the operation of the inlet to the engine operation was also done in order to make lines expressing engine operation on the control maps. Finally, validation of the control of the inlet was carried out. The control tests were performed under the conditions of the Mach numbers of 1.5, 1.7 and 2.0. In the experiment, demonstrations avoiding buzz in the process of deceleration of the engine rating was performed.

## 4 Results and Discussion

### 4.1 Aerodynamic performance of inlet

Figure 12 shows the variation of the inlet pressure ratio obtained experimentally at the condition of Mach number of 2.0 and angle of attack of 2.0 deg. In the diagram, engine operating conditions were lined together with the performances of the inlet. Maximum value of the mass flow ratio of the inlet becomes less as the angle of variable ramp increases. Buzz was occurred in any cases below a certain value of mass flow ratio. By referring engine operation lines, stable margin of the inlet for the fixed ramp correspond to the change in engine rating of 5%. This result clearly indicates that the operation range of the inlet with fixed ramp is not able to satisfy whole range of the engine operation. Figure 13 shows the variation of the bleed pressure ratio for fixed ramp corresponding to the results shown in fig.12. A boundary of the buzz occurrence was made by connecting values of corresponding bleed pressure ratio where the buzz began to occur.

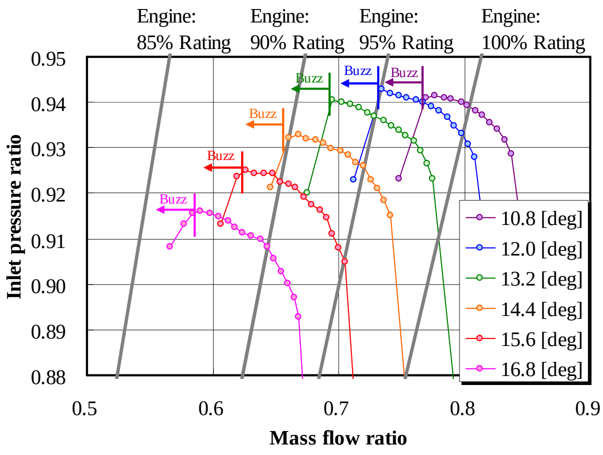


Fig.12 Buzz occurrence for fixed ramp

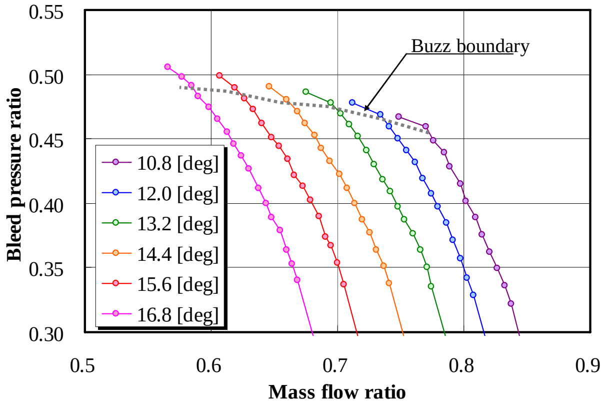


Fig.13 Establishment of buzz boundary

### 4.2 Control test for deceleration of engine

As described in previous section, buzz would not be avoided by the inlet with fixed ramp. In order to validate the control technology of the inlet to satisfy the whole range of engine operation by avoiding the occurrence of buzz, control test was performed in the process of engine deceleration. Three kind of targets as control lines shown in fig.8 were set, of which values of the bleed pressure ratio were 0.35, 0.40 and 0.45, as shown in fig.14. Boundaries of buzz limit and distortion limit was not set by purpose in order to examine the response of the inlet in detail. On the other hand, boundaries of the maximum ramp angle of 16.8 deg and minimum ramp angle of 10.8 deg were set to the control law. Consequently, the condition of the inlet ideally varies along the dashed line A-B-C-D shown in fig.14 and 15. Although the control law is active, the inlet is not controlled from point A to B as well as from point C to D due to the limitation of the movement of the variable ramp, so that the bleed pressure ratio (operating condition of the inlet) varies as the mass flow ratio of the inlet varies. As a result, the inlet works in more supercritical condition than the target set by the control objective between the points of A and B. Similarly, the inlet works in more subcritical condition between C and D. When the condition of the inlet shifts beyond then point D by further reduction of the mass flow ratio, buzz could be occurred.

