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Proceedings of NALCFD'99
National Aerospace Laboratory CFD symposium
June 16-18, 1999, Chofu, Tokyo, JAPAN

ON THE INTAKE DESIGN FOR THE NAL SST USING CFD

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ABSTRACT

Three dimensional Navier–Stokes simulation of an air–intake for NAL SST jet propulsion system was performed using a low-Re number k–ϵ turbulence model. The simulation shows that an expansion wave, which originates in a throat bleed, interacts strongly with a normal shock wave, causing a critical momentum defect of the internal flow. This momentum defect induces a boundary layer separation, which finally results in a large distortion of total pressure distribution on the outlet. A wind tunnel test was also performed to confirm this result. The result of the numerical simulation using a k-ϵ turbulence model agrees well with the result of the wind tunnel test.

1 INTRODUCTION

National Aerospace Laboratory(NAL) is now developing an experimental supersonic transport(SST). An air–intake for the jet propulsion system was designed and numerical simulation of the internal flow through the intake was being performed. An air–intake has a role of decelerating inlet supersonic air and stably supplying homogeneous air to a jet engine. The mass flow quantity of the supplied air should be properly controlled in any flight condition. All of these are inevitable for the airplane to flight safely. Moreover, it is better that the length of the intake is short, the pressure recovery is high and the external drag is small.

Two important tools for designing an air–intake are a wind tunnel test and numerical simulation. The result of numerical simulation is useful both for optimizing the design and for performing a wind tunnel test efficiently. In this paper, the internal flow through the air-intake is examined by performing both of numerical simulation and a wind tunnel test, with special focus on the analysis of the effect of a slit bleed at the throat. The result of the numerical simulation using a low–Re k–ϵ model is compared with the result of the wind tunnel test to examine the accuracy of the simulation.

2 DESIGN

Figure 1 shows the side view of the designed intake for NAL SST. The design Mach number of the airplane is 2.0. At this inlet Mach number, a two dimensional external compression intake with three–shock system(two oblique and one normal) is the best choice in view of simplicity, stability and efficiency. A 7° and 8° double-angled wedge was used to form the two oblique shock waves. The total pressure loss due to the three shock waves is 8 percent. At the throat the ramp and cowl internal surfaces are parallel. A short and compact square–to–round transition diffuser was used for subsonic compression. A slit bleed is located at the throat to stabilize the normal shock position. The cut–back side walls are applied in order to eliminate the interaction between the side wall boundary layer and the oblique shocks. Figure 2 shows the schematic view of the intake.

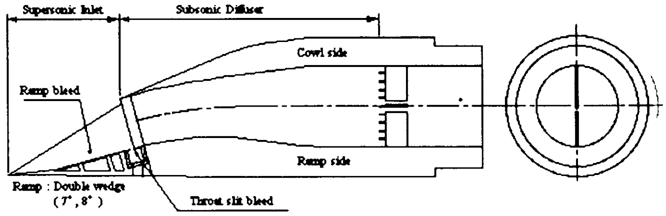

Figure 1. The air–intake for NAL SST(side view)

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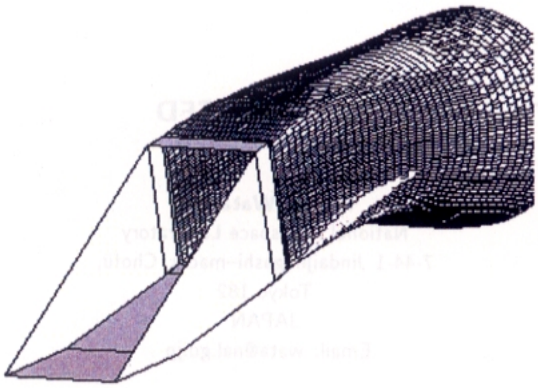

