DESIGN OF TOP MOUNTED SUPERSONIC INLET FOR SILENT SUPERSONIC TECHNOLOGY DEMONSTRATOR S3TD

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Abstract

The top mounted supersonic inlet has been designed for the silent supersonic technology demonstrator, S3TD. The inlet is fixed geometry in order not to complicate the system of the unmanned air vehicle. In order to compromise the inlet performance at both low speed and supersonic regimes, the cowl lip was designed very carefully. The bleed system through porous wall was also applied on the surface of the ramp to improve the inlet performance.

Inlet performances were evaluated by means of numerous CFD analysis with unique boundary condition which is able to estimate the bleed mass flow through porous wall. According to CFD results, aerodynamic database was made as well as the operative process of the bleed during the flight was established.

Wind tunnel tests were carried out to define the operation limit by the characteristics of the inlet in low speed regime where the temporal variation of the spatial distortion become large. Furthermore, discussion about the buzz criteria in the supersonic cruise condition was also made in this paper.

1 Introduction

The preliminary design of the silent supersonic technology demonstrator, S3TD, has been done in Japan Aerospace Exploration Agency, JAXA. Figure 1 shows the demonstrator. S3TD is an experimental unmanned air vehicle, of which length, weight and flight Mach number are about 14 meters, about 4.2 tons and 1.6 respectively. The one of the main object of developing the demonstrator is to validate the unique design technology for the reduction of sonic boom in supersonic flight. In order to minimize the effect of the propulsion system, such as exhaust jet or spillage flow, on the characteristics of sonic boom, top mounted propulsion system was adopted to S3TD[1]. Honewell's F125 afterburning engine, having sufficient performance to ensure the flight mission, was chosen as the motor.

In the preliminary design phase, there are two main objectives. One of them is to make aerodynamic database of the inlet which consist of pressure recovery, distortion and external drag. This framework also includes aerodynamic design of the inlet in order to compromise the performance in whole flight envelope, and the design of the bleed system. Another is to define the limit of the inlet operation. Temporal variation of the spatial distortion in low speed regime and buzz occurrence in supersonic condition are main subjects which should be considered. Both numerical simulations and wind tunnel tests were carried out for these matters.

Fig. 1. Schematic of S3TD

2 Aerodynamic design of inlet

2.1 Design policy

Figure 2 illustrates the system of the inlet. The supersonic inlet is fully external compression type with three shock system. The inlet is fixed geometry in order not to complicate the system of the unmanned air vehicle. Bleed system with porous wall was adopted to improve the aerodynamic performance by removing the boundary layer developing on the ramp. Design Mach number is 1.6 and the operation range of the inlet was defined from the takeoff to the supersonic cruise. The inlet was sized to fit the characteristics of Honewell's F125 engine, which is assumed to be used for S3TD.

Aerodynamic performances of the inlet were evaluated by four parameters, mass flow ratio, pressure recovery, spatial / time distortion and external drag. Spatial and time distortion indices, which limits the engine operation, are parameters to be satisfied with the highest priority in order to ensure engine operation.

2.2 Configuration of inlet

Figure 3 shows the configuration of the inlet. The supersonic diffuser ramp consists of two nearly cylindrical surfaces for three shock system with turning angle of 7 and 8 degrees respectively. S-shaped subsonic diffuser was designed to make viscous loss small as possible by setting optimal area distribution and the shape of centerline as important design parameters of a diffuser. Length of the diffuser duct is three times of the diameter of the engine fan. The cross section of the diffuser duct, of which shape at the throat is distorted to fit the lower mold of the nacelle to the fuselage, changes to be circular at the exit of the inlet.

2.3 Sizing of the inlet

The inlet was sized for maximum demand of the engine operation, including margin of 4 percent, in the envelope of the flight mission. Figure 4 shows the variation of mass flow ratio of the engine operation. In subsonic regime, engine mass flow is normalized by choked mass flow based on the flow through the throat area A_{th},

