# Inverse Wing Design for the Scaled Supersonic Experimental Airplane with Ensuring Design Constraints

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## ABSTRACT

Aerodynamic shape of a wing for NAL (National Aerospace Laboratory)'s first SST model has been designed by a supersonic inverse design method. This method handles wing-fuselage configurations and provides wing section's geometry at every span for Navier-Stokes flowfields. The design target is a NLF (natural laminar flow) wing at the speed of $M_\infty = 2.0$. The original system of the inverse design method has to be modified so that several design constraints can be satisfied. By means of the method, a wing section shape which has much more desirable characteristics has been designed than that by the traditional design method. In terms of aerodynamics to realize a NLF wing, the modified method works very well. The pressure distribution of the designed wing shows good agreement with the target pressure. In terms of constraints, most of them can be satisfied by using the modified design method; however, difficulty has been found during the process for thickness constraint control. The prospective strategy to cope with the thickness constraint is discussed.

## 1 Introduction

The scaled experimental airplane models of a Super-Sonic Transport are under development at the NAL in Japan. Unlike the traditional way, their aerodynamic shapes are being primarily designed by numerical tools such as CFD (Computational Fluid Dynamics). One of the important tools is a design method which determines the shape of a wing. We have been developing the method in which a new inverse problem has been formulated, because the NAL's SST model has a challenging design concept of an NLF wing to reduce the drag. The method provides the wing section geometry at every span station which realizes the specified target pressure distribution of an NLF wing. The method was devised and the initial (or first) version of the method was examined during 1997 and 1998[1]. After some preliminary examinations, it was practically applied to the design of the first NAL's model which had no propulsion system. Its wing-fuselage configuration used for the first practice is shown in Fig. 1. This design has been successfully ended and the designed model is under manufacturing at present. Through the experience of the practical application of the initial version of the method, we have found that improvement is needed for the method. In this article, design results by the initial version of the method are introduced and then what to be improved and how to cope with the improvement are discussed.

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## 2 Overview of the Design Method

This method designs wings for SST wing-fuselage configurations. It provides wing section's geometry at every span with the fixed planform. The design system of the method consists of an inverse problem solver and a Navier-Stokes simulation. Figure 2 illustrates the design system. The design procedure is iterative; the baseline shape is successively modified as the process of the inverse problem solver and Navier-Stokes simulation is iterated until the pressure distribution given by the designed wing can be regarded to converge to the target one. When a wing for the SST wing-fuselage model such as presented in Fig. 3 is designed, the target pressure distribution should be specified, as well as a baseline shape of the wing should be provided. The baseline wing is combined with the fuselage. Then the flow field around the wing and the fuselage combination is analyzed by Navier-Stokes flow simulation to get the current $Cp$ distribution on the wing surface. Next the inverse problem is solved to obtain the geometrical correction value $\Delta f$ corresponding to the difference between target and current pressure distributions $\Delta Cp$. The inverse problem is described as two integral equations[1]. Those equations relate $\Delta Cp$ (residual) to two values, $\Delta w_s$ and $\Delta w_a$, which are the function of the geometrical correction $\Delta f$. This formulation is similar to the singularity source method based on the small perturbation and thin wing theory[2]. So, we consider an isolated wing when the inverse problem is solved.

The integral equations are solved using piece-wise function approximation. The discretized wing surface is presented in Fig. 4. With the discretization, we solve a algebraic linear equation system instead of integral equations. Figures 5 and 6 are the brief explanation about the equation system and the coefficients. In Fig. 5, $\Delta w_s$ indicates the $x$-derivative of the thickness change of a wing, where $\Delta u_s$ is a function of pressure coefficients;

$$\Delta w_s == -\frac{1}{\beta^3}(\frac{\partial \Delta f(+0)}{\partial x} - \frac{\partial \Delta f(-0)}{\partial x}) \quad (2.1)$$

$$\Delta u_s == -\frac{1}{2\beta^2}(\Delta Cp(+0) + \Delta Cp(-0)) \quad (2.2)$$

$+0$ means the upper surface while $-0$ means the lower surface of a wing. In Fig. 6, $\Delta w_a$ indicates the $x$-derivative of the change on the camber-line of a wing, where $\Delta u_a$ is also a function of pressure coefficients;

$$\Delta w_a == -\frac{1}{\beta^3}(\frac{\partial \Delta f(+0)}{\partial x} + \frac{\partial \Delta f(-0)}{\partial x}) \quad (2.3)$$

$$\Delta u_a = -\frac{1}{2\beta^2}(\Delta Cp(+0) - \Delta Cp(-0)) \quad (2.4)$$

As illustrated in Fig. 2, the wing section shape at every span station is designed by modifying the baseline shape with $\Delta f$ which is the solution to the inverse problem. When modifying the section shape, we impose the design constraints explicitly on $\Delta f$. Now, the current shape is updated with satisfying the design constraint. Then we joint the updated wing with the fuselage and go back to the analysis part, again.

