Inverse design of biplane airfoils for efficient supersonic flight
- Preliminary trial to construct biplane airfoil data base -

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There is a biplane concept for an efficient supersonic flight. Busemann biplane is a representative airfoil which has possibility of realizing low-boom and low wave drag. Aerodynamic designs based on the Busemann biplane are demanded for future supersonic transports. In this paper, possibilities of designing supersonic biplanes by utilizing an inverse problem method are discussed based on Computational Fluid Dynamics (CFD). The inverse problem method which has been used in this paper is based on the theory of oblique shock wave. Therefore, it is necessary to examine its usefulness of designing airfoils which causes complicated phenomena such as biplanes where two airfoil elements interfere with each other and 3-dimensional wings. We attempted 2-dimensional cases in our current studies. It was confirmed that a certain biplane which differed from the Busemann biplane converged to the known Busemann biplane in 14 times iterations of design procedure. This knowledge is stated in the previous paper of this one. Then a practical biplane configuration was designed by utilizing the inverse problem method. After 14 times iterations, biplane configuration which has lower wave drag than a zero-thickness single flat plate airfoil at sufficient lift conditions has been successfully designed. Finally, applications to designing 3-dimensional biplane wings are attempted. Target and initial geometries are set to the same ones as the case of 2-dimensional. The above-mentioned inverse problem method was applied to total 10 sections. In 3-dimensional cases which have more complicated phenomena than 2-dimensional cases such as disparity in flow of span direction, convergence after 14 times iterations was confirmed.

Nomenclature

C_d	=	wave drag coefficient
C_l	=	lift coefficient
C_p	=	pressure coefficient
c	=	chord
M_∞	=	free-stream Mach number
t	=	airfoil thickness
D	=	drag
L	=	lift

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Re	=	Reynolds number
α	=	angle of attack
ε	=	wedge angle

1. Introduction

The objectives of low noise and high fuel efficiency are critical for the next generation supersonic transport. In a word, it is necessary to develop an airplane that has low boom and low drag. Busemann proposed a biplane configuration in a form with the possibility to satisfy these two conditions, which utilizes a favorable interaction between two wing elements[1,2]. The wave drag due to airfoil thickness can be nearly eliminated using a biplane configuration that promotes favorable wave interactions between the two neighboring airfoil elements (here, wave drag being defined as a resistant force on the airfoil due to the generation of shock-waves.). Licher extended the idea to reduce the wave drag due to lift[3]. Recently, a project of a supersonic biplane has been started around Dr. Kusunose for the purpose of a significant reduction in wave drag and sonic boom[4,5]. It is a goal of our study to develop the idea of the supersonic biplane by utilizing modern techniques, including CFD tools, advanced in the last 30 years, and also to propose a practicable biplane wing for low wave drag (therefore, for low boom) in supersonic flight.

We currently focus on designing two-dimensional (2-D) biplane configurations for low drag supersonic flight. For a design method, an inverse problem method[6,7,8] which is based on the theory of oblique shock waves and the concept of small perturbation method is used. Its usefulness of designing airfoils which has complicated phenomena such as biplanes where two airfoil elements interfere with each other was confirmed in our current studies. In this paper, distinguished results of designs for a 2-dimensional biplane airfoil utilizing the inverse problem approach are shown. Finally, we demonstrate its design capability for 3-dimensional biplane wings for the purpose of next future supersonic transport.

2. Biplane Concept for Low Wave Drag Supersonic flight

In our study, low wave drag biplane configurations are studied under the condition that the total maximum thickness ratio (thickness-chord ratios, t/c) is more than 0.10. In supersonic flight of M_∞=1.7, we consider the range of lift coefficient C_l from 0.10 to 0.20. In Fig. 1 wave drag components due to lift and due to thickness are estimated using the supersonic thin airfoil theory for a lifted diamond airfoil of t/c=0.10 at C_l =0.10, with flow condition M_∞=1.7. Here, t/c represents airfoil thickness chord ratio.

Employing the 2-D supersonic thin airfoil theory[2], the lift and wave drag coefficients of a flat plate airfoil at a small angle of attack α are expressed as

$$C_l = \frac{4\alpha}{\sqrt{M_\infty^2 - 1}} \tag{1}$$

$$C_d = \frac{4\alpha^2}{\sqrt{M_\infty^2 - 1}} = \frac{\sqrt{M_\infty^2 - 1}}{4} C_l^2 \tag{2}$$

where, C_l and C_d are defined by L/qc and D/qc, L and D being the airfoil's lift and wave drag, respectively. Symbol M_∞, q, and c represent the free-stream Mach number, dynamic pressure ($0.5\rho_\infty U_\infty^2$) and airfoil chord length. Here, U_∞ represents free stream velocity.

