Aerodynamic Design of Supersonic Experimental Airplane

Toshiyuki Iwamiya, Kenji Yoshida, Yuichi Shimbo,
Yoshikazu Makino (NAL), Kisa Matsushima (Fujitsu)

Abstract

In the first stage of the NAL's experiment for supersonic transport (NEXST-1) project, the aerodynamic design has focused on the reduction of drag at a supersonic cruising speed with a clean wing-body configuration by using Computational Fluid Dynamics (CFD). In the course of design process, four aerodynamic concepts have been applied; (1) arrow-type planform design (2) warped wing (3) area-ruled body (4) a natural laminar flow (NLF) wing. (1) and (2) are effective for the reduction of drag due to lift while (3) is effective for the reduction of wave drag due to volume. They are the concepts based on the linear theory. The concept (4) is devised for the reduction of the friction drag. The application of the NLF concept to the SST configuration has no previous instance and an original trial.

For the realization of the NLF wing at supersonic cruising speed, we first designed a pressure distribution on the wing and then applied an inverse design method based on the supersonic small perturbation equation. After less than 10 design cycles, we obtained a satisfactory design result which display a good agreement with target pressure. The transition position was evaluated by an incompressible boundary layer stability code (SALLY code) and compressible boundary layer stability code (LSTAB code), the latter of which was developed in NAL. The evaluation revealed that the turbulence transition characteristics are good.

1. Introduction

National Aerospace Laboratory (NAL) initiated a supersonic research project in 1997. This is the project including two flight experiments. The configuration of the first experimental airplane was selected to be a simple wing-body configuration with no engines to easily evaluate the relation between the design intention and the design process.

The computer simulation technology for not only structure but also aerodynamics has made rapid progress in the past several decades. It seems well developed to be incorporated in the design process as a design tool as well as analysis tool. We intended to apply the CFD based aerodynamic design approach to determine the wing-body configuration as much as possible. Hence we set that one of the objectives in the project is to test the capability of CFD technologies in their application to achieve a higher lift-to-drag ratio at the design point and to validate it by flight tests of the designed vehicles.

2. Review of Design Process

We first set a target specification that is reasonable for the next generation supersonic transport. The cruising speed is Mach 2.0 and the lift coefficient is 0.1.

The aerodynamic design process of the experimental airplane followed conventional procedures based on the linear theory (Ref.1). In this stage, three aerodynamic concepts have been applied; (1) arrow-type planform design (2) warped wing and (3) area-ruled body. See fig. 1.

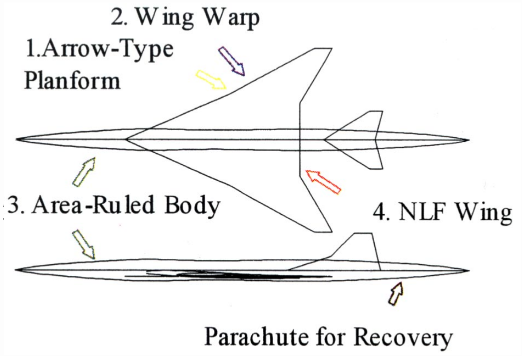

Fig. 1 Aerodynamic Concept for NEXST-1

Ninety-nine arrow wings wing with a subsonic leading edge and aspect ratio between 1.8 and 2.2 were examined by using a supersonic lifting surface theory. Among them, we chose eight planforms with the best drag-due-to-lift parameter. For each of the eight planform, a wing warp was designed with use of the Carlson's method (Ref.2). The method designed the optimal load distribution and the corresponding camber geometry that minimizes the drag due to lift at the design point. A supersonic area rule (Ref.3) was also applied to minimize a drag due to volume. The body was so designed that the cross sectional area distribution of the aircraft is the same as that of the equivalent Shears-Hack body.

For the scaled supersonic experimental airplane with a body length of 11.5m, the friction drag was estimated to occupy about a half portion of the total drag if the flow is fully turbulent over the airplane. Therefore, the fourth concept we applied to the experimental airplane is a natural laminar flow (NLF) wing concept to improve L/D.

2. Natural Laminar Flow Wing

2.1. Target Pressure Distribution

The transition from laminar to turbulent flow on a wing with a large sweptback angle is governed by the amplification of the disturbance through cross flow instability. Pressure distributions on the upper wing surface with a steep pressure drop near the leading edge followed by an almost flat distribution toward the trailing edge might be effective for the suppression of the growth. With a certain parameterization having this feature, the transition characteristics were evaluated by an incompressible boundary layer stability code (SALLY code) based on the so-called e^N method (Ref.4), where N is the amplification factor of disturbance. One of them indicating a wide laminar flow region was selected as a target pressure distribution on the upper wing surface.