Figure 2. A schematic view of the air-intake

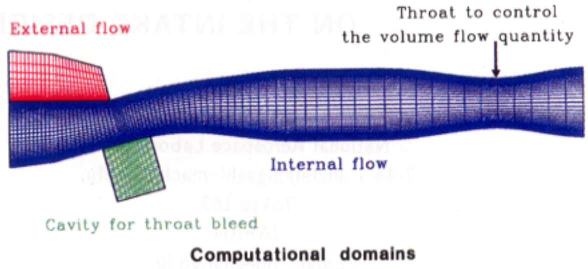

Figure 3. computational domains for the simulation

3 NUMERICAL METHODS

Three dimensional Reynolds averaged, Navier–Stokes equations were solved with a low Reynolds number k–ϵ turbulence model (Myong and Kasagi, 1988). A TVD high resolution scheme was used to evaluate the spatial difference(Chakravarthy and Osher, 1985). For time advancement, an implicit method was adopted(Beam and Warming, 1978). Figure 3 shows the computational domains used in the simulation. The red domain is added to calculate the external flow. Downstream of the intake, a straight duct and a nozzle are added to control the volume flow quantity passing through the duct, which corresponds to the flow plug in a wind tunnel test. The normal shock wave position can be controlled by changing the throat area of the nozzle.

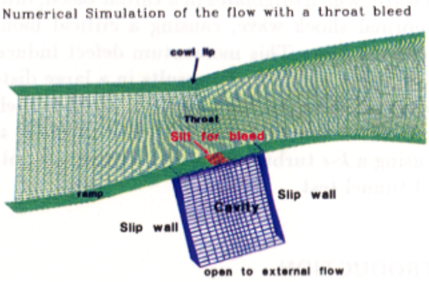

Figure 4. computational domains for the simulation with a bleed

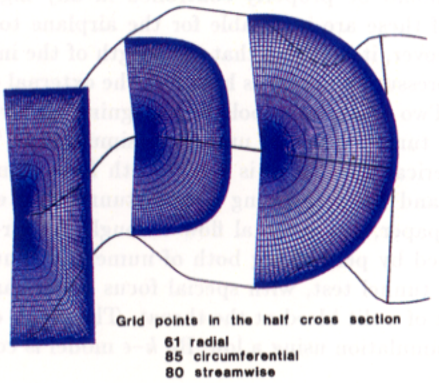

Figure 5. grid points distribution on the cross sections

A bleed was taken into account in the simulation(Figure 4). A cavity is added just below the ramp surface at the throat. There is a slit at the throat, through which some amount of the internal flow is sucked into the cavity. The cavity is bounded by slip walls, except the bottom surface which is opened to the external flow. The grid points are shown in Figure 5. The numbers of the grid points are 61 for the radial, 85 for the circumferential and 80 for the streamwise directions.

The accuracy of the numerical simulation is largely dependent on the turbulence model included. The eddy viscosity distribution obtained by using the low-Re k–ϵ turbulence model (Myong and Kasagi, 1988) is shown in Figure 6. As the eddy viscosity is usually large only in turbulent boundary layer, it can be said that the k–ϵ model gives proper eddy viscosity even in the simulation of compressible flows with shock waves. Figure 7 shows the distribution obtained by using Baldwin and Lomax algebraic turbulence model(Baldwin and Lomax, 1978). B–L model, on the other hand, shows a poor prediction because the shock waves have a bad effect on the F-function used in the model. This implies that B–L model should be carefully used in the simulation of internal compressible flows. In the following analysis, only the k–ϵ model is used.