Wave drag of a diamond airfoil is calculated using the thin airfoil theory[2] as

$$C_d = \frac{4}{\sqrt{M_\infty^2 - 1}} \left(\frac{t}{c} \right)^2 \tag{3}$$

Using biplane configurations both wave drag components due to lift and due to thickness can be reduced.

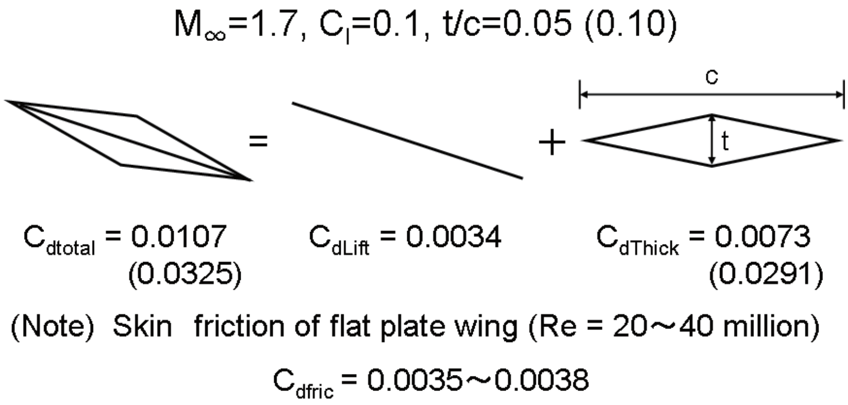


Figure 1. Wave drag components for a diamond airfoil.

2.1 Elimination of Wave Drag due to Airfoil Thickness

As shown in Fig. 1, the majority of the total wave drag of a diamond airfoil is due to its thickness. The biplane configuration can also significantly reduce wave drag due to its airfoil thickness (or volume). Favorable wave interactions between the two airfoil elements can be promoted by choosing their geometries and relative locations carefully. Busemann showed that the wave drag of a zero-lifted diamond airfoil can be completely eliminated by simply splitting the diamond airfoil into two elements and locating them in a way such that the waves generated by those elements cancel each other out[1,2] (see Fig. 2, where ε is wedge angle of a Busemann biplane). Generally, in supersonic flight, wave drag due to an airplane's volume (wing thickness, fuselage, etc.) is large relative to that due to its lift (As shown in Fig. 1). Supersonic aircraft are therefore severely limited in their wing thickness. If the wave cancellation effect can be used effectively, the strong restriction currently imposed on the wing thickness of supersonic aircraft may be relaxed considerably.

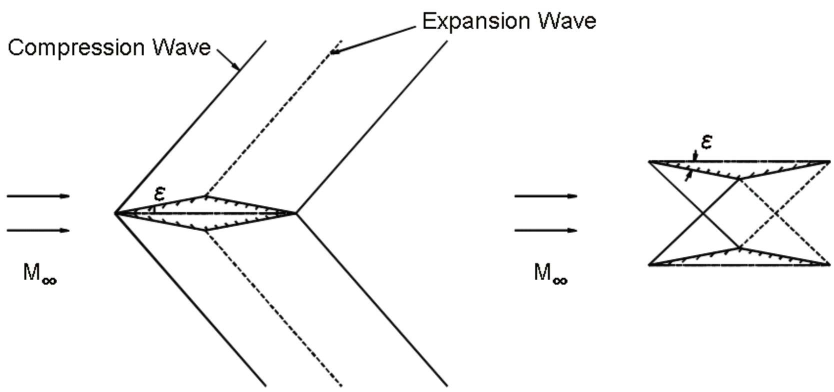


Figure 2. Wave cancellation effect of Busemann biplane.

2.2 Reduction of Wave Drag due to Lift

To achieve minimum wave drag under a given lift condition, we chose the biplane configuration discussed by R. Licher in 1955[3] (see Fig.3, where α is the angle of attack for the lower surface of the lower element) as one of the baseline configurations. This particular biplane configuration exhibits two desirable characteristics: the wave reduction effect due to airfoil lift and the wave cancellation effect due to airfoil thickness. By promoting favorable wave interactions between the upper and lower elements, the wave drag due to lift can be reduced to 2/3 of that of a single flat plate under the same lift condition. Additionally, Busemann's wave-cancellation concept can be applied to the system to reduce wave drag due to airfoil thickness.

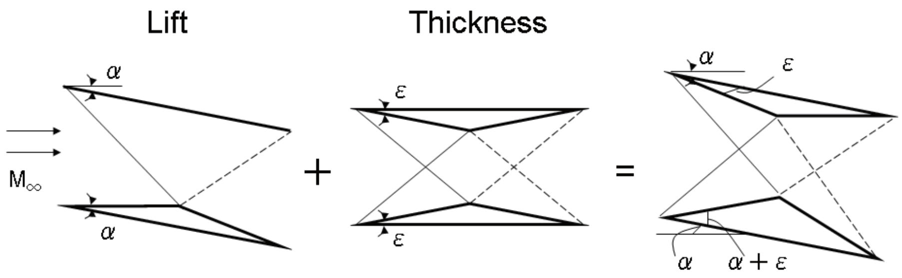


Figure 3. Licher type Biplane including Busemann Biplane.

