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FEASIBILITY STUDY OF SHORT SUBSONIC DIFFUSER CONCEPT FOR SUPERSONIC INLET

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Abstract

Two design concepts for shorting a subsonic diffuser for supersonic air-inlet were studied for examining those effects on engine thrust, airframe drag and wight of supersonic aircraft. One is bifurcated subsonic diffuser concept which divides a single duct into two equal area ducts, and the other is constant area duct concept which replaces a subsonic diffuser for zero divergent angle duct with bypass system. Those aerodynamic performances were examined by using CFD technique, and total effects on a cruise range was evaluating with assuming the small supersonic aircraft proposed by JAXA. It is found that the bifurcated subsonic diffuser concept has a potential to increase a cruise range of supersonic aircraft. The constant area duct concept requires both internal and external drag reduction for improving its feasibility.

Keywords: Supersonic aircraft, Propulsion/Airframe Integration, Inlet, Subsonic diffuser, CFD

1. Introduction

Future commercial supersonic aircraft need to achieve high performance in both economic potential and environmental suitability. Propulsion/airframe integration, PAI, design is a key technology. Supersonic inlet, which is an important component for propulsion system, should be designed to improve not only the thrust but also aerodynamic drag and structural weight with considering PAI.

One of a direction of technology development of supersonic inlet is shortening a subsonic diffuser for reducing weight of engine nacelle [1][2]. On the other hand, it accompanies with disadvantage on aerodynamic performance of the inlet. In inlet design, an area ratio of subsonic diffuser is determined basically from an engine demand, and a diffuser length is set long enough for preventing flow separation.

To shorten the subsonic diffuser with keeping the area ratio means that increasing a divergence angle of the subsonic diffuser. The minimum length is generally restricted by the maximum divergence angle which does not cause flow separation [3]. Thus, some design technique which reduce the divergence angle would be required for shorting the subsonic diffuser beyond the usual limit. The authors have been examined a concept which bifurcates the subsonic diffuser by inserting a splitter plate. In the past study, it showed a benefit on suppressing flow instability caused in a subsonic diffuser with a conventional length. As another approach for decreasing the divergence angle and shortening the subsonic diffuser, the authors put an expectation on a concept applying smaller area ratio compared to a conventional inlet design. Ultimately if the area ratio is set to one, the divergence angle become zero. It would allow that designing the subsonic diffuser as short as possible. On the other hand, since the smaller area ratio reduces a compression function of subsonic diffuser, a reinforcing method should be combined with it and a use of flow bypass is considered in this study.

In order to examine the feasibility of these two concepts in design of short subsonic diffuser, CFD analysis was conducted against supersonic inlet models. These aerodynamic performances were compared with that of a baseline inlet. Variations in not only propulsive performance and external drag but also nacelle weight were evaluated in cruise range as a total effect on aircraft performance.

2. Research method

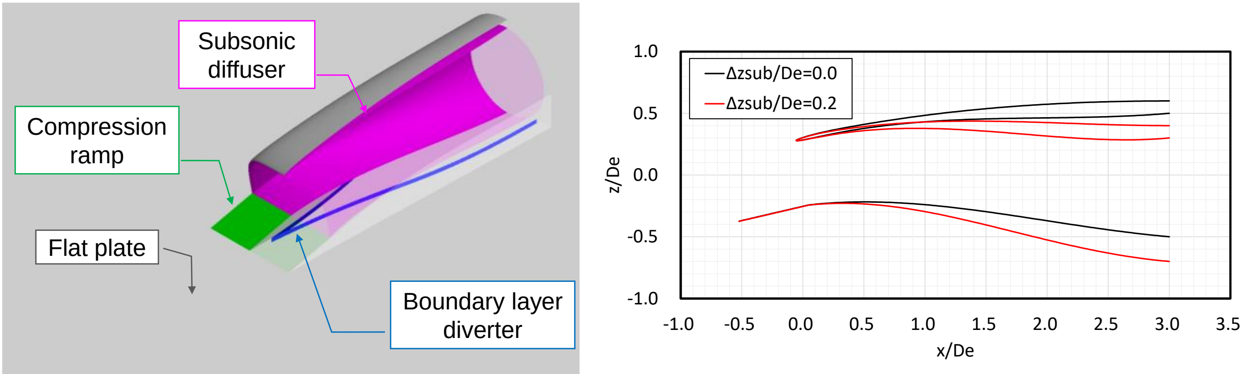
2.1 Baseline model

A baseline inlet was set in order to examine effects of the two concepts for short subsonic diffuser described in the last section. Figure 1 shows a configuration and cross-sectional shape of the baseline inlet. It is conventional external compression type using two shock waves, and consists with single wedge ramp, subsonic diffuser and cowl. The inlet is placed on a flat plate which simulates an airframe surface accompanying with a boundary layer diverter. A design Mach number of the baseline inlet is 1.6.

An area ratio and length ratio of the subsonic diffuser are 1.5 and 3.0 respectively. These values were determined with reference to JAXA's Silent SuperSonic Technology Demonstrator (S3TD) [4] and small supersonic aircraft [5]. A duct offset is varied for examining effects of nacelle placement to airframe. A cross-sectional shape of the subsonic diffuser smoothly changes from rectangular entry to circular exit. A width of the entry is close to a diameter of the exit, and this gives smaller pressure drag on the cowl. A cross-sectional area increases linearly from the entry to the exit. The subsonic diffuser exit corresponds to an aerodynamic interface plane, AIP, with engine.

The cowl has a lip shape with NACA 4 digit airfoil and its thickness 6% of the AIP diameter. The maximum diameter of the cowl is given at the AIP station, and it is 1.2 times to the AIP diameter.

