Numerical Analysis and Design of Supersonic Wings Based on Busemann Biplane

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Abstract
Busemann biplane is the representative airfoil which has possibility of realizing low-boom and low-drag. In this paper, possibilities of designing supersonic biplanes are discussed based on Computational Fluid Dynamics (CFD). Busemann biplane causes high drag at off-design conditions as a result of choking. Aerodynamic designs over flight Mach numbers including the off-design conditions were conducted. A lower wave drag biplane configuration than that of single flat-plate at the cruise condition was designed at the cruise condition. Based on the biplane, wing forms were proposed from take-off to the cruise state by utilizing hinged slats and flaps or morphing mechanism.

1. Introduction

The objectives of attaining low noise and high fuel efficiency are critical for the next generation of supersonic transport. In other words, it is necessary to develop an airplane that has low boom and low drag. Busemann proposed a biplane configuration with the potential for satisfying these two conditions, by utilizing favorable interactions between the two wing elements[1,2]. The wave drag due to airfoil thickness can be nearly eliminated by a biplane configuration that promotes favorable wave interactions between the two neighboring airfoil elements (here, wave drag being defined as the 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 supersonic biplane project was started in order to significantly reduce sonic boom[4,5].

The shapes of these supersonic biplanes are similar to nozzles and intake diffusers. As a result, the internal flow of the biplane will be choked at off-design conditions. This phenomenon was confirmed by Ferri[6] in experiments. In our research, improvement of aerodynamic performance of supersonic biplanes at the both designs and off-design conditions are aimed.

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[2] 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.

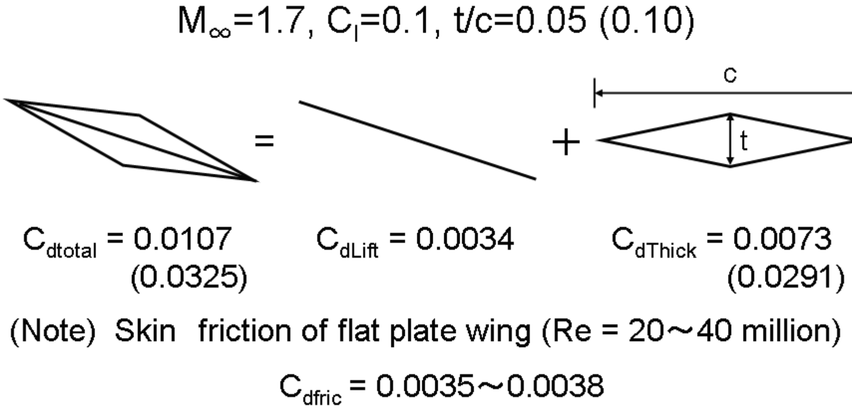


Figure 1: Wave drag components for a diamond airfoil

2.1 Reduction 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.

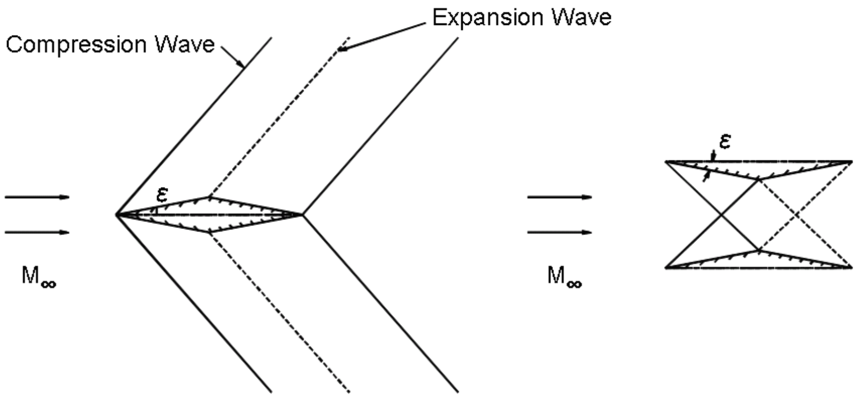


Figure 2: Wave cancellation effect of Busemann biplane

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.