On the other hand, Navier-Stokes analysis indicated the discrepancy in load distribution from the optimum one which was derived in the warp design. The second strategy of the target pressure design on the wing is to set the pressure distribution on the lower wing surface to recover the optimum load distribution by subtracting from the upper surface pressure distribution. The target pressure distribution at the 30% semi span station is shown in fig. 2.

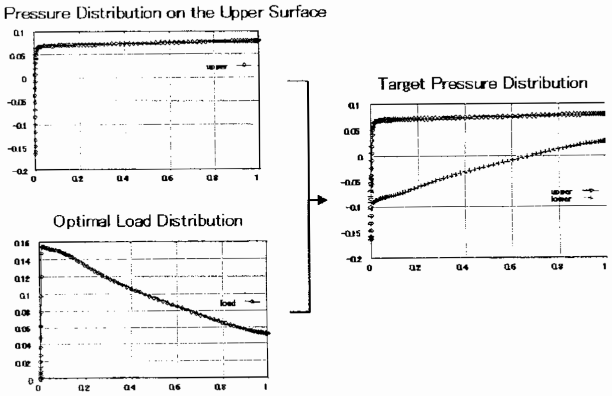

Fig. 2 Target Pressure Distribution

2.2 Inverse Design Method

In order to realize the target pressure distribution defined as above, a newly developed inverse design method was applied. The feature of the method is the utilization of linearized supersonic small disturbance equation to connect a pressure difference with an increment of the geometry. The formulation like this is originated by Takanashi (Ref.5). He treated the transonic wing design. We can say that this method is a supersonic version of Takanashi's method. The flowchart of the inverse design is shown in fig. 3. The design system consists of an inverse problem solver and a Navier-Stokes solver. The geometry is successively modified until the pressure distribution can be regarded as the target.

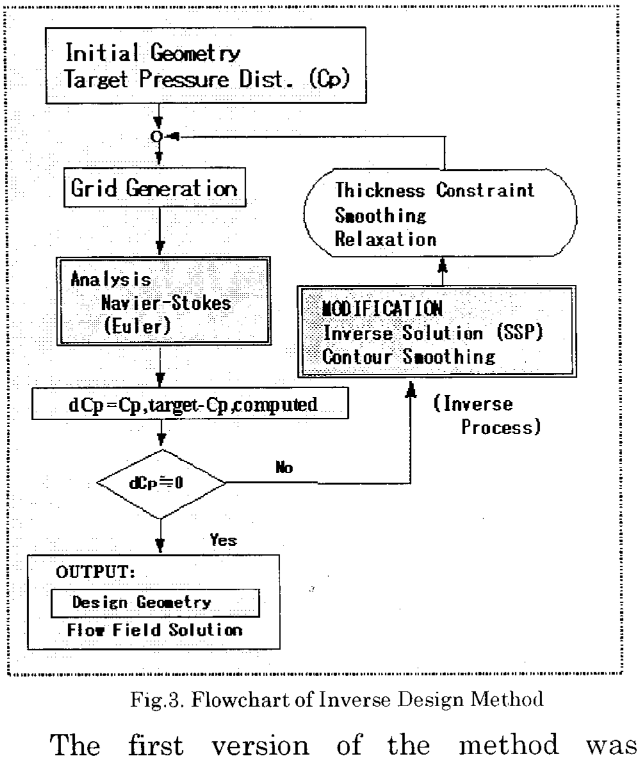

Fig.3. Flowchart of Inverse Design Method

The first version of the method was examined during 1997 and 1998 (Ref.6). We improved the way of treatment of the constraints such as wing thickness that come from structural requirements. These constraints were imposed after the geometry modification. After the first inverse design, we found that the body volume should be increased due to the installation of equipments. Therefore, we had to change the sectional area distribution of the body. We applied the improved version of the inverse design system to the new wing-body configuration. With the geometry designed in the previous design process as the initial geometry, we executed 6 design cycles to obtain a admissible coincidence.

Figure 4 shows the target and final pressure distribution at 30% semi-span location with the wing section. The feature of the target pressure distribution is well reproduced and the good agreement can be seen. Good transition characteristics are expected. Refer to Ref.7 for more detail of the treatment of constraints.