The ramp has no side walls. Its turning angle was set to decelerate a captured free stream to under 1.3 of Mach number and avoid a cause of boundary-layer separation due to an interaction with a terminal shock wave. Its length was set to make shock-on-lip condition at free stream Mach number of 1.65.



(a) Entire configuration (b) Cross-sectional shape

Figure 1 – Inlet model

2.2 CFD analysis method

Aerodynamic performance of the baseline inlet and inlets with short subsonic diffuser concepts were examined by using CFD technique. A free stream Mach number was 1.6, and a Reynolds number is 1.0×10^6 based on the AIP diameter.

Figure 2 shows a computational grid generated around the baseline inlet. A computational domain is half side of a symmetry plane. A long straight duct with a second throat is connected to the subsonic diffuser. The CFD analysis was conducted to several conditions of the second throat area in order to obtain flow field from supercritical to subcritical operation of inlet. A total number of grid points is 4.5 million.

A computational code owned by JAXA was used for numerical calculation, in which the basic equations are 3D-compressive Navier-Stokes equation with k-ε model as a turbulence model [5]. This CFD code was validated through inlet design for JAXA's experimental airplane.

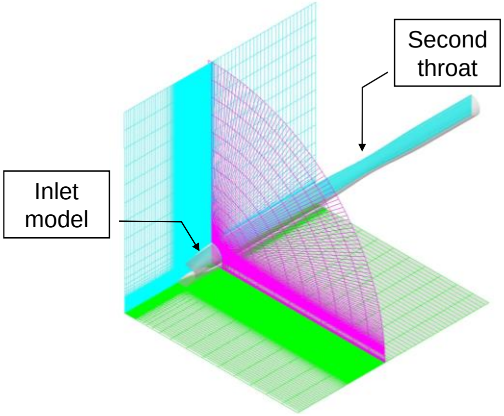


Figure 2 – Computational grid

2.3 Aerodynamic performance evaluation

The length of subsonic diffuser influences not only propulsion performance but also airframe performance since it is a design parameter changing external shape of engine nacelle. In order to examined feasibility of the short subsonic diffuser concepts in terms of the PAI design, both inlet and airframe performance were evaluated from the CFD data.

The inlet performance was composed of mass flow rate, pressure recovery and spatial distortion of supply airflow to engine and drag. A performance index of the mass flow rate is a ratio of mass flow through the AIP to the maximum captured mass flow calculated from the maximum captured area and free stream condition. It is denoted as MFR. The pressure recovery, PR, is a ratio of mean total pressure on the AIP to the free stream total pressure. $D.I._{abs}$ was used as a distortion index in this study. It is a ratio of the maximum pressure difference on the AIP to the free stream total pressure. A pressure loss estimated by the CFD analysis method used in this study was validated through JAXA's inlet developments. The inlet drag, $C_{D,inlet}$, included additive drag, variations of cowl drag and ramp drag from the supercritical condition and internal drag. A reference area of the drag coefficient was the maximum captured area of inlet.

An external drag caused on a nacelle is evaluated as the airframe performance. The nacelle drag, $C_{D,nacelle}$, is defined as a sum of cowl drag, ramp drag and diverter drag at the supercritical condition.

3. Effect of Bifurcated Subsonic Diffuser

3.1 Concept and Verification Method

Figure 3 shows a concept of bifurcated subsonic diffuser in 2D schematic. An original diffuser has a certain divergence angle θ_0 and length L_0. When shortening the diffuser to the half of the original length ($L_1 = 0.5L_0$), its divergence angle becomes twice as much as the original one ($\theta_1 = 2\theta_0$). If a plate is inserted between the diffuser walls, a divergence angle for one of two split ducts becomes half. It is same with the original one ($\theta_2 = 0.5\theta_1 = \theta_0$).

Aerodynamic improving effect of the bifurcated subsonic diffuser was examined by using CFD analysis. Figure 4 shows an inlet model applied the concept. A length of its subsonic diffuser is 1.5 times to the AIP diameter. It is half of the baseline inlet. A plate with zero thickness is placed within the subsonic diffuser to split cross sections horizontally in half. Its leading edge takes distance for 7.5% of the AIP diameter from the entry of the subsonic diffuser with the aim for avoiding pressure loss due to a sharp flow turning. A trailing edge of the plate is positioned on the AIP.