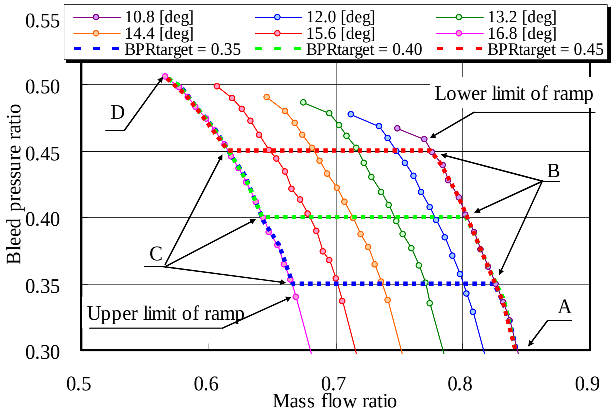


Fig.14 Setting of control line

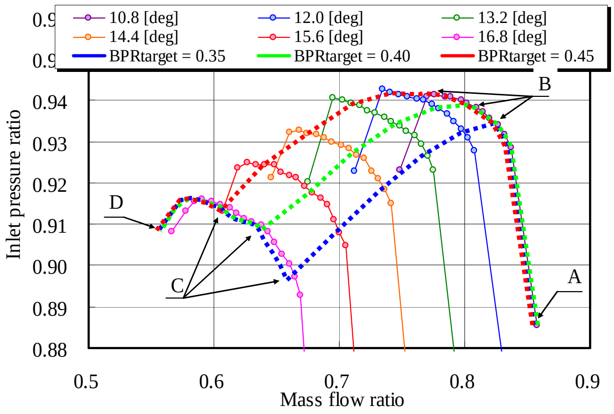


Fig.15 Ideal variation of inlet pressure ratio for various control settings

Figure 16 shows time variation of position of the inlet flow plug as a disturbance. The change in position of the inlet flow plug was given to simulate deceleration of the engine rating from maximum to 85%. The deceleration rate of the engine was set at its maximum ability. Figure 17 shows time variations of the angle of second ramp as a manipulated variable and the bleed pressure ratio as a controlled variable for the cases of the target bleed pressure ratio of 0.35 and 0.40. The ramp has moved till it reached to the limitation being set as the boundary on the control map. Although the target bleed pressure ratio was kept constant at target value initially, it increased as the movement of the inlet flow plug. The bleed pressure ratio decreases toward the target once in the controllable region, but it increases again after the ramp reached to the movable limitation.

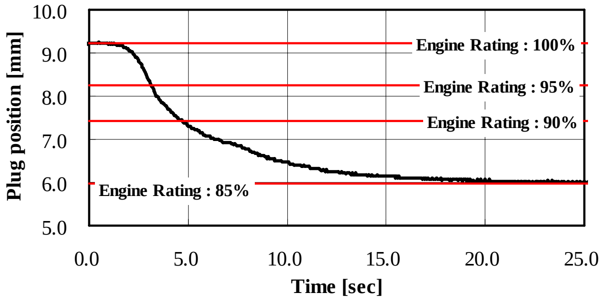
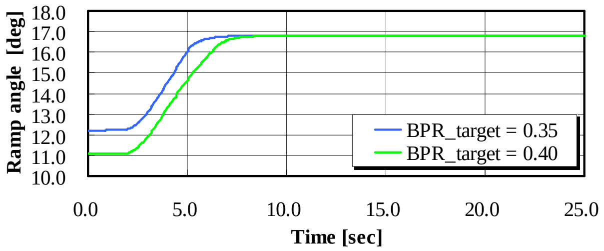
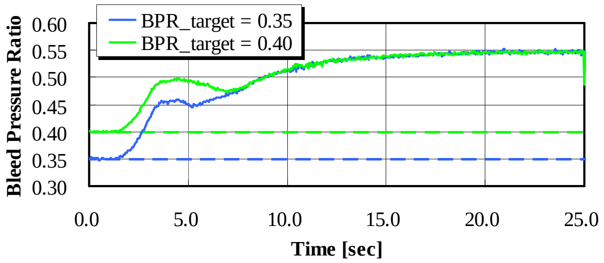