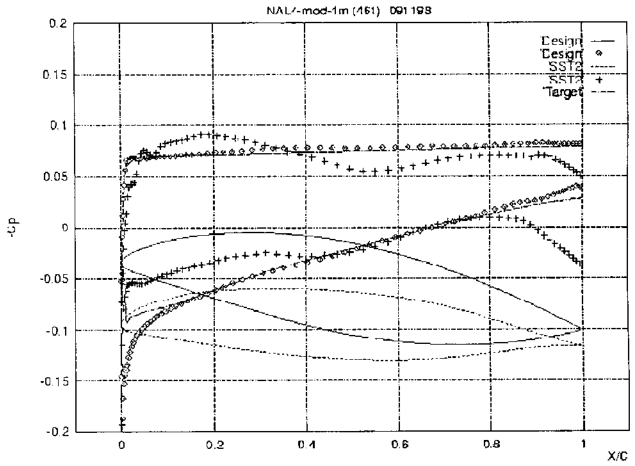

Fig.4. Comparison of Pressure Distribution at 30% semi span

2.3. Transition Characteristics

The key point in the design of the NLF wing is how the transition characteristics can be estimated correctly. The SALLY code has been utilized to estimate the transition location when the target pressure distribution was set. The SALLY code is well known but based on the stability theory for the incompressible flow and does not take the compressibility of the flow into account. To improve this point, the LSTAB code was developed which considers the compressibility of the flow. Figure 5 and 6 display the transition locations corresponding to each N value estimated by the SALLY code and by the LSTAB code, respectively. Although the N values estimated by the LSTAB code are about a half of those estimated by the SALLY code, the qualitative tendencies are the same. Since there is no database of the N value for the transition point in the flight environment, it is difficult to predict the transition location quantitatively, but we can conclude that the application of the SALLY code that accounts for the transition in our design is turned out reasonable. Refer to Ref.8 for more detail.

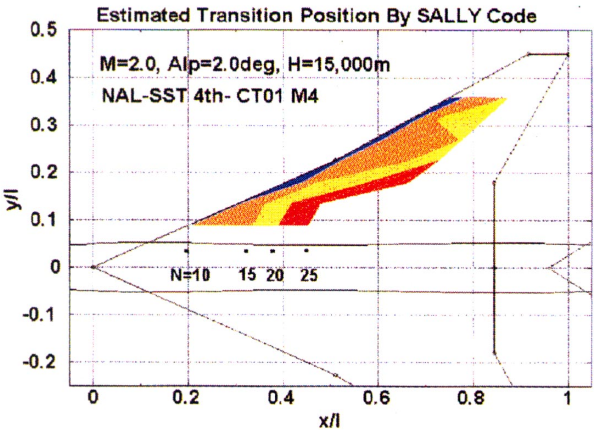

Fig. 5. Transition Location Estimated by SALLY code

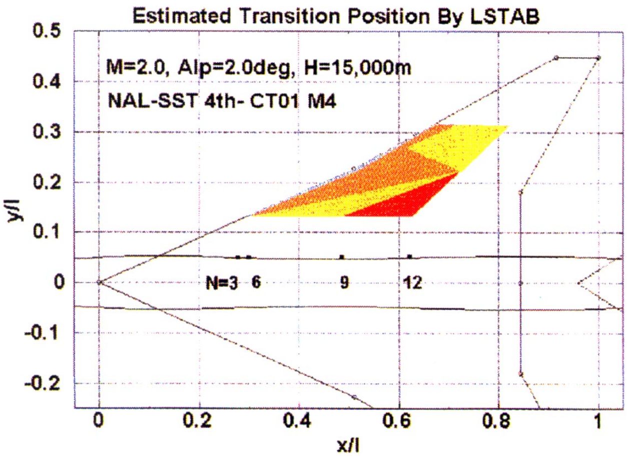

Fig. 6. Transition Location Estimated by LSTAB

3. Stability around the Design Point

Stability around the design point was also examined. Figure 7 shows the pressure distribution at the 30% semi span station with the angle of attack varied. No big change in characteristics can be seen. Estimated friction drag corresponding to the attack angle is shown in fig. 8.