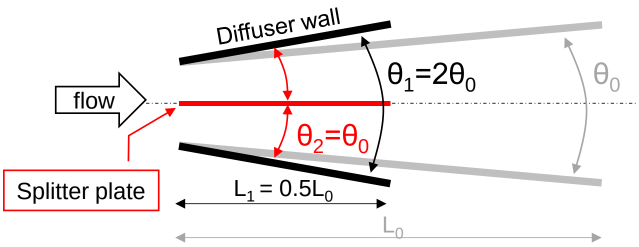


Figure 3 – Concept of bifurcated subsonic diffuser

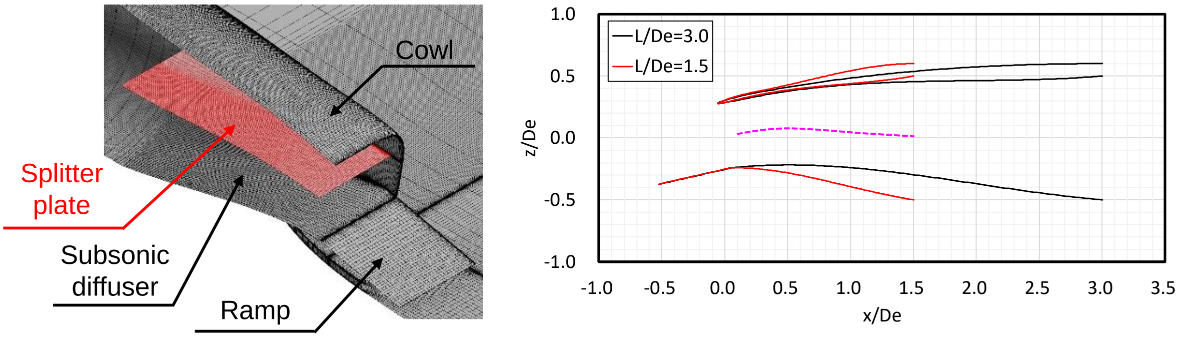
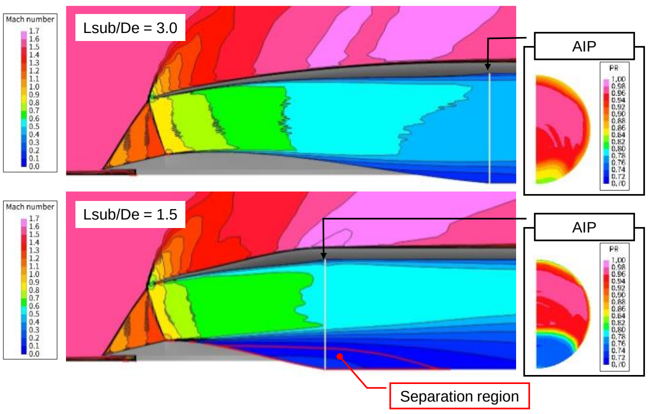


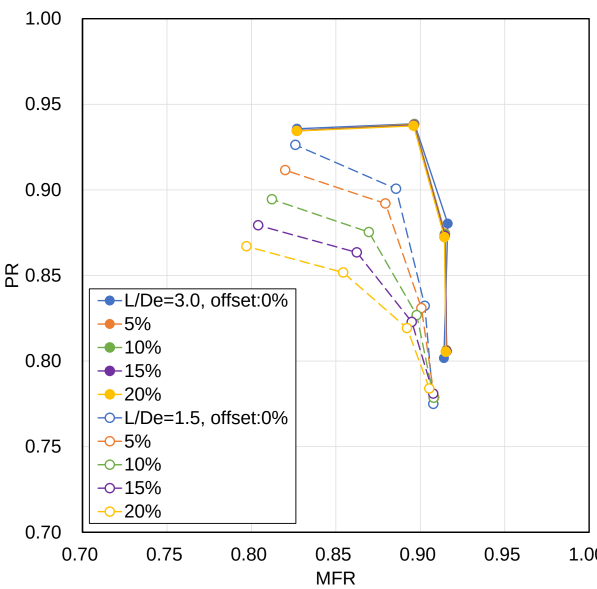
Figure 4 – Configuration of inlet applied bifurcated subsonic diffuser

3.2 Results and Discussion

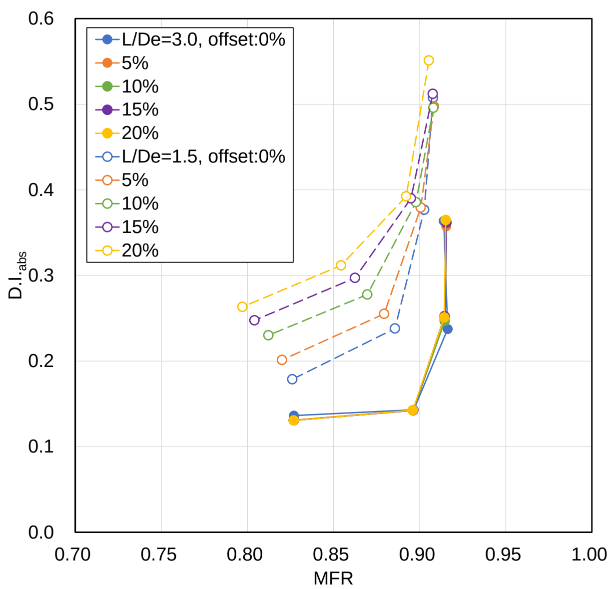
Figure 5 shows CFD results for the baseline inlet (L_{sub}/D_e = 3.0) and the inlet which has the half long subsonic diffuser (L_{sub}/D_e = 1.5) without the splitter plate. A flow separation region could be seen within the shorter subsonic diffuser in fig.5 (a). As a result of the flow separation, low total pressure distributed on the AIP. Its pressure recovery and spatial distortion became worse compared with the baseline inlet as shown in fig.5 (b) and (c). In addition, the higher the subsonic diffuser offsets, the greater the inlet performance degraded.



(a) Flow field



(b) Pressure recovery



(c) Spatial distortion

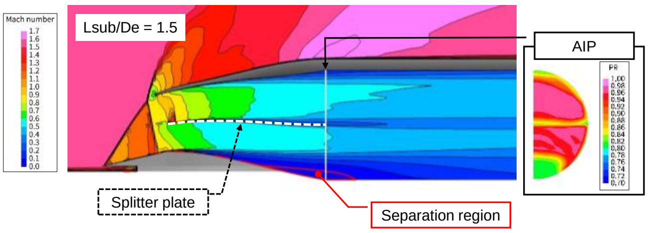
Figure 5 – Influence of subsonic diffuser length

Figure 6 shows CFD results for the inlet with the bifurcated subsonic diffuser. A flow separation region was smaller than the case without the spitter plate shown in fig.5 (a), and higher total pressure distributes on a lower side of the AIP. The pressure recovery was improved as shown in fig.6 (b) although an additional total pressure loss is caused by a development of boundary layer on an upper and lower surface of the splitter plate. The spatial distortion also got better in fig.6 (c). In addition, both the performances became robust to the duct offset. Note that a shock wave occurred on the upper surface of the splitter plate. This implies that the pressure recovery and spatial distortion get better by improving a way of the duct splitting.