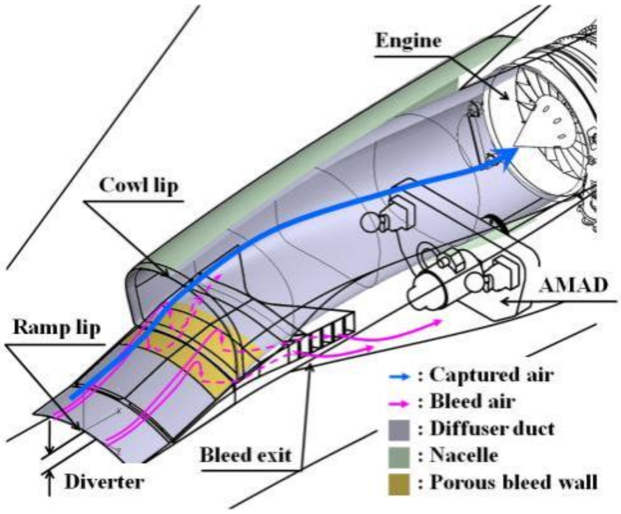
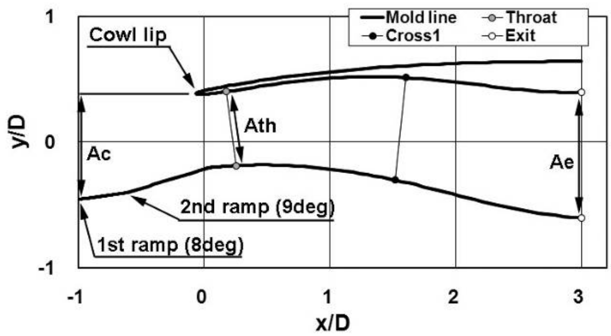
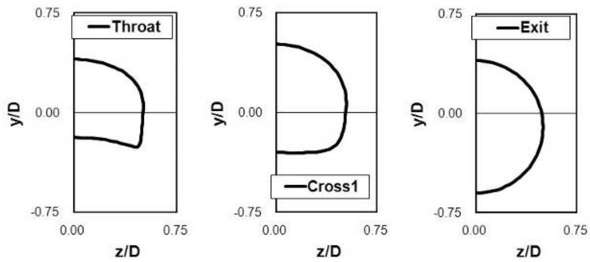


Fig. 2. Detail of inlet system



(a) Side view diffuser



(b) Front view of cross section

Fig.3. Configuration on inlet

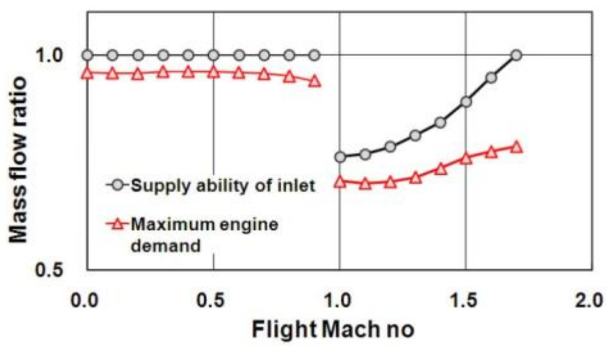


Fig.4. Supply ability of inlet and demand of engine

otherwise it is normalized by captured mass flow based on the capture area A_c. The maximum demand of the engine air flow condition appears at the condition of high subsonic and high altitude. Thus the difference of mass flow between supply ability of the inlet and demand of the engine at supersonic cruise condition is significantly large and it causes high spillage drag.

2.4 Design of cowl lip

Cowl lip is one of the important portion of an inlet, by which aerodynamic performance can be affected considerably in both low speed and high speed regime. Generally, thin cowl lip improves aerodynamic performance in high speed regime with its low drag characteristics, whereas it impairs performance in low speed regime by causing lip separation. Thus the compromizing, especially about design of the thickness of the cowl lip, is important. The thickness ratio of the cowl was given based on the definition of NACA 4-digit series, which chord length is equal to the diameter of the engine fan. Camber line of the cowl lip depends on the area distribution of the subsonic diffuser. The thickness of lower portion from the camber was changed while upper portion was kept thin. This is based on the fact that thicker upper portion of the cowl increase the drag in high speed regime without making the performance better in low speed regime. Figure 5 shows three kinds of mold line of the cowl lip, C1, C2 and C3, which were examined in this study. The thickness ratio of the upper portion is 3 percent for all configurations, while that of lower side is changed from 3 (C1) to 9 (C3) percent every 3 percent.

Figure 6 and 7 show the change in supply ability of the inlet in subsonic regime and change in external drag of the inlet at full flow condition in supersonic regime respectively. Both results were obtained by means of CFD analysis. Air supply ability of the inlet with thinnest cowl lip configuration C1 is low so as to a strict limit to operation of the engine at takeoff condition have to be taken. C3 configuration has the best performance at low speed regime, however, the external drag in