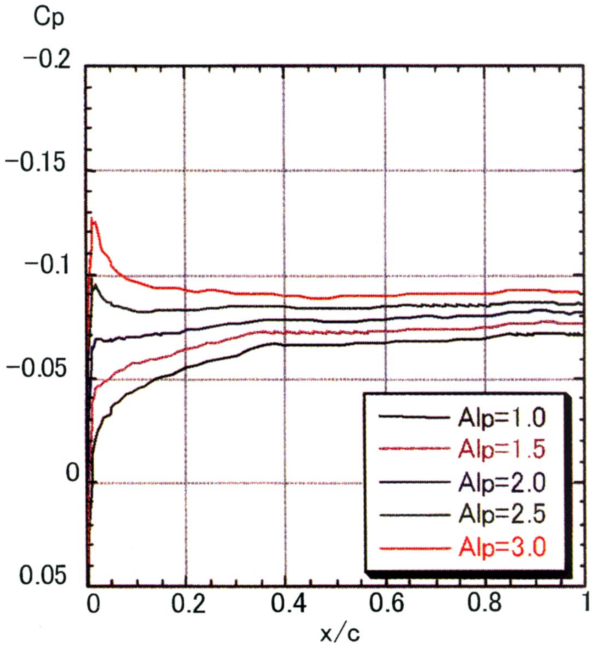

Fig. 7. Pressure Distribution at off-design points

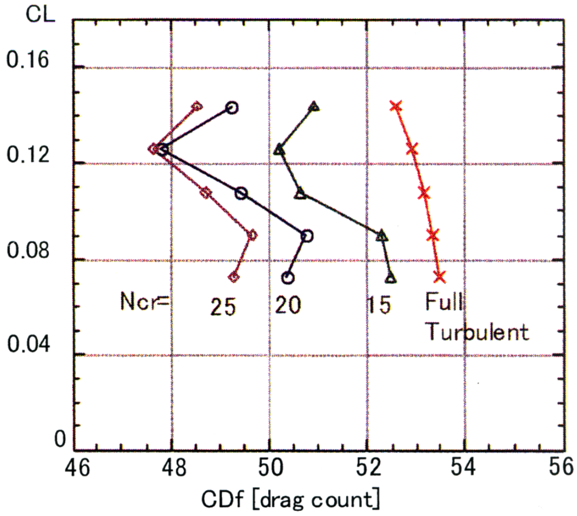

Fig. 8. Estimated Friction Drag

Several wind tunnel experiments were done and are planned by the transition experiment team in NAL to ensure the transition characteristics of the designed configuration Figure 9 shows a comparison. of a supersonic wind tunnel test and a CFD analysis, that shows the good agreement. The detail of the experiments will be reported in the near future.

In the flight tests that will be performed in 2002, the transition location will be measured with the use of hot-films(x), thermocouples(+), unsteady pressure transducer(*), and Preston tube(*). Figure 10 shows the location of measurement points. Pressure distribution is also measured to compare with the CFD analysis.

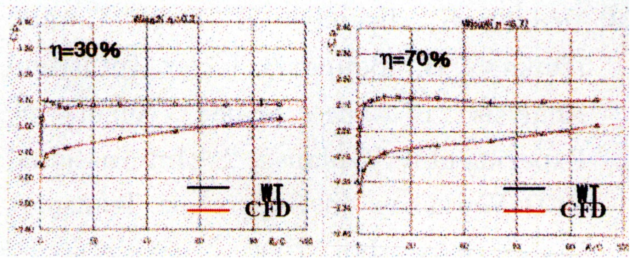

Fig. 9. Pressure Distribution (M=2, α=2deg)

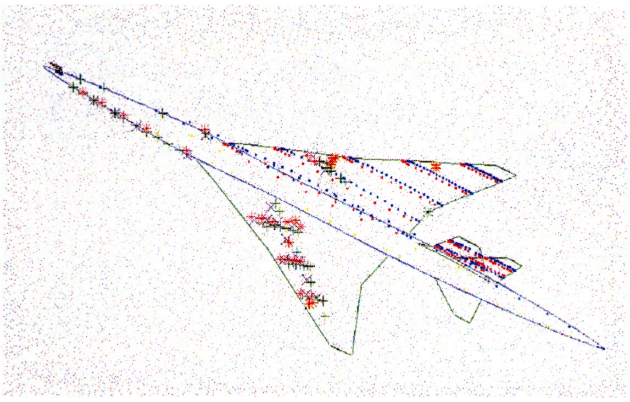

Fig. 9. Measurement points of NEXST-1

3. Toward NEXST-2

The critical design of NEXST-1 has been completed in 1999. The next target of CFD-based design is NEXST-2, which is now on the preliminary design phase. The target is the same, the reduction of the drag. For the purpose, we are preparing both analysis and design tools and trying a preliminary design.