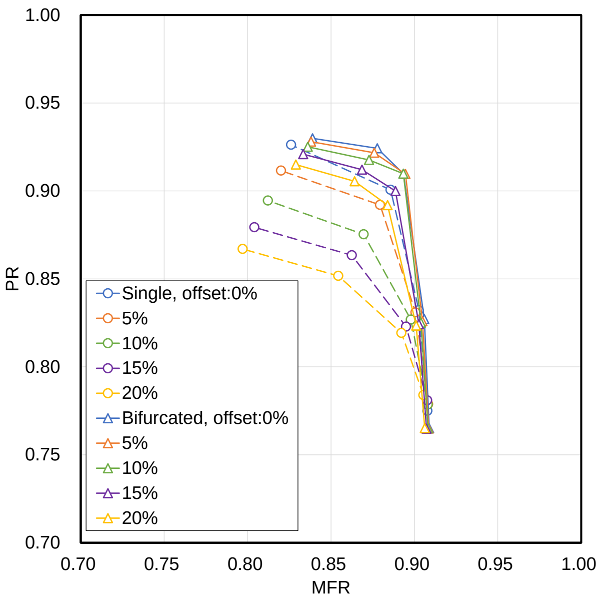
Variation of the nacelle drag is shown in fig.7 (a). It could be said that the nacelle drag become small by applying the short bifurcated subsonic diffuser. The major reason was that the cowl friction drag became half of the baseline inlet as shown in fig.7 (b). Furthermore, amount of the nacelle drag decrease was increased as the offset ratio became large. This effect was produced by the decrease of the cowl pressure drag difference since the slope of cowl surface was decreased with increasing of the offset ratio.

Total improving effect of the bifurcated subsonic diffuser was evaluated in terms of cruise range with assuming a small (50 seats class) supersonic aircraft presented by JAXA [5]. The aircraft was designed to achieve both low sonic boom and low drag. Its specifications are shown in Table 1.

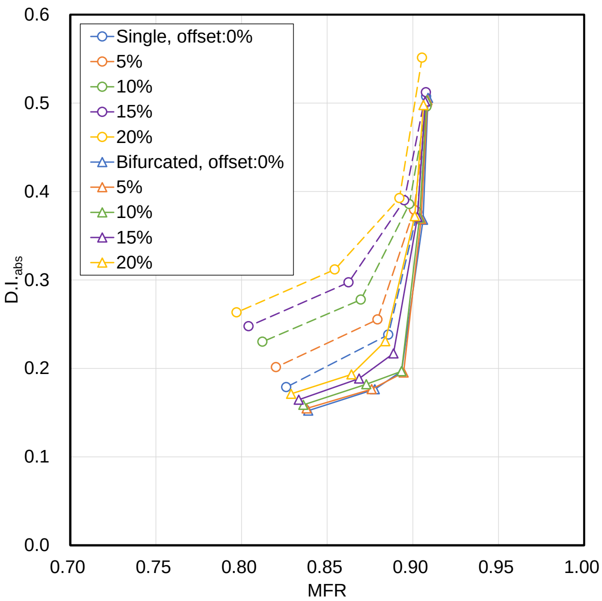
Relationships between the range and variation of the thrust, the aerodynamic drag and the weight were modeled based on the Breguet range equation. One percent decrease on the pressure recovery corresponds 0.9% decrease on the cruise range [7]. In addition, five percent decrease on the spatial distortion was counted as 1% decrease on the pressure recovery since impact on propulsion efficiency was limited when the spatial distortion was within engine operational range [8]. For the nacelle drag, the cruise range was increased by 1.2% when the drag coefficient was decreased by 0.01. Note that variation of the inlet drag was ignored in this section considering that the inlet operated in the critical condition regardless of whether application of the bifurcated subsonic diffuser concept. For the weight, a decrease of 0.1 ton improved the cruise range by 0.2% on a supposition that 70% of the fuel was consumed during the cruise flight.



(a) Flow field

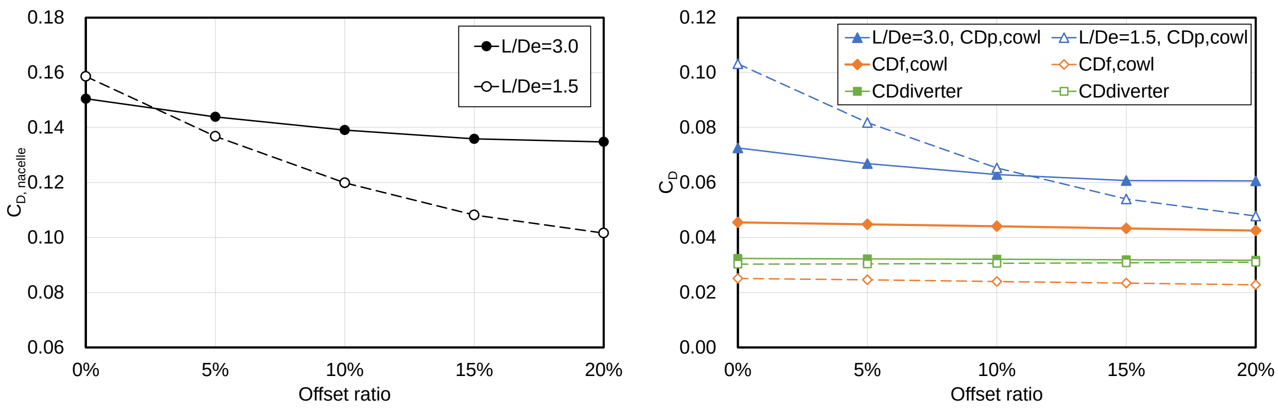


(b) Pressure recovery



(c) Spatial distortion

Figure 6 – Effect of bifurcated subsonic diffuser on inlet performance



(a) Total (b) Components

Figure 7 – Effect of bifurcated subsonic diffuser on nacelle drag

Table 1 – Specifications of small supersonic aircraft

Cruise speed	Mach 1.6	
Range	3500nm	
Lift to drag ratio	8	
Lift coefficient	0.15	
Wing area	175m^2	
Takeoff weight (Fuel weight)	66.6ton (33.8ton)	
Number of engines	2	
Fan diameter	1.7m	
Takeoff thrust	15ton	

The variation of the pressure recovery and spatial distortion were defined as the difference at a same engine speed. Specifically, a value of MFR/PR at the maximum pressure recovery of the baseline inlet was took as the reference engine speed, and both performances for the inlet with the bifurcated subsonic diffuser was obtained by linear interpolation.