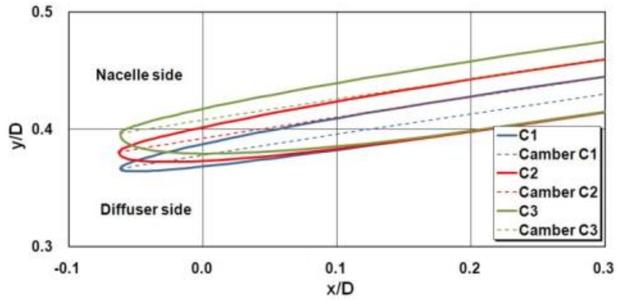


Fig.5. Mold line of cowl lip

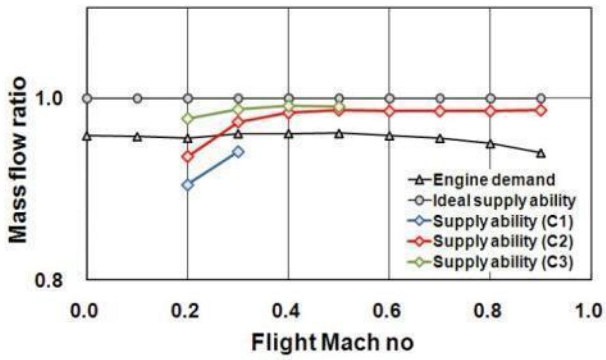


Fig.6. Change in supply ability

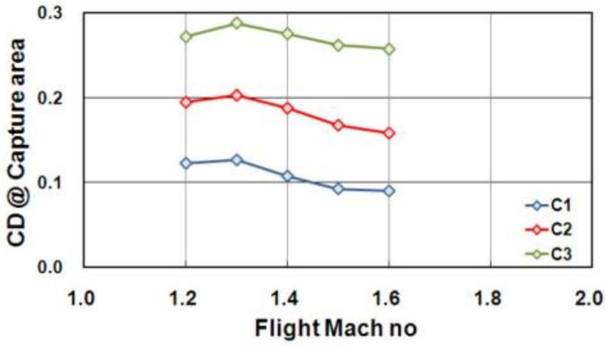


Fig.7. Change in external drag at full flow condition

supersonic flight condition is too high to ensure the flight mission. Thus the C2 configuration was chosen on the basis of these results in this study. When C2 configuration is adopted, the flight mission would be ensured, although the limitation of the engine operation still remains at a certain range.

2.5 Design of bleed system

Figure 8 illustrates the bleed system. Boundary layer developing on the ramp is removed through the porous wall, of which aperture ratio is about 20 percent of capture area A_c. Bleed air is ejected from the bleed plenum to outside. It is regulated by bleed exit with opening of about 8

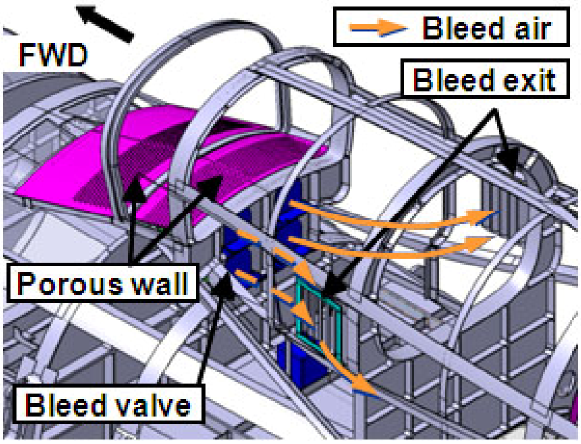


Fig.8. Schematic of bleed system

percent of the capture area. Four valves installed in the bleed plenum are used to prevent reflux of bleed.

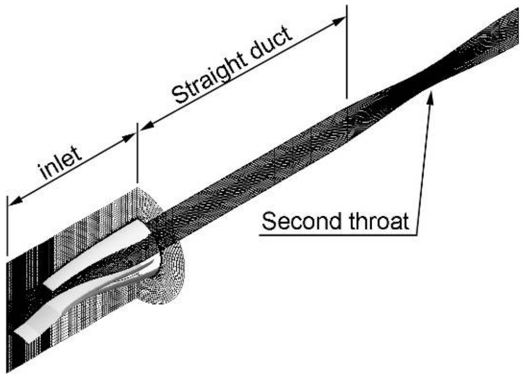
3 Inlet performance

3.1 CFD analysis

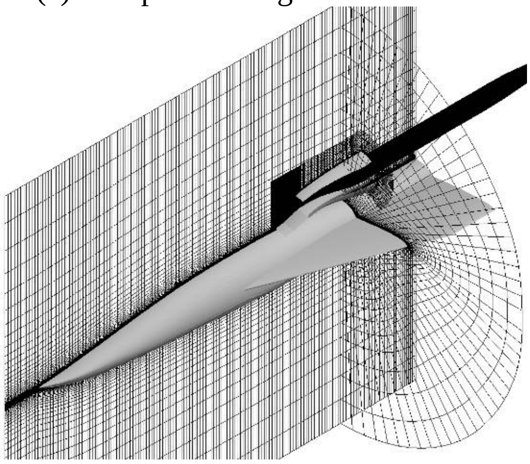
CFD analysis was employed to evaluate inlet performances. Especially, the estimation of the external drag of the inlet, which is thought to be difficult to evaluate by wind tunnel tests, is expected. Three dimensional N-S equation was solved by CFD method including turbulence model. Both internal and external flow fields were calculated by using overset grid with about two million points shown in fig. 9. A straight duct followed by the second throat was connected downstream of the inlet in order to simulate throttling of the engine by changing its area. Aerodynamic database on the pressure recovery and the external drag, as a result of matching the inlet condition to the engine operation, was made for the numerous conditions including whole flight envelope. Unique boundary condition[2], which is able to estimate the flow rate of the bleed through porous wall even in the case of reflux, was applied. By the use of this technique, the point of operation of the bleed valve was established.