3. Aerodynamic Design of Practical Biplane Airfoils by Using an Inverse Problem Method

Using the inverse problem method, a 2-dimensional biplane airfoil design has been performed. In this research, a flow solver named TAS code (Tohoku University Aerodynamic Simulation) using a three-dimensional unstructured grid[9,10], was used to evaluate aerodynamic performance. In simulation, the Euler/Navier-Stokes equations are solved by a finite-volume cell-vertex scheme. The lower/upper symmetric Gauss-Seidel (LU-SGS) implicit method for an unstructured grid[11] is used for the time integration. The theory and method and its usefulness for biplane configurations are shown in the previous paper[8]. The design procedure of the inverse deign cycle for biplane airfoils is shown in Fig. 4.

For designing biplane airfoils, a Licher type biplane (see Fig.3) was selected as the initial configuration. As a design condition, free stream Mach number M_∞=1.7, and angle of attack α=1deg. were selected (here, α representing the angle of the lower surface of the lower element against the free stream direction). Here, the total thickness-chord ratio (*t/c*) is 0.106. Both the target and initial pressure distributions for both the upper and lower elements used for the biplane design were shown in Fig. 5. Our design concept is to meet a demand of C_p distributions, having more lift on the upper surface of the upper element and also generating additional lift, but having lower drag on the lower surface of the upper element, especially near the trailing edge. The obtained C_p distributions (after 14 times iterations) of the upper and lower element, using plots and lines, respectively are shown in Fig. 6. The initial and designed geometry are compared in Fig. 7. The gain of the angle of attack of the lower surface on the lower element against the flow direction is 0.19deg. compared to the initial Licher type biplane. The total maximum thickness ratio (*t/c*) is 0.102. C_l =0.115, C_d =0.00531 (*L/D*=21.72). A C_p visualization map at this design point is shown in Fig. 8. Wave drag polar diagrams are shown in Fig. 9. When C_l =0.14, total wave drag is lower than that of the zero-thickness single flat plate airfoil. Thus, by the use of the inverse problem design method, a biplane configuration having a distinguished aerodynamic performance was successfully designed. It may seem surprising to find a biplane configuration that has a lower wave drag than that of a flat plate airfoil, however, this was already predicted by Moeckel more than 50 years ago[12].

Observing the designed shape in detail, the trailing edge of the upper element of the designed biplane configuration was modified to align the concave curve and the shape parallel to the free stream, creating more lift. It should also be noted that the compression waves generated at the leading edge of the elements and the expansion waves generated at the throats of the elements nearly cancelled each other out, thus eliminating the initial pressure peaks at the throat.

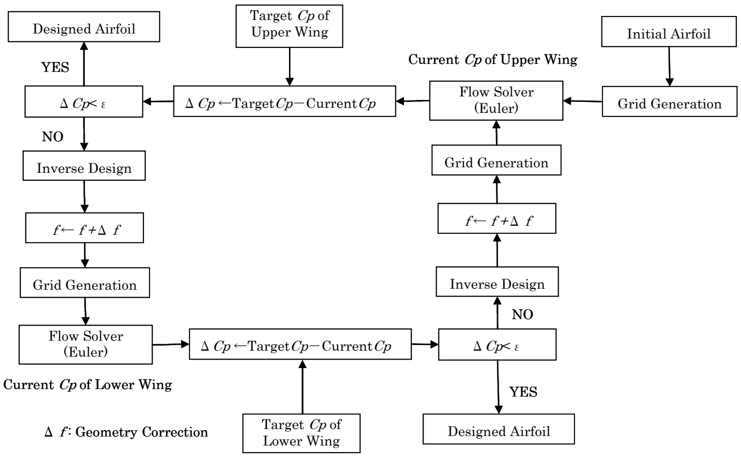


Figure 4. Design cycle.

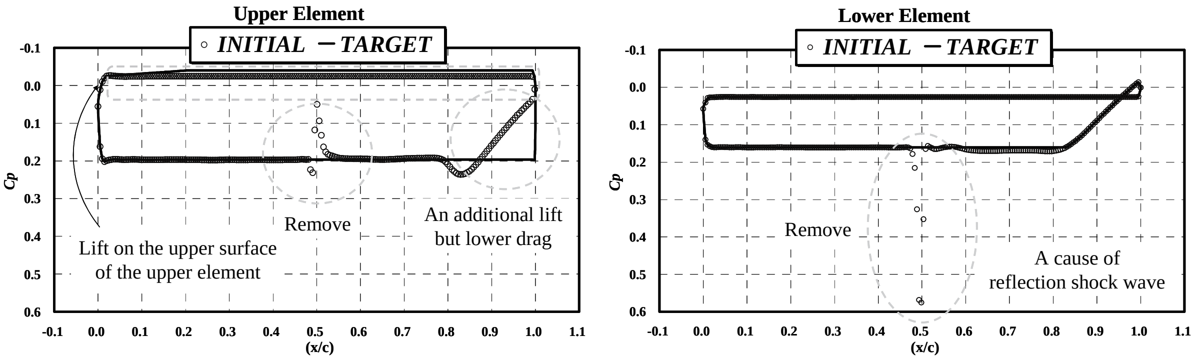


Figure 5. Target C_p distributions.