For practical design, the consideration of design constraints is inevitable. The first version of the method adopted the simple way to apply constraints. The constraints were imposed on the geometry after the inverse problem was solved. Thus, the geometry was modified explicitly. We admit that the imposition of constraints may put the geometry off from the exact solution to the inverse problem. However, this treatment is justified because If the difference between an exact solution and an imposed one is in a proper range, the geometry will still converge with iterations.

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# 3 Design, Results and Discussion

A wing for the SST wing-fuselage model whose planform is presented in Fig. 3 was designed in 1998[1]. The design target was a NLF wing at the speed of $M_\infty = 2.0$. The profile of the target pressure distribution is presented by chain lines in Fig. 7. The baseline shape was the results designed by the traditional linear theory. Every wing section shape was NACA66003 airfoil geometry. The baseline wing section shape is drawn with dashed lines and its pressure distribution is presented by + lines in Fig. 7. The final (converged) wing section shape is drawn with solid lines and the realized pressure distribution is presented by $\diamond$ lines. For the design, we used 50 ($x$:chord-wise) $\times$ 80 ($y$:span-wise) panels on a semi-span wing surface, when solving the inverse problem. Several design constraints have been intended to be satisfied. They are 1) to assure the closed trailing edge, 2) to assure the twisting axis of every span section to be on a certain straight line, 3) thickness constraints of wing sections such as $0.03 \leq (t/c)_{max} \leq 0.037$ at each span station, and so on. As one can see from Fig. 7, the designed wing shape by the method is having the pressure distribution that almost completely agrees the target one. As a whole, the new method worked very well to design the wing section geometry except thickness control. In fact, we have encountered difficulty to enforce the thickness constraint. Sometimes the explicit enforcing of thickness control deteriorated the performance of the designed wing. For this design, we gave up controlling the thickness on the inner part of the wing than 40% semi-span station. However, without the thickness control, the largest "$t/c$" is still around 4.10% that is acceptable for manufacturing a real airplane. The situation of the thickness control is described in the following paragraph.

Figure 8 shows the design results of two different ways for the thickness control, at two locations of 30% and 70% semi-span stations. The plots on the left-hand side of the figure present the results designed with thickness constraint control. Those on the right-hand side are the results designed without the control. The dashed line and the solid line indicate the geometry of the baseline and designed wing section shape respectively, while + and $\diamond$ lines do pressure distribution of the both. The target pressure is indicated by chain lines. As expected, the resulting wing designed without the thickness control realizes much closer pressure distribution to the target than the other one dose. We admit the explicit enforcing of thickness control sometimes deteriorates the performance of the designed wing. The extent of the deterioration is to be verified. The deterioration dose not violate the NLF concept on the outer part of the wing than 40% semi-span station. The situation at the 70% semi-span station shown in Fig. 8 is one typical example of non-violated cases. On the other hand, the situation at the 30% semi-span station in Fig. 8 is the example where the thickness control violates the concept.

From the investigation done before[3], thickness is best controlled through careful specification of the target pressure. We are thinking there will be some range of the variation of target Cp, which does not violate the design concept for the SST. This encourages us to study a good algorithm to determine the optimized target pressure distribution. For more sophisticated thickness control, additional module to modify the target Cp to the design system of Fig. 2 is needed. In the module, investigation on target Cp will be conducted.

# 4 Conclusions

The inverse design method ensuring design constraints were introduced. The method is practical, efficient and accurate. It was shown through the design of an NLF wing for the wing-fuselage configuration of NAL's Scaled Supersonic Experimental Airplane. The method worked well with this practical aerodynamic design except satisfying thickness constraint for the inner part of the wing. To settle this difficulty, more sophisticated thickness control strategy and investigation

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on target Cp are needed.