3.2 Wind tunnel tests

Wind tunnel tests were also employed to evaluate inlet performances. Especially, the estimation of spatial and time distortion, which



(a) Computational grid around inlet



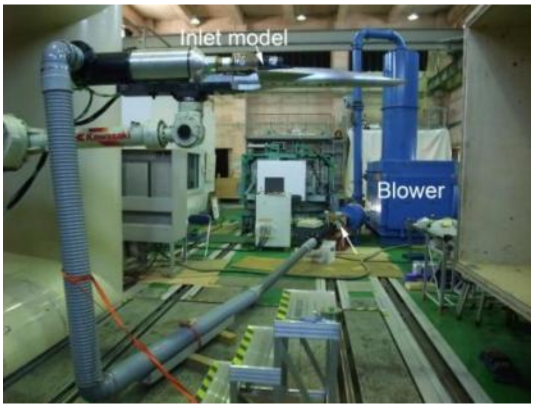
(b) Overset grid

Fig.9. Computational grid

is hard to evaluate by means of CFD analysis used in this study, is expected. Three kinds of wind tunnel tests were carried out at JAXA's 2m×2m Low-speed Wind Tunnel, 2m×2m Transonic Wind Tunnel and 1m×1m Supersonic Wind Tunnel as shown in fig.10. Making of aerodynamic database, verifying the limit of engine operation at low speed condition, verifying the operation point of the bleed valve in transonic regime and verifying of avoidance of the occurrence of buzz in supersonic regime are major objectives of wind tunnel tests.

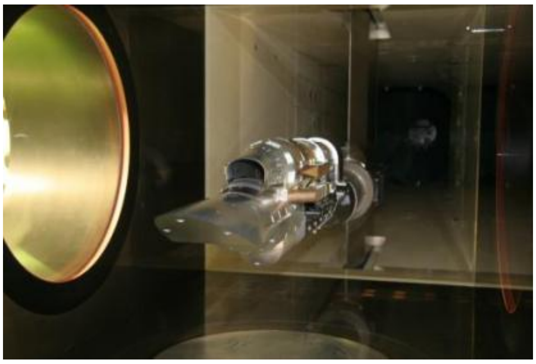
3.3 Inlet performance

Figure 11 shows the results of CFD analysis for the inlet condition corresponding to maximum rating of the engine as an example. Variations of pressure recovery and the external drag by the change of the inlet operation condition were obtained as shown in fig.12. The performance data obtained from the result shown in fig.11



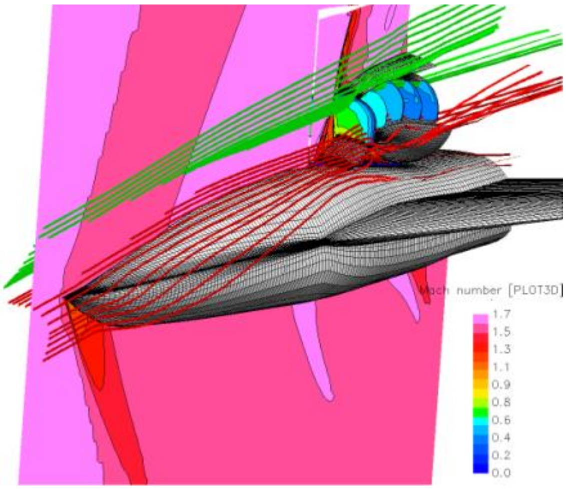
(a) Low speed wind tunnel tests


(b) Transonic wind tunnel tests


(c) Supersonic wind tunnel tests
Fig.10. Overlook of wind tunnel tests

corresponds to only one point in this chart. Engine operation with maximum rating matches to the subcritical inlet operation condition, which is far from critical condition, in the case of Mach number of 1.6. It implies the external drag is considerably high at the matching point. This is because the supply ability of the inlet is much more than the demand of the engine as a result of sizing of the inlet. Removal of air by the bleed has the effect that the inlet operation condition shifts toward the critical. Although internal drag caused by the bleed increases, quantity of the decrease of the spillage drag is larger. Thus, applying the bleed system relieves the tendency that the external drag is high. When the object of applying bleed is only the improvement of pressure recovery, only a few percent of the bleed was found to be sufficient. However, when the reduction of the external drag is expected to the bleed, more bleed would be required. It is the reason that the quantity of the bleed was set to 8 percent. On the other hand, the bleed more than 8 percent was found to have an influence to the sizing of the inlet.

Figure 13 shows inlet performances as the function of flight Mach number. Each value indicates the result of matching to the maximum rating of the engine. Angle of attitude was assumed to be a nominal condition. Pressure recovery of the inlet is achieved as high as a performance of the military specification in supersonic condition. Performances of pressure recovery in the case with and without bleed system reverse mutually at around Mach 0.8. It is caused by the reflux of the bleed from the bleed plenum to the diffuser duct. This result implies that the bleed valve, which prevent the