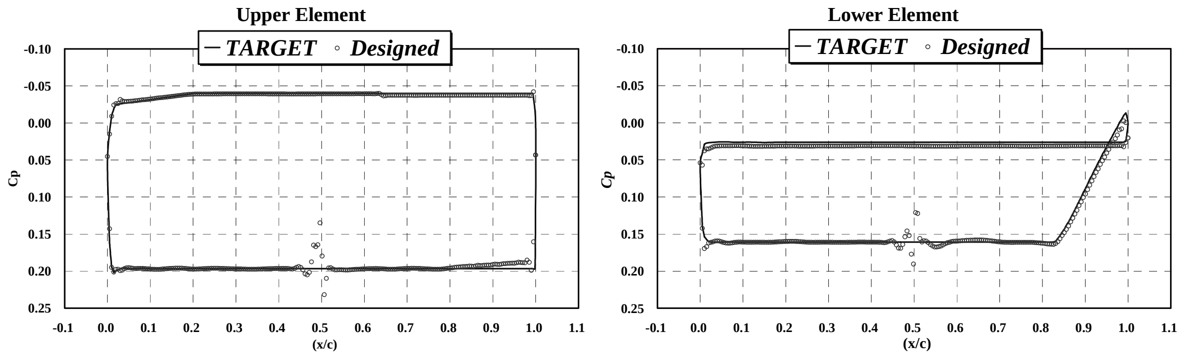


Figure 6. C_p distributions of the designed biplane configuration.

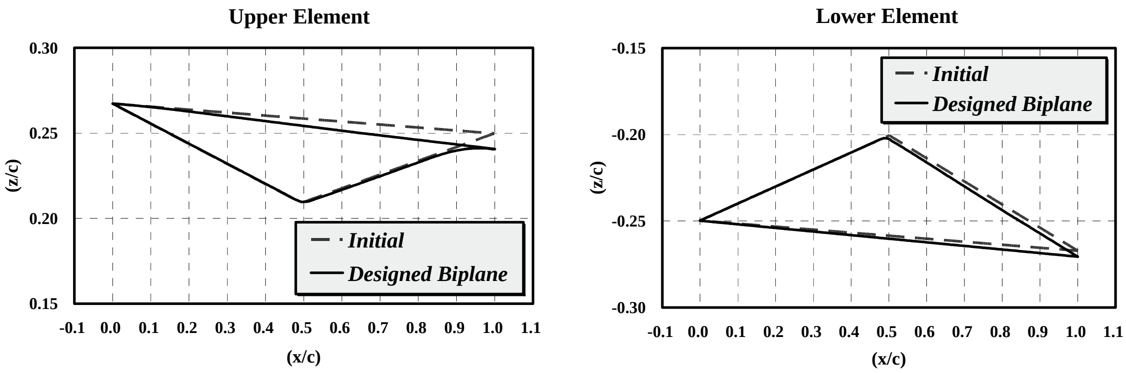


Figure 7. Section airfoil geometries of designed biplane configuration (t/c=0.102).

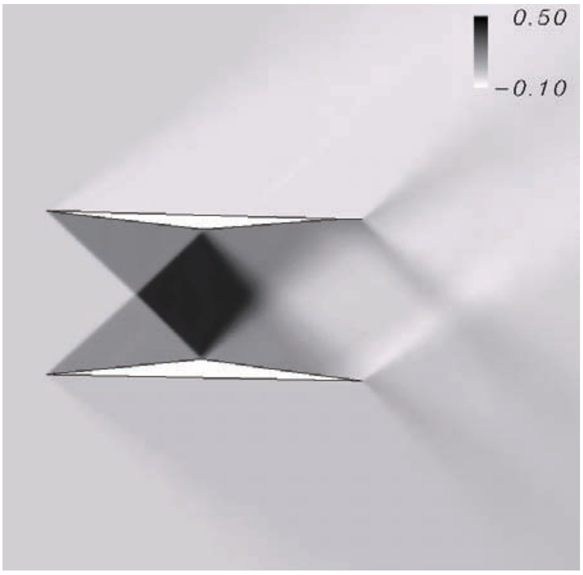


Figure 8. C_p visualization of designed biplane at M_∞=1.7 (α=1.19deg).