The evaluation results are summarized in fig.8. The variation of the thrust showed negative effect on the cruise range since the pressure recovery was still decreased even though the bifurcated subsonic diffuser was applied. For the variation of the drag, the cruise range was extended with the increase of the duct offset. The weight variation gave a constant positive effect to the cruise range independent of the duct offset. Note that a nacelle weight for the twin engines was calculated to 1.8 ton from the takeoff thrust and a supposition of bypass ratio around 3 [9], and the reduction in the inlet weight by halving the subsonic diffuser was estimated to 0.4 ton from length ratio for supersonic transports.

The total effect in fig.8 means a sum of the cruise range variation by the thrust, drag and weight. It showed the positive effect when the duct offset was more than 10%. In addition, it became closer to the weight effect as the duct offset increased. For this reason, the duct offset is an important parameter for gaining the improving effect of the bifurcated subsonic diffuser concept, and it should be applied to supersonic inlet design in case of an engine largely embedded in an airframe.

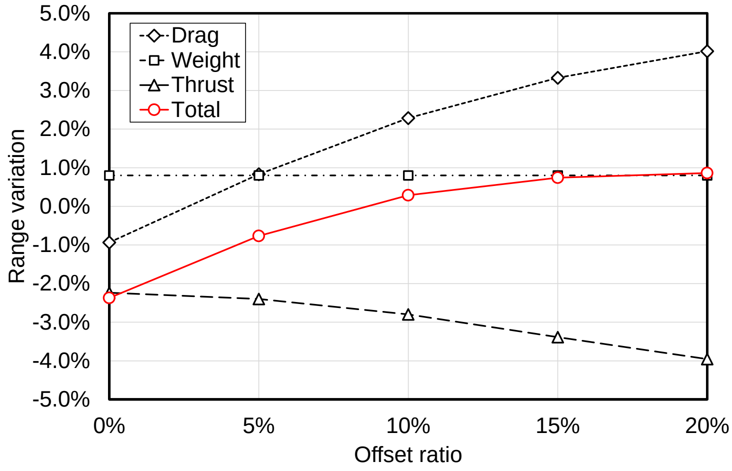


Figure 8 – Total effect of duct splitting

4. Effect of Constant Area Duct

4.1 Concept and Verification Method

Figure 9 shows an inlet concept which has a constant area duct instead of a subsonic diffuser. Since a divergence angle of the duct is zero, its length would be able to shorten without a limit. In contrast, the constant area duct does not have a compression function.

For a conventional external compression inlet, flow through a shock wave system is decelerated by a subsonic diffuser to a Mach number which matches an engine requirement. If this deceleration is not given by the subsonic diffuser, it must be completed before the flow enters the duct. It means that a terminal shock wave of the shock system stands far upstream from the duct and spills a lot of flow captured by the inlet to expand a flow tube accompany with a huge additive drag. Consequently, a propulsion efficiency would drastically deteriorate.

The authors propose that applying a bypass technique with the constant area duct as shown in fig.6 for solving this problem. If some flow is sucked out from the constant area duct, a flow tube would be expanded by that amount.

A wind tunnel test was conducted to verify the compression function by the bypass [10]. Figure 10 shows a bypass inlet model mounted on JAXA's 1m x 1m supersonic wind tunnel. It had a constant area duct which cross-sectional shape transited smoothly from rectangular to circular. Several bypass ducts were connected to the constant area duct through porous wall. A total exit area of the bypass duct, A_{be}, was changed by replacing parts which had several throat areas. A flow plug moved to vary a inlet mass flow during a run, and it was measured by a pitot rake. A compression performance was evaluated from wall pressures measured at upstream and downstream of the porous wall. A free stream Mach number was 1.8.