Fig.16 Variation of inlet flow plug

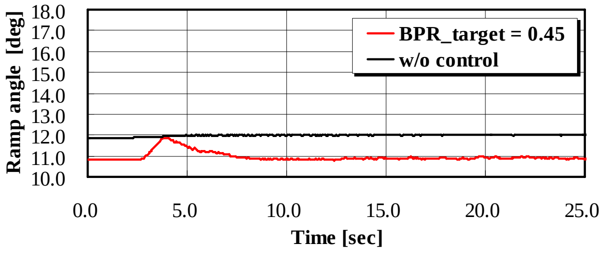


(a) Variation of ramp angle

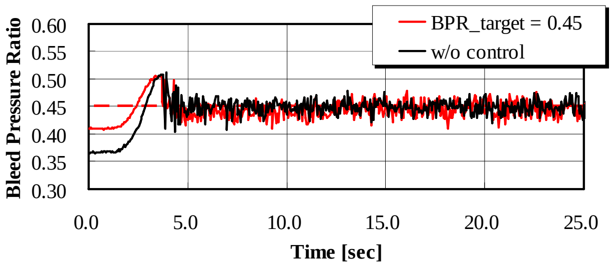


(b) Variation of bleed pressure ratio

Fig.17 Effect of control target on inlet control for buzz avoidance



(a) Time variation of ramp angle



(b) Time variation of bleed pressure ratio

Fig.18 Result of inlet control accompanying buzz

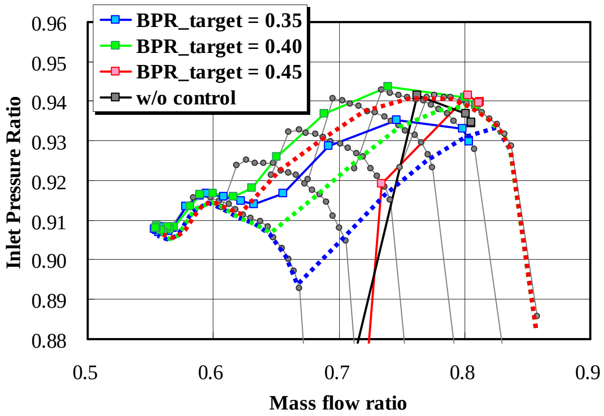


Fig.19 Inlet performance with its control

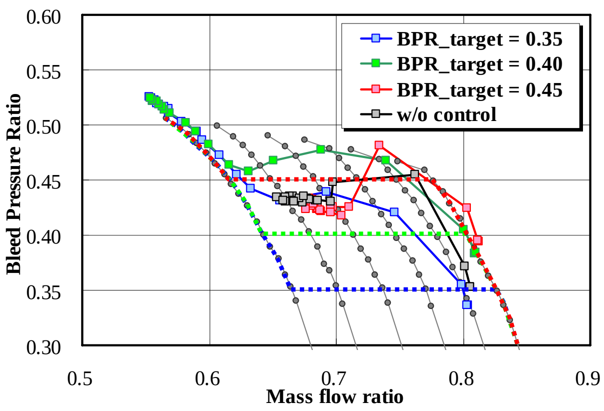


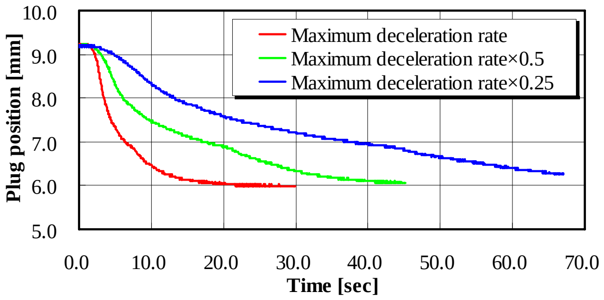
Fig.20 Variation of bleed pressure ratio