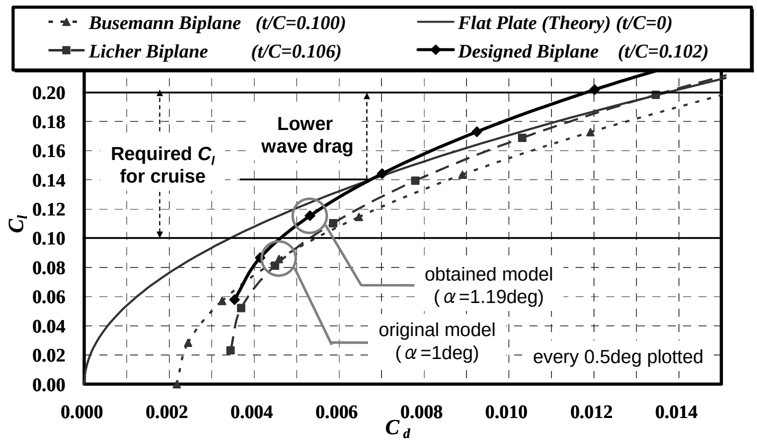


Figure 9. Wave drag polar diagrams of designed biplane at M_∞=1.7.

4. Application to 3-dimensional supersonic biplane

A successful design of 2-dimensional supersonic biplane was shown in the previous paper[8]. Then we are going to challenge to design practical 3-dimensional biplane wings. As a first step of designing practical 3-dimensional biplane wings, we attempted to redesign a known 3-dimensional biplane wing by utilizing the above-mentioned inverse problem method. The residual – correction design strategy utilizing small perturbation form[6,7,8] of the basic equation makes 3-dimensional design possible enables to take the 3-dimensional effects into account, even though the basic equation is for 2-dimensional (a wing of infinit span length). The 3-dimensional effects and interacting effect between the upper and lower wing can be counted by iterations of 3-dimensional flow simulations and the inverse problem solver.

As a design object, the known Busemann biplane whose half-span length is 1 (There is no influence of Mach cones emanuated from wing tips and 2-dimensionality is maintained at the symmetry section) was used as an existing wing shape for target pressure distributions (Fig. 10). The biplane where the upper wing in the Busemann biplane was replaced by a flat plate was used as an initial shape wing (Fig. 11). As the sections for the inverse design, the sections at 10 span stations are located from the symmetry section to the wing tip every 10% span length intervals. The airfoil tip was excluded from designing, and shape on the wing tip is assumed to be the same shape as the shape at 90% span section. The pressure distributions of the Busemann biplane, namely, target pressure distributions appear in Fig. 10. It can be seen that Mach cones influence the C_p distributions at sections from the 30% span station to the wing tip. Detailed pressure visualization of Mach cones and the mesh for CFD analysis are shown in Fig. 12.

Figure. 13 shows obtained geometries and C_p distributions at some sections of the currently designed biplane after 1, 2, 5, 7 times iterations. Equations of the inverse problem method are based on the condition that a flow deflection angle is less than 0.2 radian in supersonic flow. The condition includes the case of thin airfoils. As seen in Fig. 13(a), the obtained geometries agree well with the target ones in the region where there are no influences except for shock waves from the leading edges, that is, in the region from the leading edges to the mid chords at sections within 60 % span (see Fig. 10). According to Fig. 13(b), the obtained geometries after 2 times iterations agree well with the target ones in the region from the leading edges to mid chord sharp apexes at all sections. However, the geometries from the mid chords to the trailing edges are greatly different from target ones and the values of modifications of the geometries among iterations are also very large.

As seen in the obtained shapes after 5 and 7 times iterations (Fig. 13(c) and (d)), the geometries from the leading edges to the mid chords agree well with the target geometries at all sections. Let us see the geometries after 5 times iterations (Fig. 13(c)), the geometry at the 90% span section realizes almost the same shape as the target geometry. This is because influences of Mach cones are primary there and there is little physical interference from the lower wing. Next, let us take a look at the geometries after 7 times iterations (Fig. 13(d)), the geometries at the almost all sections except for the symmetry section are very close to the target geometries. To compare the results after 7 iteration with the geometries after 5 times iterations which have large changes to the span direction, it is confirmed that many iterations are not needed to settle down to the target geometries at many sections. However, the convergence of the obtained geometry at the symmetry section is slow because it is indirectly influenced by other span stations including tip section geometry changes.

The geometries and C_p distributions after 14 times iterations are shown in Figs. 13 and 14. We can observe convergence to the target geometries and C_p distributions at all sections. Table 1 summarizes the absolute RMS (Root Mean Square) errors between the realized C_p distributions and the target ones at all sections. It has been confirmed that the simple inverse problem method is capable of performing the aerodynamic design of 3-dimensional biplane wing shapes where airfoil geometries are changed into a span direction and two airfoil elements interfere with each other. Furthermore, it has been also confirmed that almost the same iteration times are needed to design 3-dimensional wings as the iteration times to 2-mensional airfoil geometry.