## References


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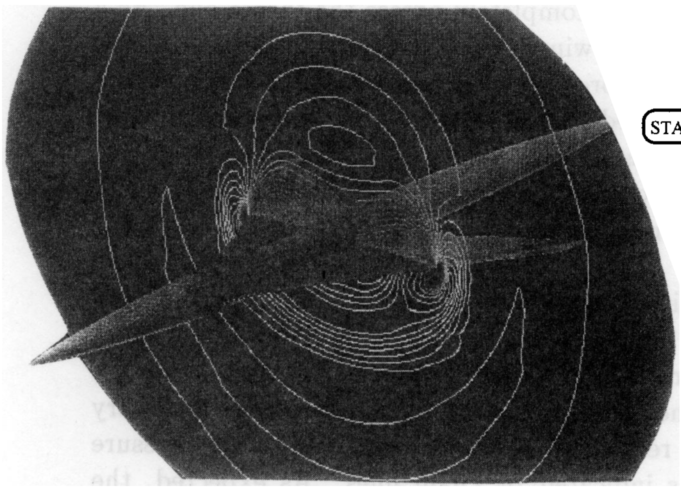

Figure 1 SST Wing-Fuselage Configuration.

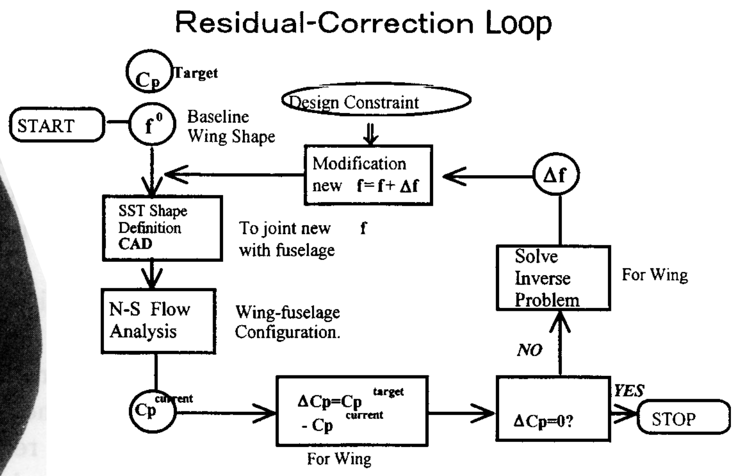


Figure 2 Design Method,(1st ver.).

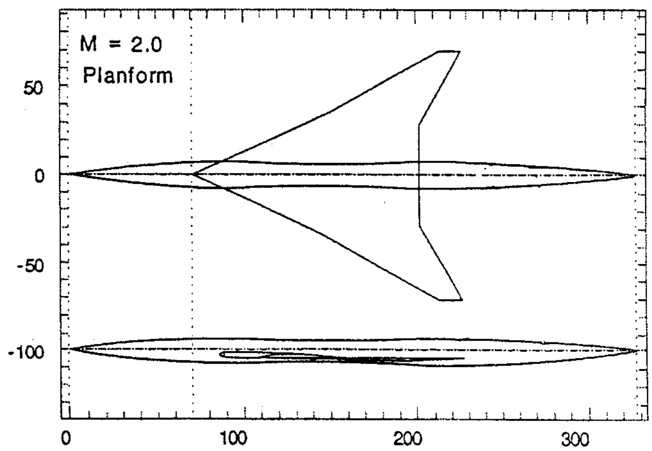


Figure 3 SST Planform.

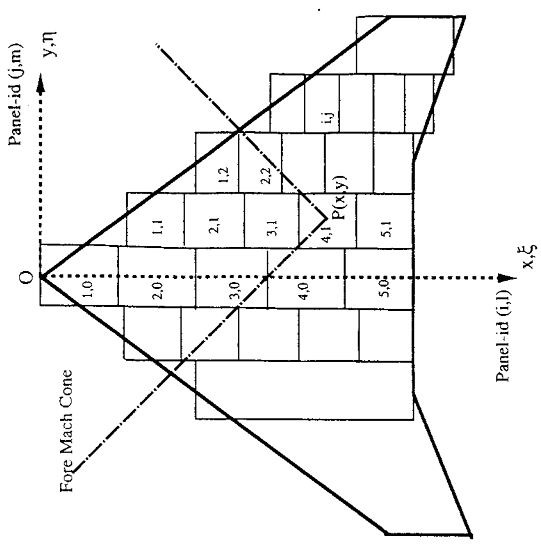


Figure 4 Discretization of Wing Surface.