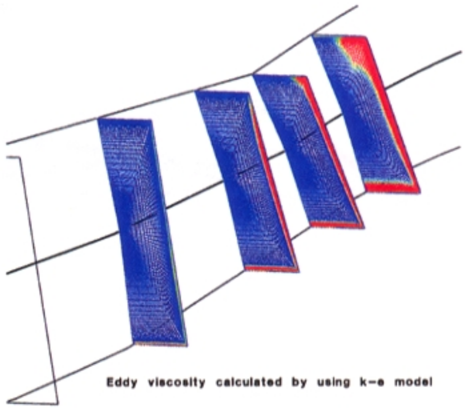

Figure 6. eddy viscosity distribution by k–ϵ model

4 RESULTS OF THE SIMULATION

Figure 8 shows the Mach number distribution at critical operation. An expansion wave can be observed near the throat slit. The expansion wave reaches to the normal shock wave causing the increase of the local upstream Mach number and decrease of the local downstream Mach number. Thereby, a momentum defect region comes out downstream of the interaction. The momentum defect induces a boundary layer separation downstream of the throat. The close view of the flow near the slit is shown in Figure 9. The streamline near the slit bends toward the cavity, while the core flow, which is not affected by the suction, is going straight. The total pressure distribution of this flow is shown in Figure 10. The large total pressure loss in the lower half(ramp side) part is due to the separation caused by the momentum defect.

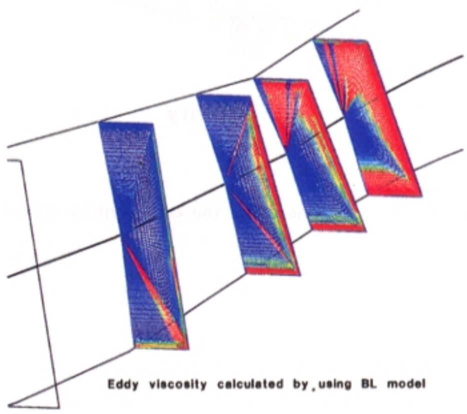

Figure 7. eddy viscosity distribution by BL model

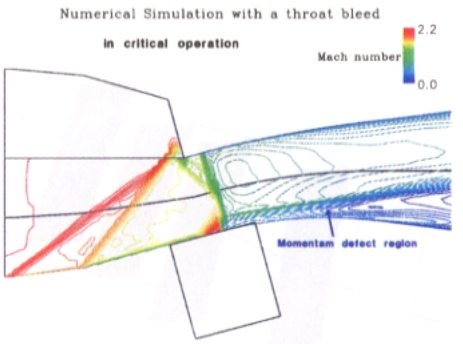

Figure 8. Mach number distribution at critical operation

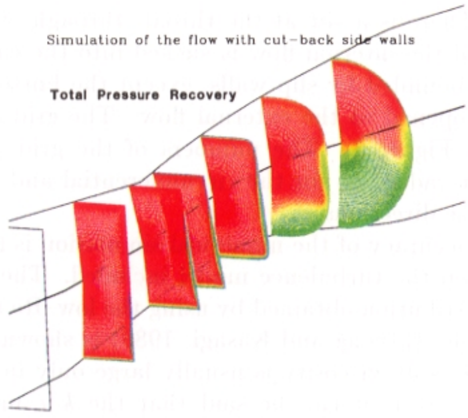

Figure 10. total pressure distribution

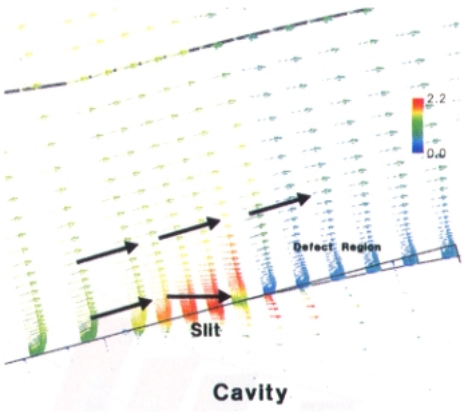

Figure 9. Close view near the slit at critical operation

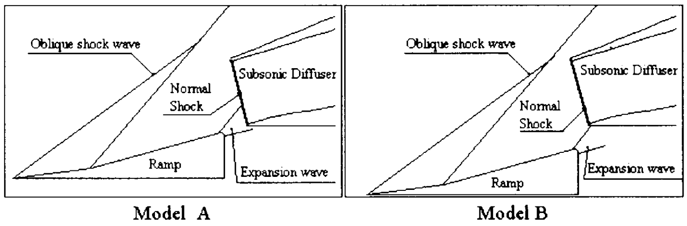

Figure 11. Wind tunnel test Models A and B

5 THE EFFECT OF THE BLEED

The simulation result shown in the previous section implies that the interaction between the expansion wave with the normal shock is fairly strong.