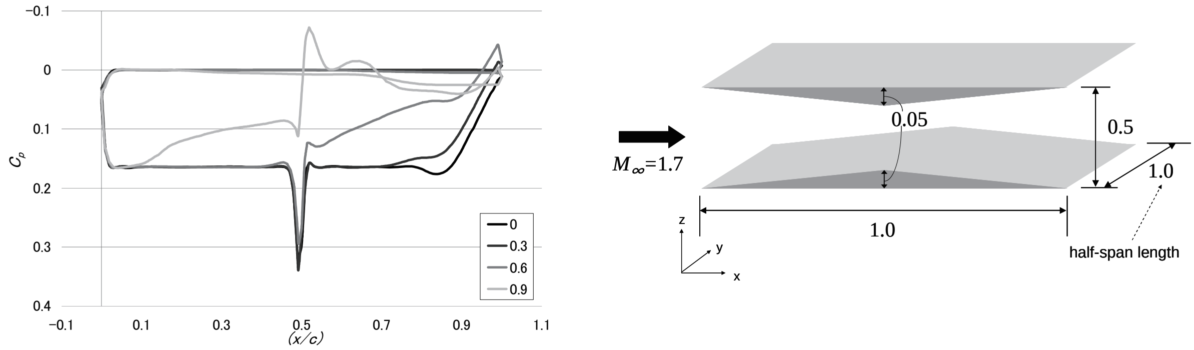


Figure 10. Target C_p distributions at some sections
(C_p distributions of the Busemann biplane at each section).

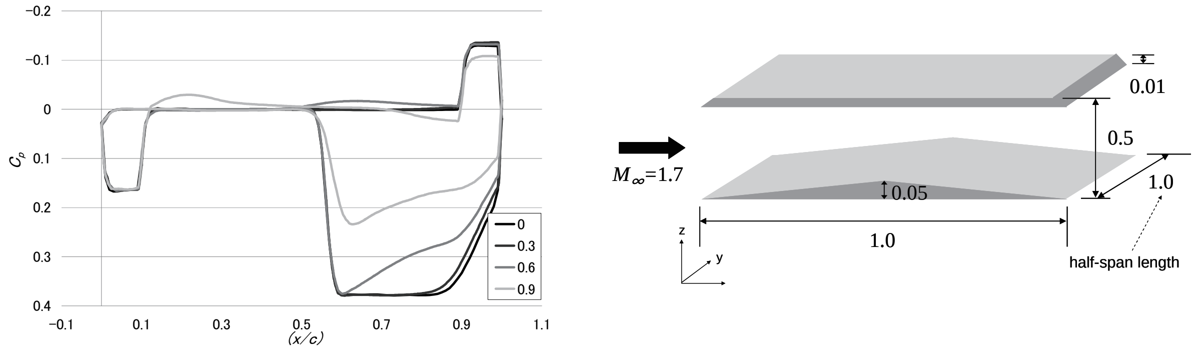


Figure 11. Initial C_p distributions at some sections.