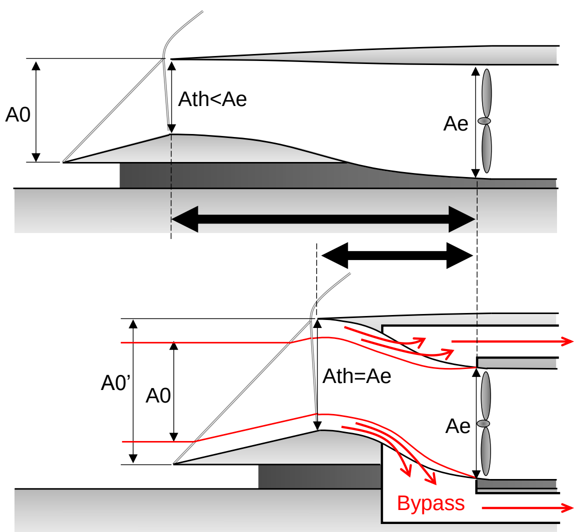


Figure 9 – Concept of inlet with constant area duct

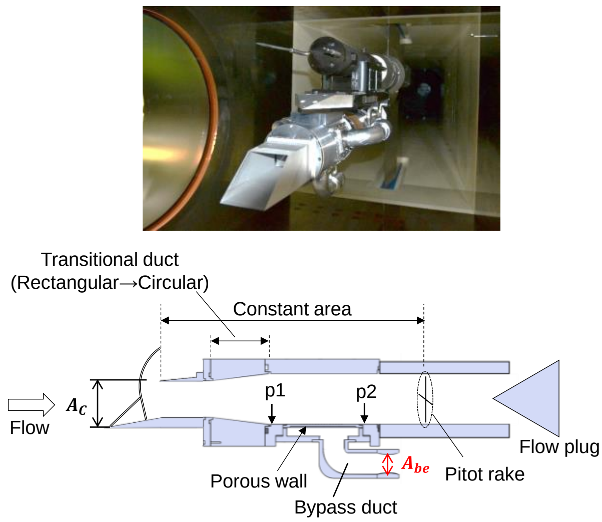


Figure 10 – Wind tunnel model

Figure 11 shows results of the wind tunnel test. The y-axis takes pressure ratio p_2/p_1 to present the compression performance. In case of the bypass duct was close (A_{be}/A_c = 0%), the pressure ratio became around 1.0. It means no compression is performed in the constant area duct. In case of the bypass duct was open, the pressure ratio was more than 1.0 and increased with increasing of the bypass exit area. Besides, a gray solid line in fig.8 shows a theoretical pressure ratio for a subsonic diffuser with an area ratio of a conventional supersonic inlet. The test data for A_{be}/A_c = 40% almost matched with the line. This means that the constant area duct could perform a practical compression function by adapting the bypass mass flow correctly.

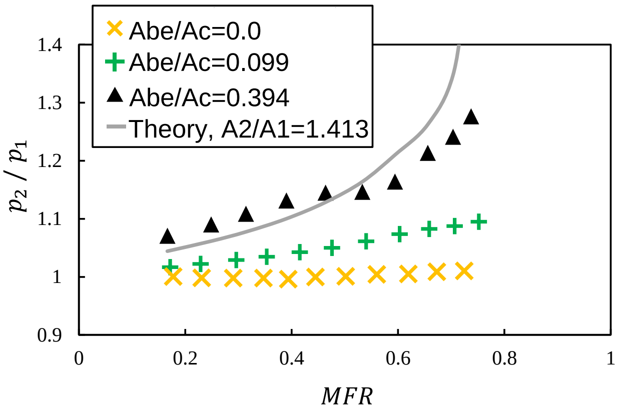


Figure 11 – Compression performance of constant area duct with bypass

In this study, the constant area duct concept was applied to a higher fidelity inlet model for examining its effectiveness on the short subsonic diffuser design. Figure 12 shows a cross-sectional shape of the applied inlet model. It had a short constant duct instead of the subsonic diffuser. Its duct length was 1.5 times to the AIP diameter, and the entry area is equal to the AIP area.

The porous wall bleed system illustrated in fig.13 was assumed to use as the bypass method in this study. Porous wall was applied to the duct wall from the AIP (x_{sub} = 1.5D_e) up to x_{sub} = 0.5D_e station. The maximum cowl diameter, namely the nacelle diameter was 1.5 times to the AIP diameter. It is larger than that of the baseline inlet in order to make space for inner bypass ducts as illustrated in fig.9. The required bypass duct area was estimated by using the Harloff's bleed model [11]. The ramp was extended from that of the baseline inlet for keeping the shock-on-lip design on Mach 1.65. The maximum captured area was 1.5 times to that of the baseline inlet.

In the CFD analysis, the boundary condition model of porous wall bleeding [12] was used to simulate effect of the bypass for saving calculating cost. This model could simulate not only bleeding but also blowing through a wall as shown in fig.14.

An aerodynamic drag caused by the bypassing counted as the internal drag of the inlet was evaluated from the CFD data. The bypass drag was calculated from a momentum equation between the free stream and the exit plane considering a chocked flow at the bypass exit. Furthermore, the following things were assumed to predict the bypass drag: the bypass air flew the inner duct at 0.3 of Mach number, the bypass flow lost 30% of its dynamic pressure within the inner duct, and the direction of discharged flow was inclined 30deg from the free stream direction.