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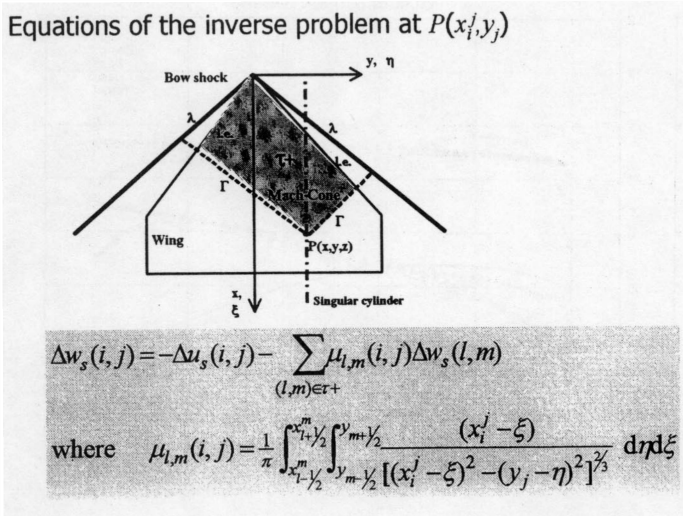


Figure 5 Discretized Equation System(1).

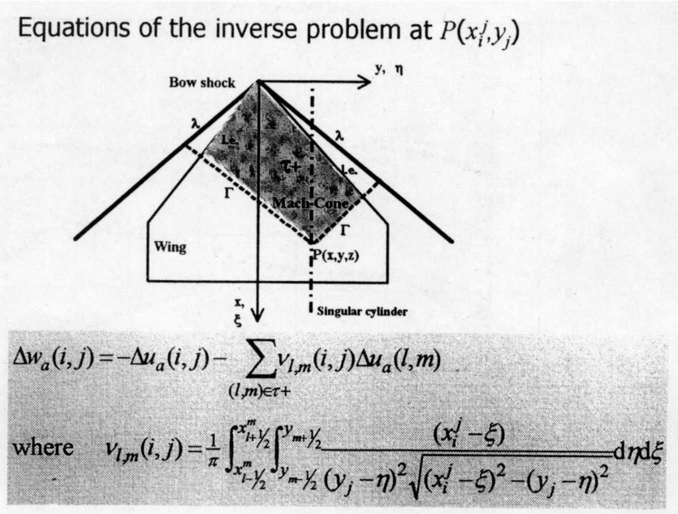


Figure 6 Discretized Equation System(2).