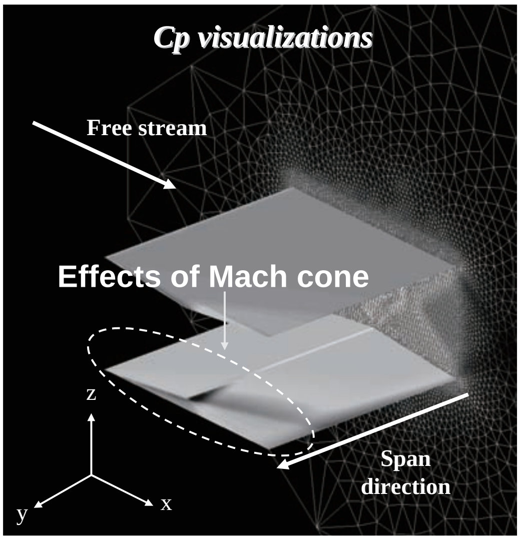
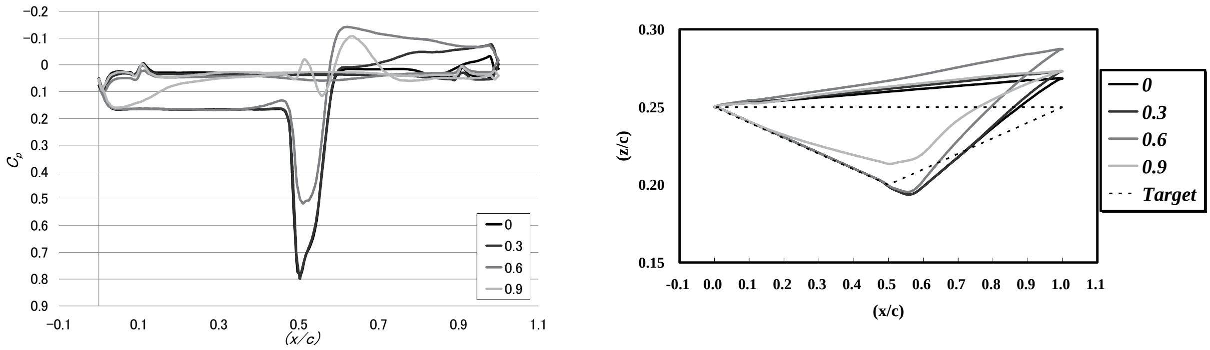
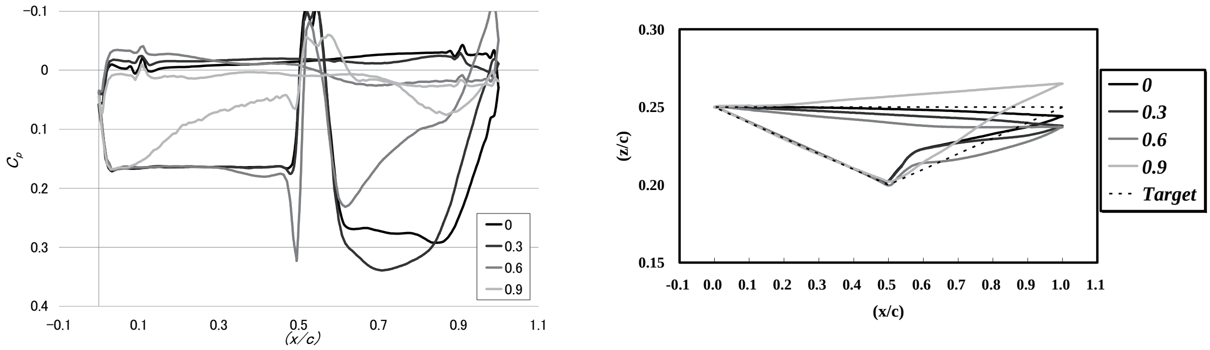


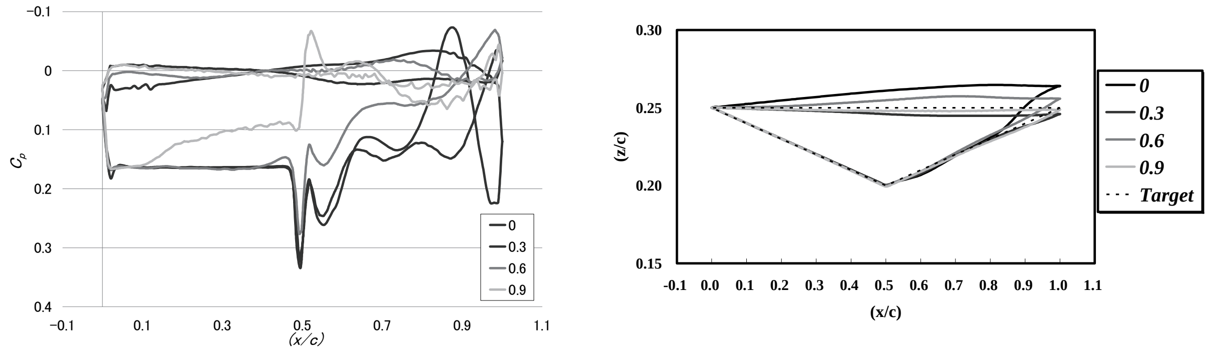
Figure 12. C_p and mesh visualizations around the Busemann biplane at M_∞=1.7 (half-span length 1).



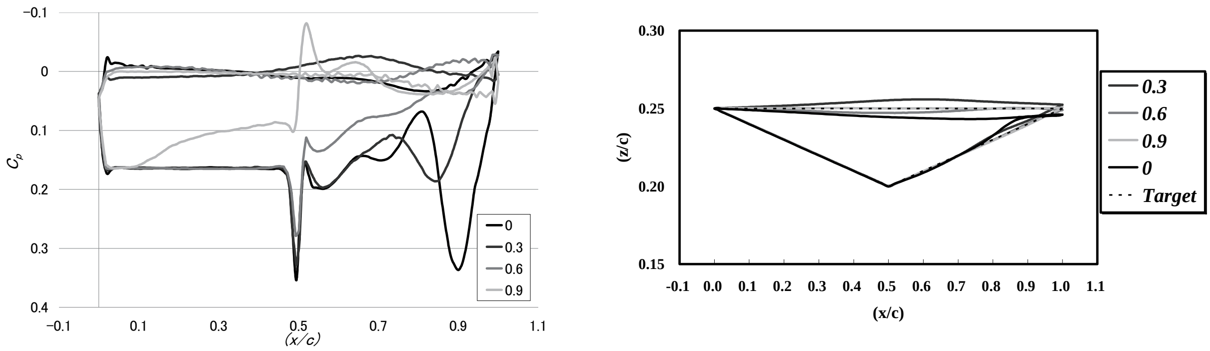
(a) 1st iteration



(b) 2nd iteration



(c) 5th iteration



(d) 7th iteration

Figure 13. C_p distributions and geometries of the modified airfoils after certain iterations.