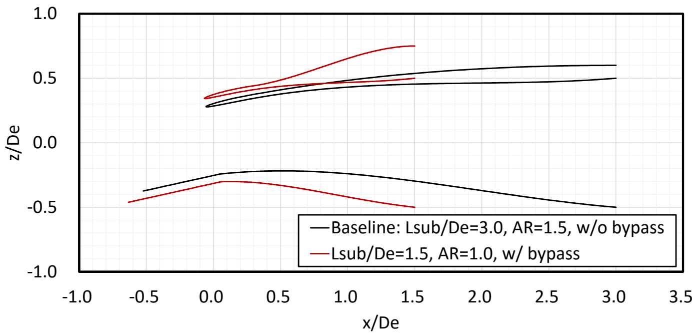


Figure 12 – Configuration of inlet applied constant area duct

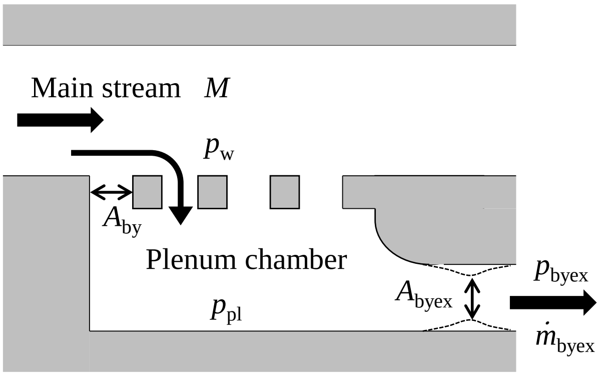


Figure 13 – Porous wall bleed system

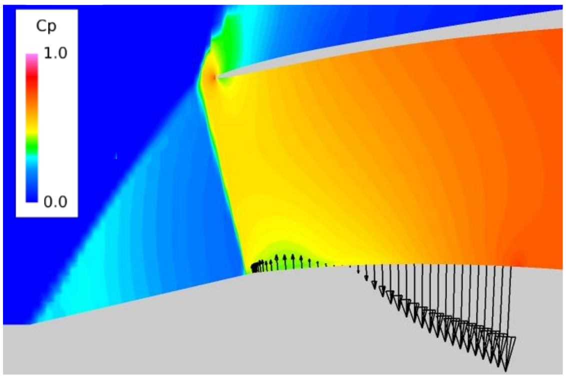


Figure 14 – Boundary condition for porous wall bleed

4.2 Results and Discussion

Figure 15 shows flow field around the inlet with constant area duct at the critical operation. The flow within the constant area duct was decelerated due to the bypass effect. In spite of the flow compression within the short duct, no flow separation was observed.

The pressure recovery of the inlet with the constant area duct is compared with that of the baseline inlet in fig.16 (a). The x axis takes MFR'/PR which means engine speed, and MFR' means the mass flow ratio based on the maximum captured area of the baseline inlet. The pressure recovery was improved in wide range of the engine speed since the boundary layer distributed on the duct wall was removed with the bypass flow. The spatial distortion also improved as shown in fig.16 (b).

Figure 17 shows the variation of the inlet drag. The y-axis takes C_D' whicih means the drag coefficient based on the maximum captured area of the baseline inlet. In fig.17 (a), the inlet drag was increased from the baseline inlet. Figure 17 (b) shows variations for the components of the inlet drag. The most difference with the baseline inlet was made by the bypass drag. Although the bypass performed to suppress an increase of the additive drag, its drag became very large due to treat the large amount of bypass flow. Note that it corresponded to above 30% of the maximum captured mass flow when the inlet operated at the critical condition.

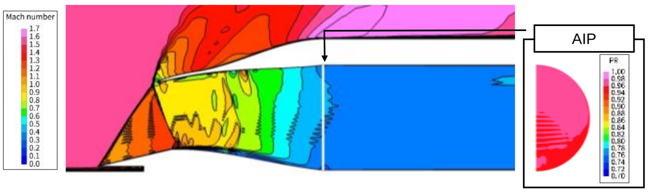
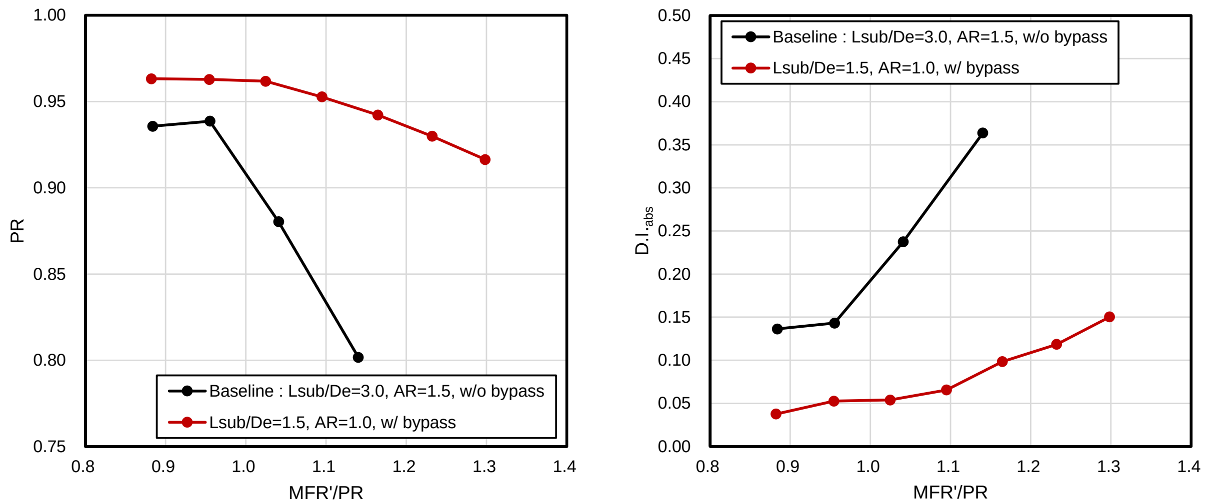


Figure 15 – Flow field of constant area duct inlet



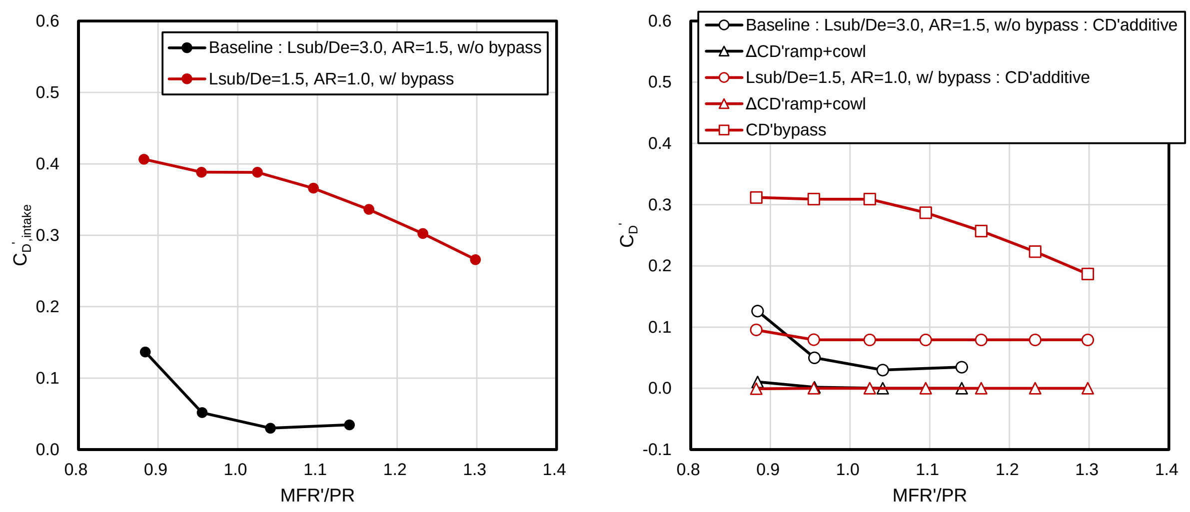
(a) Pressure recovery (b) Spatial distortion