(a) Mach contour and stream line

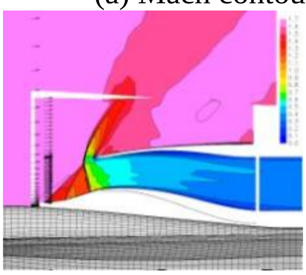
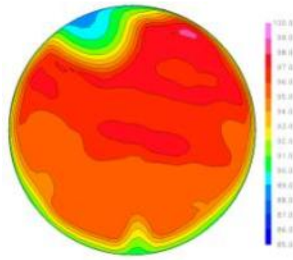
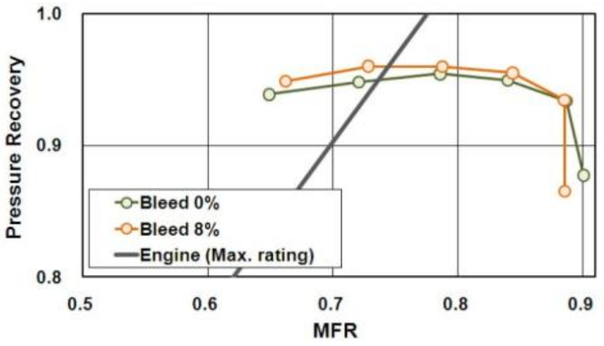
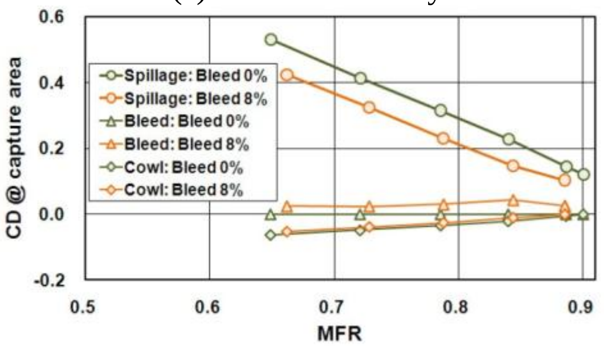


(b) Mach contour (c) Total pressure distribution

Fig.11. Result of CFD analysis
(M=1.6, α=6deg, β=2deg, Bleed:8%)

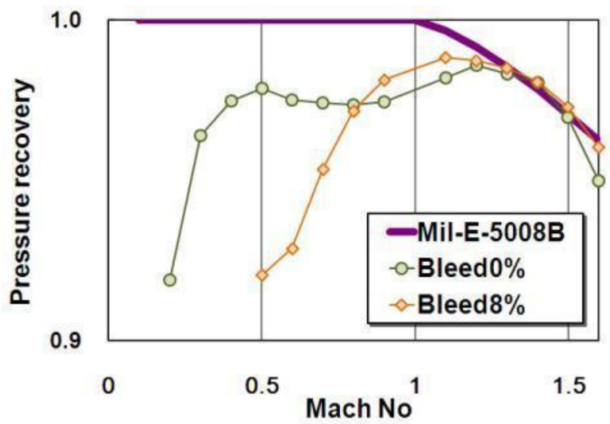


(a) Pressure recovery

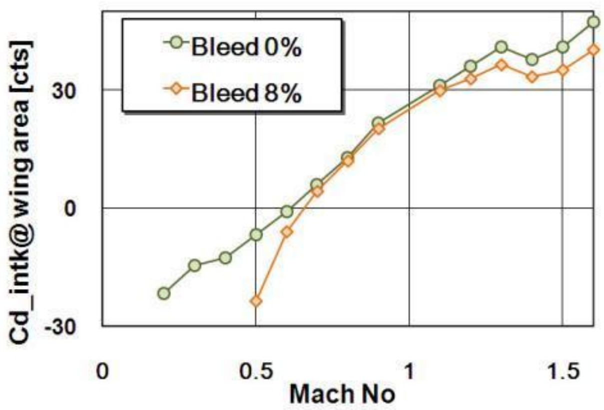


(b) Component of external drag

Fig.12. Inlet performance at a certain condition (M=1.6, α=4deg, β=0deg)



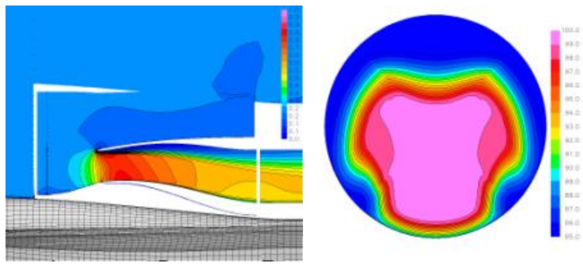
(a) Pressure recovery



(b) External drag based on wing area

Fig.13. Variation of inlet performance

reflux, should work at around Mach 0.8. Abrupt drop of pressure recovery seen at Mach number 0.2 is caused by the lip separation as shown in fig.14. External drag of the inlet, to which the bleed system is applied, is lower in whole flight Mach number. The effect of the bleed system on the reduction of external drag is remarkable with about 8 counts at high supersonic condition. These database of the inlet was utilized for performance analysis of the vehicle. As a result, the inlet system was found to be designed to have sufficient performances to ensure flight mission.