- CFD analysis of interaction between wings, body and nacelles.
  - ➢ Improvement of accuracy of a structured grid based CFD analysis in simulating a flow around supersonic transports, especially the interaction between wings and nacelles (fig.10).

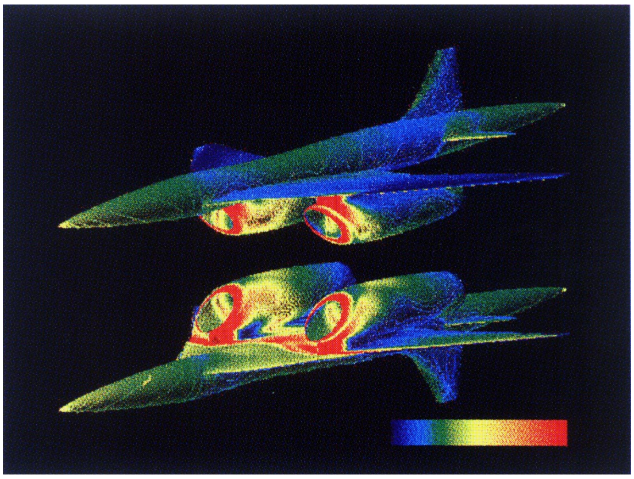

Fig. 10. Navier-Stokes Analysis with Multiblock Grid

- Try again the NLF concept on the upper surface of the wing (the prediction of transition position and widen the applicability of the inverse design method)
  - ➢ Establish the construction of target pressure distribution introducing a relaxation of wing-nacelle interaction
  - ➢ Widen the applicability of the Inverse wing design method with ensuring design constraint
  - ➢ Improve the boundary layer transition analysis to predict a precise transition location
- Use the optimization technique to attenuate the interference from the nacelle
  - ➢ Aerodynamic nacelle shape optimization (See ref. 9)
  - ➢ Wing shape optimization

4. ConclusionNAL's first supersonic experimental airplane (NEXST-1) was designed and the CFD design tools based on a supersonic inverse problem were successfully used for incorporating the NLF concept. Stability analyses show the good characteristics of transition. Wind tunnel experiments under way also support the features. A farther wind tunnel tests are planed to improve the prediction tools of transition. The flight test is planned to perform in 2002.

References

(1) Shimbo Y., Yoshida K., Iwamiya T., Takaki R. and Matsushima K., Aerodynamic Design of the Scaled Supersonic Experimental Airplane, 1st International CFD Workshop on Supersonic Transport Desigh, Tokyo, Mar., 1998.

(2) Carlson H. W. and Miller D. S., Numerical Method for the Design and Analysis of Wings at Supersonic Speeds, NASA TN D-7713, 1974.

(3) Ashley H. and Landahl M., Aerodynamics of Wings and Bodies, Addison-Wesley Publishing Company, Inc., 1965.

(4) Srokowski, Mass Flow Requirements for LFC Wing Design, AIAA 77-1222

(5) Takanashi S., Iterative Three Dimensional Transonic Wing Design Using Integral Equations, J. of Aircraft, Vol. 22, No. 8, pp. 655-660, 1985.

(6) Matsushima K., Iwamiya T., Jeong S., and Obayashi S., Aerodynamic Wing Design for NAL's SST Using Iterative Inverse Approach, 1st International CFD Workshop on Supersonic Transport Design, Tokyo, Mar., 1998.

(7) Matsushima K., Iwamiya T., and Zhang W., Inverse Wing Design for the Scaled Supersonic Experimental Airplane with Ensuring Design Constraints, 2nd International CFD Workshop on Supersonic Transport Design, Tokyo, Jan., 2000

(8) Yoshida K., Iwamiya T., Ueda Y., and Ishikawa H., Boundary Layer Transition Analysis of the Scaled Supersonic Experimental Airplanes, 2nd International CFD Workshop on Supersonic Transport Design, Tokyo, Jan., 2000

(9) Makino Y., Iwamiya T., and Lei Z., Aerodynamic Nacelle Shape Optimization for NAL's Experimental Airplane, 2nd International CFD Workshop on Supersonic Transport Design, Tokyo, Jan., 2000