In the case for the target bleed pressure ratio of 0.45, the ramp slightly moved. In the process of the variation of bleed pressure ratio, there appeared abrupt decrease accompanying considerable oscillation, which is similar to the case without inlet control (fig.18).

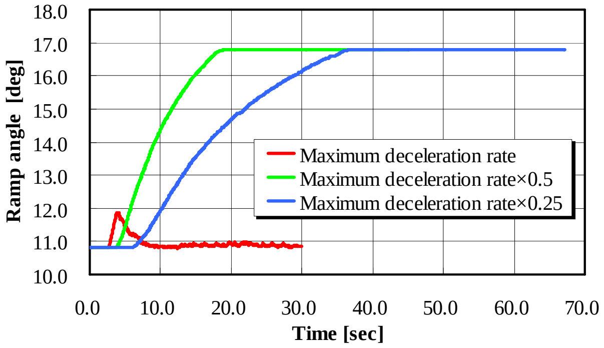
Figures 19 and 20 shows the diagram adding the experimental results to the diagram shown in figs.14 and 15. It is clearly found that the oscillation of the bleed pressure ratio shown in fig.18 is caused by the occurrence of buzz. In addition, the experimentally obtained inlet operating conditions are different to ideal ones even when the buzz did not occur. It is thought that these discrepancies are due to the slow movement of the actuator of the variable ramp rather than the response delay of the control law. Experimental results also indicated an important knowledge that the inlet operating condition was never recovered from buzz by the current control law because there are two operating conditions for one value of the bleed pressure ratio as shown fig.4. Consequently, for the process of the engine deceleration, it is important to set the target bleed pressure ratio far from the boundary of buzz initiation or to pay considerable attention to the rate of engine deceleration in order to avoid the buzz occurrence.

### 4.3 Requirement to engine operation

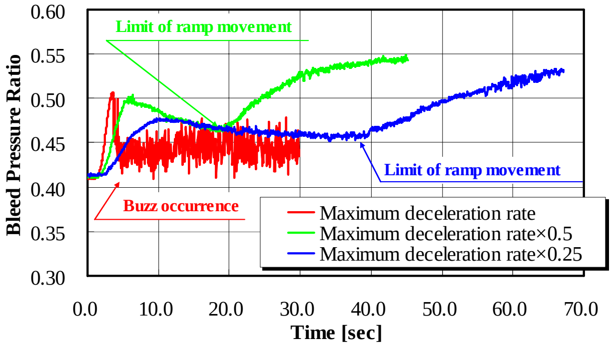
The problem caused by the slow movement of the actuator of the variable ramp was point out in previous section. As a solution for this serious problem, it is thought to be effective to apply more powerful actuator to the variable ramp system as an alternative. However, the actuator becomes more powerful, the weight would be heavier. It is not good from the viewpoint of equipment to the airplane system. According to the viewpoint mentioned above, making certain limitation about the rate of change of the engine operation would become important. In order to clarify the requirement to engine operation, three rates of the engine deceleration were examined (fig.21). The condition of which deceleration rate is maximum coincides with the case shown in fig.16. The target bleed pressure ratio was set to the value of 0.45, which is nearest to the buzz boundary in examined cases. The results shown in figs.21, 22 and 23 clarify that the discrepancy of the experimental result to the ideal performance becomes smaller as the rate of the engine deceleration rate is slower. Especially in the case of the slowest engine deceleration rate, the bleed pressure ratio was kept almost constant, and the inlet pressure ratio varied along the ideal line. As a result, buzz of second stage occurred for the fastest rate, and stable inlet operation was never recovered. For the medium rate, buzz was observed partially in the process, however it was first stage where the bleed pressure ratio still increases as reducing mass flow rate (fig.4), so that the stable inlet operation was recovered from the buzz condition. Buzz was successfully avoided only for the case for slowest rate. Consequently, the engine should be operated with its rate at least as slow as quarter to the maximum rate as the requirement for the stable inlet operation.