(a) Mach contour (b) Total pressure distribution

Fig.14. Result of CFD analysis (M=0.2, α=15deg, β=0deg, Bleed:0%)

3.4 Temporal variation of spatial distortion

As shown in fig.14, lip separation occurs in low speed regime. It is thought to enhance the unsteadiness of the flow inside the diffuser, which is main concern in a point of view of distortion criteria of the engine. Actually, engine rating is limited in order not to exceed the distortion criteria. Wind tunnel tests were carried out to verify the limit of the engine rating. Indices which express distortion in circumferential and radial direction, prescribed in SAE guideline[3], were used to evaluate spatial distortion. Total pressure rake, which consist of 50 unsteady pressure transducers exposed in flow directly as shown in fig.15, set downstream of the exit of the inlet was used in the test.

Figure 16 illustrates the result of low speed wind tunnel tests with experimental setup shown in fig.10a. Numbers put on the diagram correspond to the total pressure distribution at the exit of the inlet. A line, named "throttled operation", means the limit of the engine

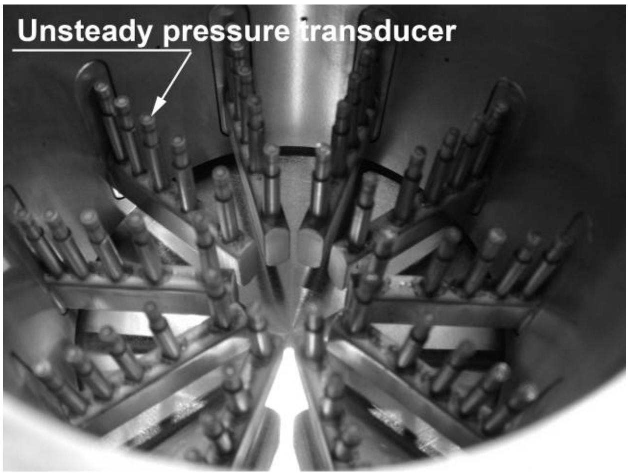
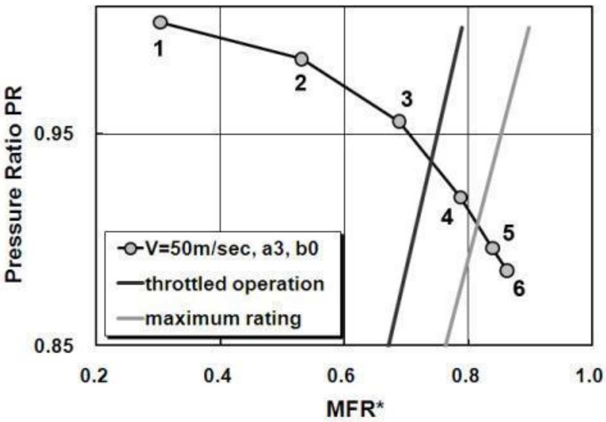
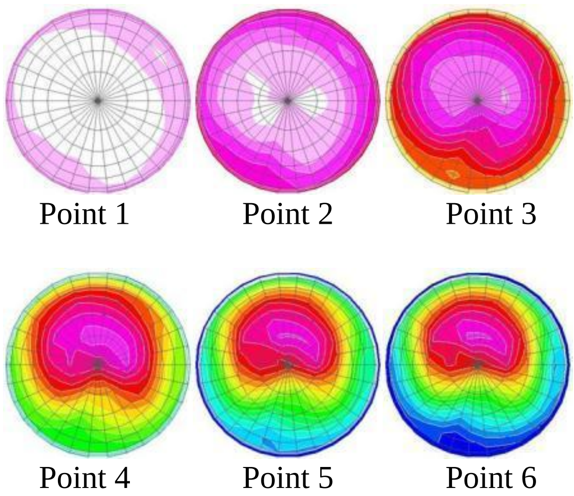


Fig.15. Unsteady total pressure rake



(a) Pressure recovery



(b) Total pressure distribution

Fig. 16. Example of experimental result
(V = 50m/sec, α=3deg, β=0deg)

operation prescribed on the basis of the result of preliminary design. Total pressure distributions are the results of averaging the data acquired by the unsteady total pressure rake. Instantaneous patterns of the total pressure distribution are shown in fig. 17 marching to lower right from upper left. Experimental condition corresponds to the point 4 shown on the diagram fig.16a. Variation seems not to be periodic. Temporal change in pattern is evaluated by the use of distortion indices. Figure 18 shows the change