A wind tunnel test was performed to examine the effect of the above interaction on the total performance of the air-intake. Two models, A and B, were constructed which are shown in Figure 11. In the flow through the model A, the interaction do exist. On the other hand, the double wedge ramp of the model B is set lower relative to the subsonic diffuser. This prevents the expansion wave from entering into the diffuser. In the flow through the model B, therefore, the interaction between the expansion and normal shock waves is avoided.

The Figure 12 compares the total pressure distributions of the flows through the models A and B, measured with the Pitot lake at the outlet(see Figure 1). The X and Y-axes show the position and the total pressure[kPa], respectively. The total pressure of the free stream was 223[kPa]. The

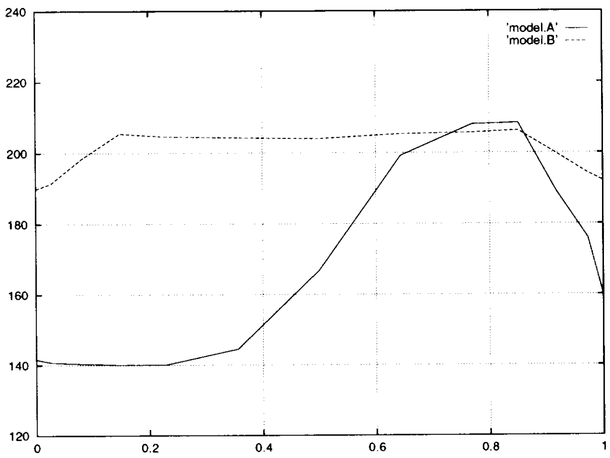

Figure 12. total pressure distribution on the outlet(Model A and B)

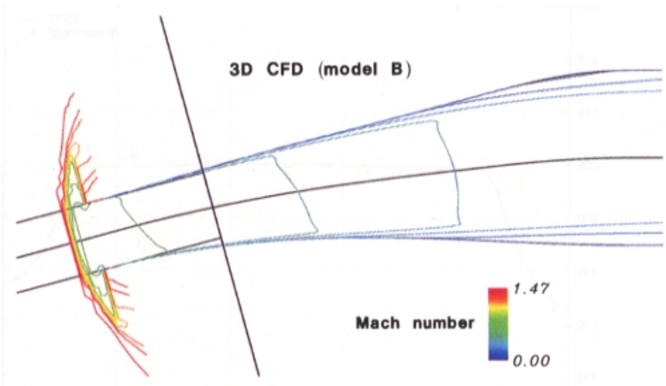

Figure 13. Mach number distribution at nearly critical operation(Model B)

position $X = 0$ corresponds to the ramp side wall, while $X = 1$ corresponds to the cowl side wall. In both cases, the volume flow quantity was controlled to keep the normal shock wave position just outside the subsonic diffuser. In the flow through the model A, a large momentum defect region exists on the ramp side, while, in the flow through the model B, the total pressure distribution is nearly symmetric. This implies that the interaction between the expansion and normal shock waves has a large influence on the total performance of the air–intake.

3D Numerical simulation of the flow through the model B was performed and the result was compared with that of the wind tunnel test. The volume flow quantity of the simulation is nearly the same as that of the wind tunnel test. The Mach number distribution is shown in Figure 13. The normal shock wave is just outside of the subsonic diffuser. Figures 14 and 15 plot the wall static pressure distributions on the ramp and cowl sides in the subsonic diffuser. The solid lines show the simulation result, while the dods show the measured value in the wind tunnel test. The X-axis shows the distance[mm] from the tip of the wedge, while the Y-axis shows the static pressure[kPa]. Figure 16 compares the total pressure measured with the Pitot lake at the outlet(see Figure 1) with the simulation value. The X and Y–axes are similar to those of Figure 12.