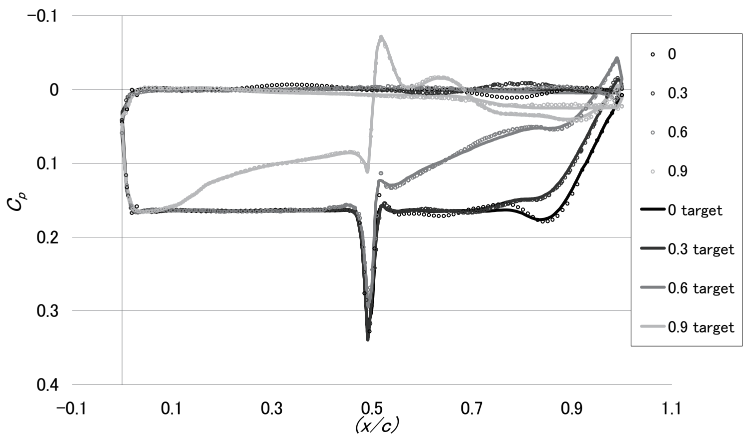


Figure 14. C_p distribution of the upper element of the biplane after 14 times iterations of inverse problem method.

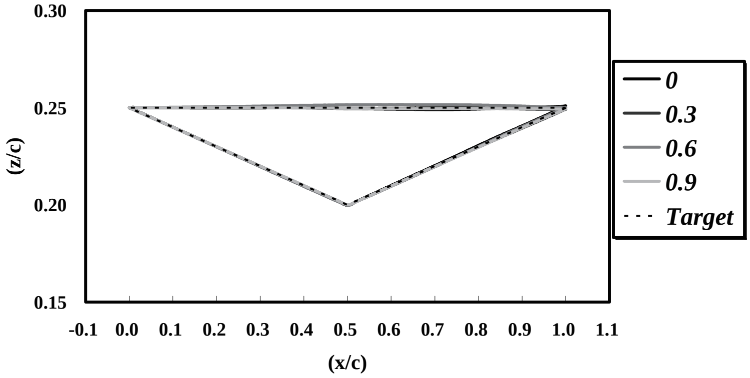


Figure 15. Section airfoil geometries of the upper element after 14 times iterations of inverse problem method.

Table 1. The absolute RMS errors between the realized and initial C_p distrivutions at each section.

(y/c)	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
RMS (*10E-4)	1.99	1.42	2.35	1.53	2.27	1.58	1.74	0.958	1.18	1.09

5. Conclusion

For the purpose of designing a better aerodynamic biplane airfoil than a Busemann biplane and Licher type biplane, an inverse problem method in the previous paper was uded. Concretely, a lower wave drag biplane airfoil than the Licher-type biplane at sufficient lift conditions (C_l>0.1) was aimed under the conditions of a cruise Mach number 1.7 and total thickness-chord ratio about 0.1. Designs are conducted by applying the inverse problem method to the upper element and lower one of the biplane airfoil alternately. Target pressure distributions for the inverse problem method were set to have more lift than the initial airfoil (the Licher-type biplane) with restraining increment of wave drag at chiefly the upper element. We successfully designed a biplane airfoils which achieved lower wave drag compared to both the Busemann biplane and Licher type biplane at C_l>0.07, having a total maximum thickness ratio 0.102. Especially at C_l >0.14 wave drag was lower than that of a (zero-thickness) single flat plate airfoil which had the lowest wave drag in monoplanes in supersonic flight (for instance, M_∞=1.7).

The inverse problem method was applied to designs of 3-dimesional biplane wing. There are some problems in designs of 3-dimensional biplane such as interference of the upper and lower element, and diversity of span direction flow, and both of them. We set the C_p distributions of the Busemann biplane wing as target ones at 10 sections and a biplane wing whose upper wing is flat plate as an initial geometry. The same design cycle of the 2-dimensinal cases at 10 sections are conducted. It was seen that section geometries which were becoming the target one were becoming away by the influences of changes of span direction flow. After 14 times iteration, all sections converged to the target geometry within around 0.0001 or 0.0002 of the absolute RMS errors between realized C_p distributions and target ones. It can be said that the small perturbation form in the inverse problem method makes possible to design biplane airfoils or wing which has strong interference among other elements. In the future, practical designs of 3-deimensional biplane wings are considered by utilizing this method.

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