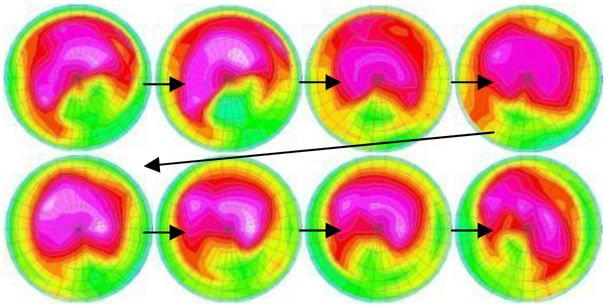
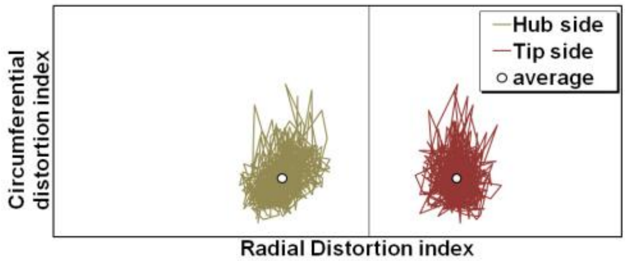
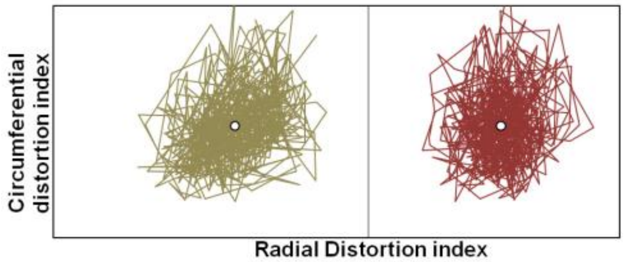


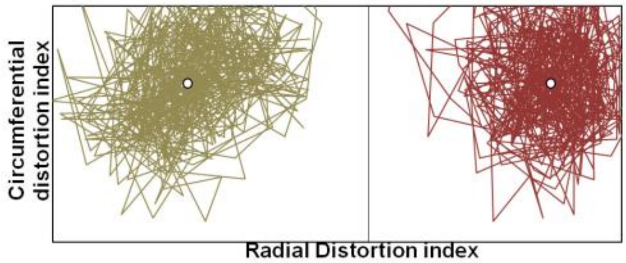
Fig.17. Temporal variation of total pressure distribution



(a) Point 3



(b) Point4



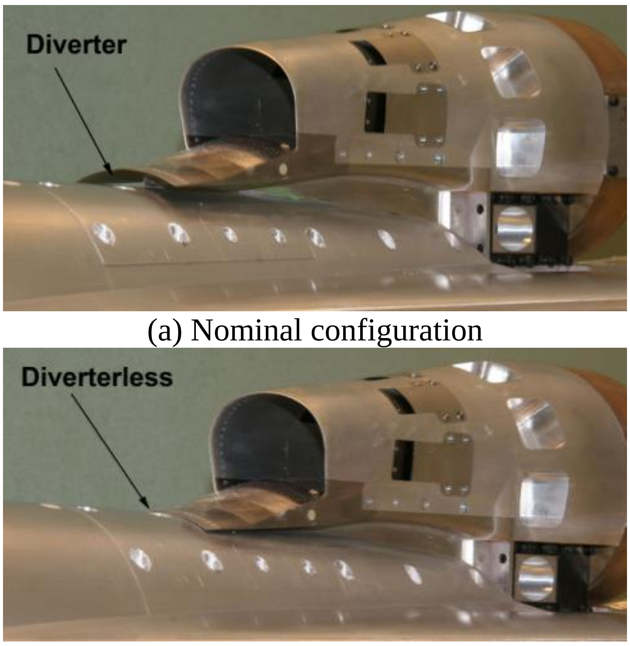
(c) Point 5

Fig.18. Change in distortion indices
(V = 50m/sec, α=3deg, β=0deg)

in distortion indices. Bounds of a diagram indicate the distortion criteria of the engine, in which the engine operation is guaranteed. As the engine rating rises, variation of distortion indices becomes large. Finally, it exceeds the limit as shown in fig. 18c. However, in the condition approximately equal to the throttled operation, the variation of distortion indices satisfies the limit (fig.18b). Throttled operation, which is set as the limit of engine operation, is decided to be suitable by verifying the variation of distortion indices for the whole assumed flight conditions.

3.5 Criteria of Buzz Occurrence

To define the criteria of buzz occurrence in supersonic regime is important in order to ensure the engine operation. In this study, conditions of the buzz occurrence was examined by the supersonic wind tunnel tests (fig.10c). One of the main objects of the test is to clarify the effect of the boundary layer developing on the fuselage on the occurrence of buzz. However, forward half of the fuselage of the inlet model was cut away as shown fig.10c, because the model is large relative to the blockage ratio of the wind tunnel. This means the boundary layer at the tip of inlet ramp of the model is relatively thinner than that of the S3TD.



(a) Nominal configuration

(b) Diverterless

Fig.19. Setting of diverter

In this situation, the effect of the boundary layer could be underestimated. In order to deal with this concern, the inlet model without the diverter was prepared as shown in fig.19.