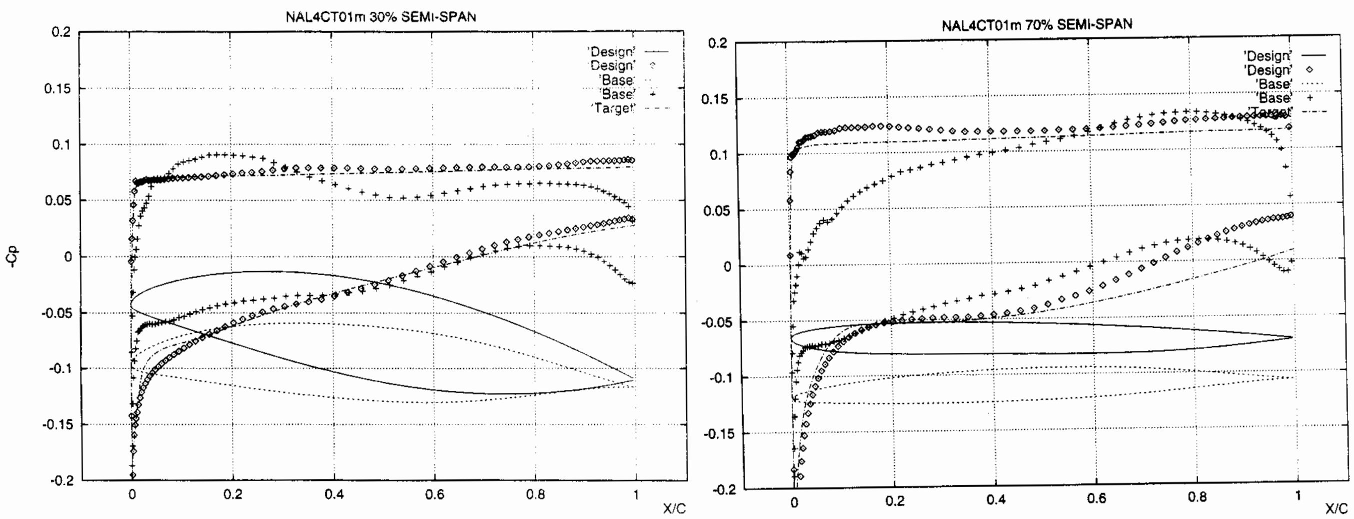


Figure 7 Final Design Results at 30% and 70% Semi-span Stations

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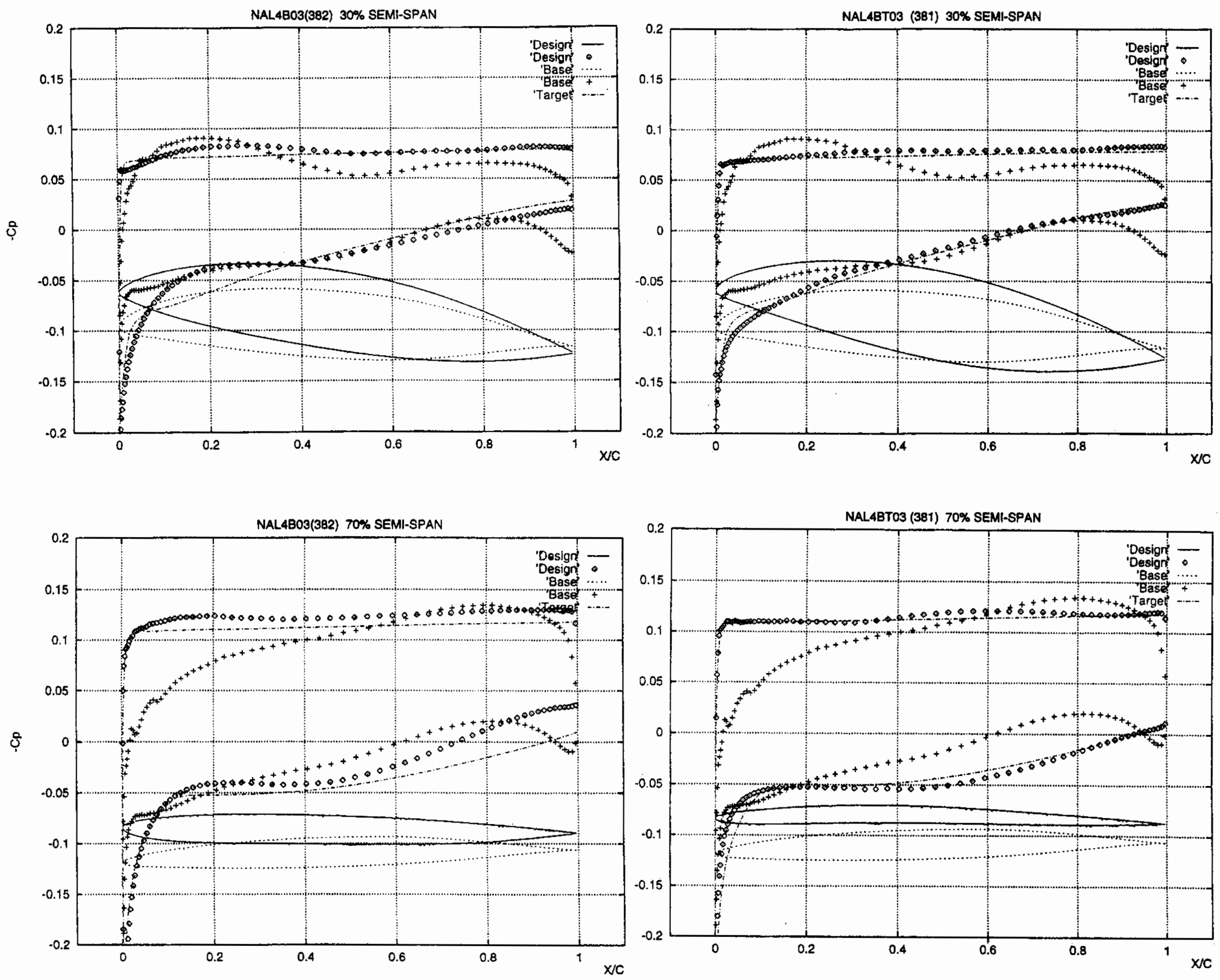


Figure 8 Design Results on 30% and 70% Semi-span Stations
Comparison of Realized Pressures by Design Method with/without Thickness Control

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