(a) Various setting for engine deceleration rate



(b) Time variation of ramp angle



(c) Time variation of bleed pressure ratio

Fig.21 Effect of engine deceleration rate on inlet control for buzz avoidance

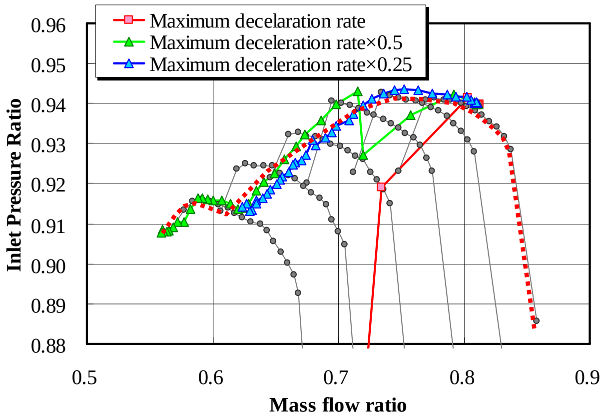


Fig.22 Effect of engine deceleration ratio on variation of inlet performance

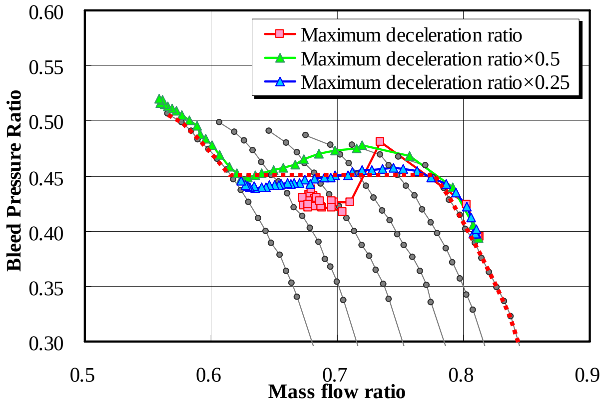


Fig.23 Effect of engine deceleration ratio on variation of bleed pressure ratio

## 5 Conclusions

In this study, validation of the control concept for the stable inlet operation was performed. It was proofed that the range of stable inlet operation could be extended by the control using variable ramp. Because the function to emulate actual behavior of the engine or actuator was installed to the experimental model, the knowledge about the response of variable ramp system and the requirement for the engine operation was obtained.

## References

[1] Ferri A and Nucci L M. The Origin of Aerodynamic Instability of Supersonic Inlets at Subcritical Conditions. *NACA-RM-L 50K30*, 1951.

[2] Dailey C L, Supersonic Diffuser Instability. *J. Aeronautical Sciences*, Vol. 22, No. 11, 1955.

[3] Murakami A, Watanabe Y and Fujiwara H. Aerodynamic Design and Wind Tunnel Tests of 2nd Configuration Air-Intake for Jet-Powered Supersonic Experimental Airplane. *NAL TM-774*, 2003. (in Japanese)

[4] Watanabe Y, Murakami A and Fujiwara H. Effect of Sidewall Configuration on the Aerodynamic Performance of Supersonic Air-Intake. *AIAA2002-3777*, 2002.

[5] Fujiwara H, Murakami A and Watanabe Y. Numerical Analysis on Shock Oscillation of Two-Dimensional External Compression Intakes. *AIAA2002-2740*, 2002.

[6] Seddon J and Goldsmith E L. *Intake Aerodynamics*. 2nd edition, AIAA Education Series, 1999.