Figure 20 shows the variation of pressure recovery. Buzz occurs in the subcritical condition far from the range of the engine operation for the nominal configuration. Whereas for the diverterless configuration, thicker boundary layer facilitates the buzz occurrence, although the point of buzz occurrence is outside the range of the engine

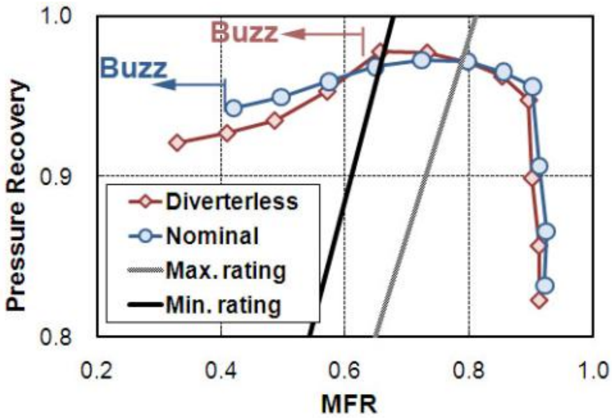
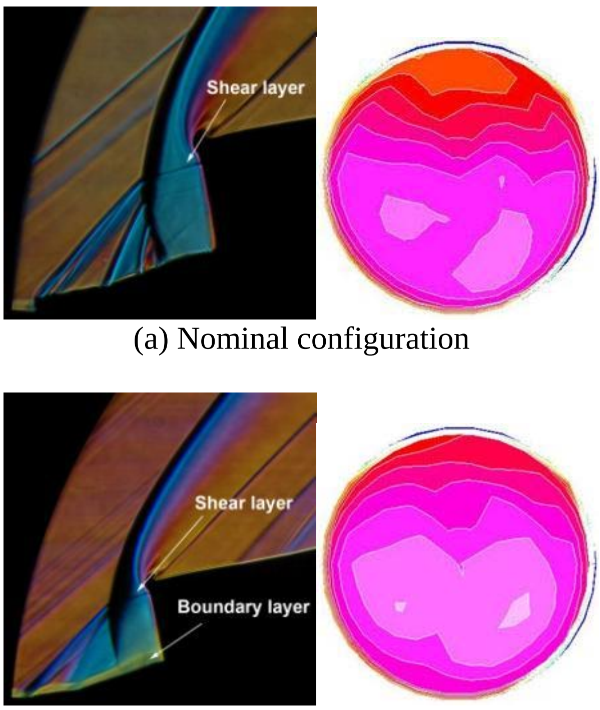


Fig.20. Pressure recovery
(M=1.6, α=0deg, β=0deg)



(a) Nominal configuration

(b) Diverterless

Fig.21. Shock pattern and pressure distribution

operation. Therefore, it seems that special procedures are not necessary to avoid the buzz. Figure 21 shows the shock pattern around the supersonic diffuser and the total pressure distribution at the exit of the inlet. The flow condition corresponds to the matching point of the engine operation with minimum rating. The shock pattern is slightly different by the configuration of diverter. This difference causes the change in height of shear layer ingested into the subsonic diffuser. Thus the low pressure region in the exit plane for the nominal configuration is larger than that of the diverterles configuration. The buzz appeared in this study would be Dailey type[4][5], because the shear layer is ingested under the stable condition in the case of all. Once buzz occurs, pressure oscillates accompanying very large amplitude which is about half of total pressure as shown fig.22, and the shock wave also oscillates in flow direction periodically as shown in fig.23.

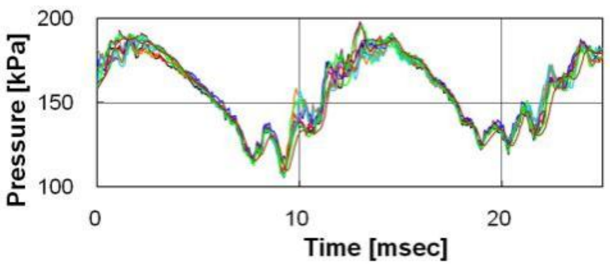


Fig.22. Pressure oscillation under buzz

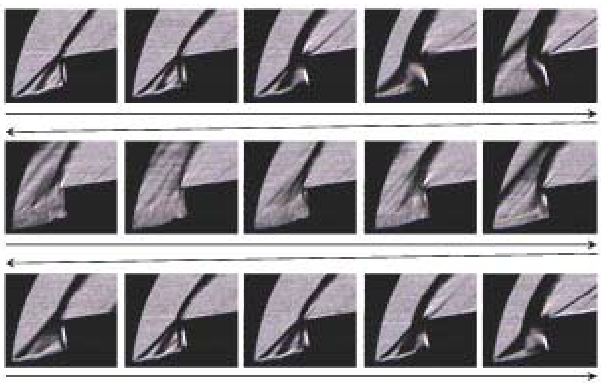


Fig.23. Result of observation of buzz

4 Conclusions

The top mounted supersonic inlet for the technology demonstrator S3TD developed in JAXA has been designed. By compromizing the configuration of cowl lip, the flight mission of the S3TD would be ensured, although the limitation of the engine operation, which was verified by the low speed wind tunnel tests, still remains at a certain range. The bleed system was also designed including its operation method. The aerodynamic database obtained by means of CFD analysis showed that the inlet has sufficient performances to ensure the flight mission of S3TD. Criteria of buzz occurrence was examined by the supersonic wind tunnel tests. It was found the special procedure is not necessary for the avoidance of buzz.

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