These figures show that the numerical simulation using the low-Re k–ϵ model(Myong and Kasagi, 1988) agrees fairly well with the result of the wind tunnel test, even though the model was originally developed for incompressible flows. This is because the compressibility effect on eddy viscosity is fairly small in this flow.

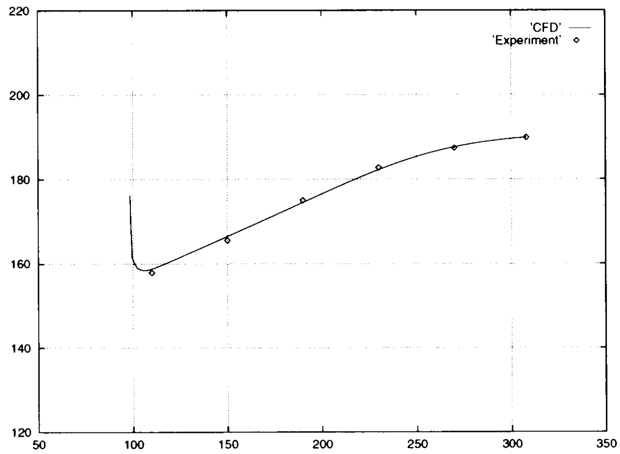

Figure 14. static pressure distribution on the ramp surface(Model B)

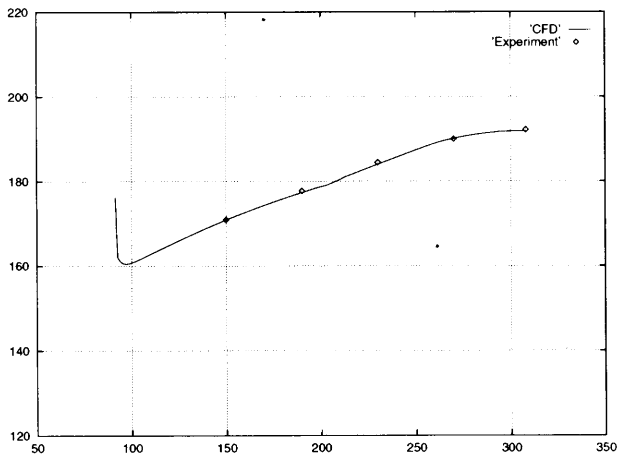

Figure 15. static pressure distribution on the cowl surface(Model B)

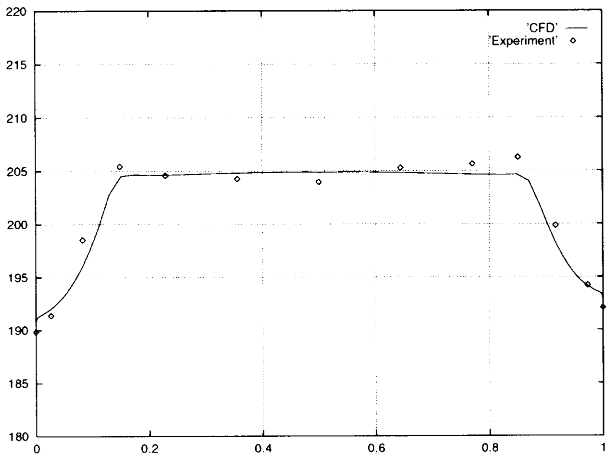

Figure 16. total pressure distribution on the outlet(Model B)

6 SUMMARY AND DISCUSSION

Numerical simulation of the internal flow through the intake for the NAL's experimental airplane was performed. The effect of the throat bleed was examined by performing both of numerical simulation and a wind tunnel test. The result of the simulation agrees well with the wind tunnel test, implying that the compressibility effect on eddy viscosity is fairly small in the internal flow presented above.

On the other hand, it has been often reported that the growth of the supersonic mixing layer cannot properly calculated using the incompressible turbulence model(for example, Sarkar et al. 1991). This is because the reduced growth rate with increasing Mach number is due to the effect of compressibility on turbulence. You should note, however, that such compressibility effect on turbulence is limited in the boundary layer flows such as the flow shown in this study. This point should be taken into account in developing a compressible turbulence model.

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