Figure 16 – Effect of constant area duct on inlet performance

The nacelle drag also increased by applying the constant area duct as shown in fig.18 (a). The first reason is that the slope of cowl surface become large with the increase of the nacelle diameter. The cowl pressure drag tripled to the baseline inlet in fig.18 (b). The second reason is that the ramp surface become longer and wider with the increase of the duct entry area. Although the turning angle was constant, the ramp pressure drag became 1.6 times to the baseline inlet.

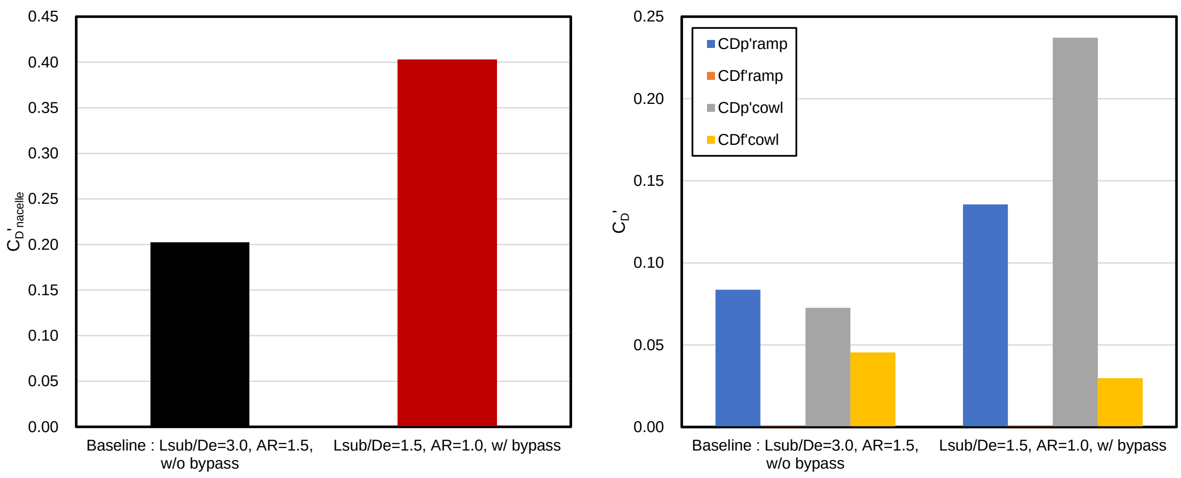
The effect of the constant area duct concept was evaluated in term of the cruise range by using the model described in section 4.2. The additive drag was included to the variation of the inlet drag. When comparing with the baseline inlet at MFR'/PR = 0.96, which was the critical operating point of the baseline inlet, the constant area duct concept improved 0.024 and 0.090 in the pressure recovery and spatial distortion respectively. These corresponded to 2.3% improvement in the cruise range. On the other hand, the inlet drag and nacelle drag increased 0.337 and 0.201 of the drag coefficient respectively. The total drag increase corresponded to 65.0% deterioration in the cruise range. Therefore, it can be said that the constant area duct concept causes big disadvantage on the aircraft performance.

The major technical problem for improving a feasibility of the constant area duct concept is to decrease the bypass drag and nacelle drag. The former might be better by applying a small divergent angle to the duct unless flow separation occurs since it makes the maximum captured area small and decreases the amount of bypass flow. The latter requires decrease in the nacelle diameter. One of the approaches might be applying another bypass system which does not use the inner duct.



(a) Total (b) Components

Figure 17 – Effect of constant area duct on inlet drag



(a) Total (b) Components

Figure 18 – Effect of constant area duct on nacelle drag

5. Conclusion

This paper presented feasibility study for short subsonic diffuser design of supersonic inlet using the two concepts which focused on reducing its divergence angle. One was bifurcated subsonic diffuser concept which divides a single duct into two equal area ducts, and the other was constant area duct concept which replaces a subsonic diffuser for a zero divergent angle duct with bypass system. The baseline inlet was external compression type designed for Mach 1.6, and it had a subsonic diffuser which length was three times of the AIP diameter. Its area ratio of was 1.5. The two concepts were applied to the half long subsonic diffuser. Their aerodynamic performances were compared with that of the baseline inlet by using CFD technique. Furthermore, the improving effect on vehicle performance was evaluated in terms of cruise range assuming the JAXA's small supersonic aircraft. The results of this study were summarized as below.

- On the bifurcated subsonic diffuser concept:
  - The concept reduces flow separation region and improves total pressure recovery and spatial distortion compared with a non-bifurcated short inlet.
  - When an offset of subsonic diffuser is higher than a certain condition, the concept makes its external drag smaller than a conventional long inlet.
  - Duct offset is an important parameter for producing positive effect on a cruise range by applying the concept, and its potential is equal to an improvement by nacelle weight reduction.
- On the constant area duct concept:
  - The concept improves total pressure recovery and spatial distortion compared with a conventional long inlet.
  - A bypass system for compensating compression function, which consists with porous bleed and additional nacelle inner duct, largely increases both internal drag and external drag.
  - Drag reduction is essential for improving feasibility of the concept.

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7. Copyright Statement

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