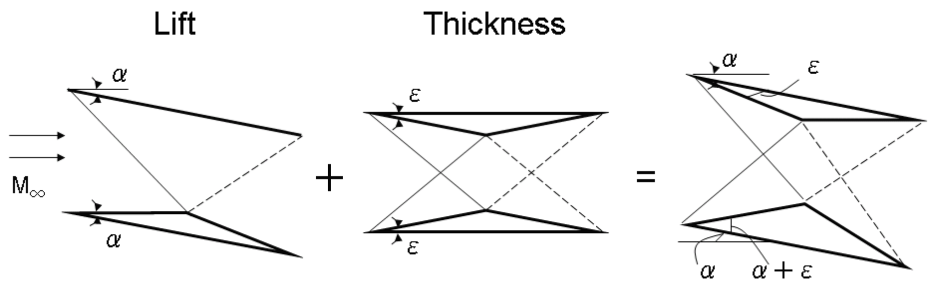


Figure 3: Concept of Licher biplane

2.3 Off-design performance

The different phenomenon, choking, occurs on off-design conditions of supersonic biplanes. Figure 4 shows C_d vs M_∞ characteristics of a Busemann biplane (0.3<M_∞<3.0) comparing with a diamond airfoil whose thickness-chord ratio is the same as that of the Busemann biplane. Analysis results are simulated by TAS-code. The detailed explanation about TAS-code is mentioned next chapter. Here, a cruise Mach number is 1.7. As shown in Fig. 4, in the case that shock waves and expansion waves are cancel each other effectively ('Busemann biplane deceleration' at M_∞=1.7), the C_d of the Busemann biplane is less than one tenth of that of the diamond airfoil (C_d of the diamond airfoil is 0.0291). However, we can observe the high drag over a wide range of free stream Mach number, including the cruise Mach number on acceleration. The flow is choked in these Mach numbers, especially, the choking is continues to be kept up to Mach numbers greater than the cruise Mach number (an effect of hystresis). The hysteresis of choking is also observed in experiments[6]. These characteristics are similar to those in intake diffuser. The critical Mach numbers on acceleration and deceleration are the same as those obtained by the theory of start and un-start on intake diffuser[7]. Choking and its hysteresis are demerits of supersonic biplanes and have to be avoided. The possible strategy to overcome the demerits will be discussed in section 3.2.

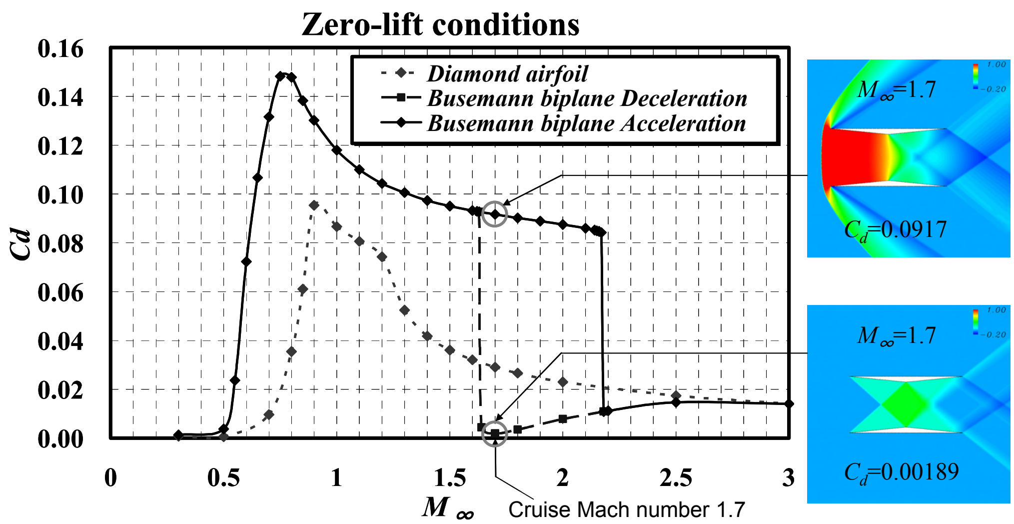


Figure 4: C_d vs M_∞ characteristics of the diamond airfoil and the Busemann biplane (zero-lift conditions)

3. Numerical analysis and design

In this research, a flow solver named TAS code (Tohoku University Aerodynamic Simulation), using a two or three dimensional unstructured grid[8,9], 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[10] is used for the time integration.

3.1 Aerodynamic design at a cruise Mach number

In order to improve aerodynamic performance of the Busemann biplane and Licher-type biplane, a two-dimensional biplane airfoil design has been performed by using an inverse problem method[11.12]. It is the method that the geometry which realizes the specified pressure distribution we set is obtained. Better performance airfoils are designed by setting target pressure distributions intentionally. This theory is based on that of oblique shock wave and the small perturbation form is used for equations. The design procedure of the inverse deign cycle for biplane airfoils is shown in Fig. 5. The geometry correction term ΔF is obtained by the difference between the target C_p and realized one by CFD analysis by utilizing the inverse problem method. The inverse design cycle are conducted to the upper and lower wing alternately.

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. C_l=0.0812, C_d =0.00449 (L/D=18.06). Our concept is to design a biplane configuration which has a lift coefficient more than 0.10 (C_l >0.10). Both the target and initial pressure distributions for the upper and lower elements used for the biplane design were shown in Fig. 6. Target C_p distributions were set to meet a demand of 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. After 14 times iterations of the inverse design process, the biplane configuration which realized target C_p distributions were successfully designed. The upper and lower biplane geometries are shown 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=21.7). C_p visualization map at this design point is shown in Fig. 8 compared to the Busemann biplane (C_l=0.115, C_d=0.00647, L/D=17.7, α=2deg) and the Licher biplane (C_l=0.110, C_d=0.00586, L/D=18.8, α=1.5deg) at the same lift conditions. Weaker shock waves generated from the lower surface of the lower element than the other biplanes can be observed because of lower angle of attack.

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. It may seem surprising to find a biplane configuration that has a lower wave drag than that of a flat plate airfoil, which was predicted by Moeckel more than 50 years ago[13], but have not been realized till this research.

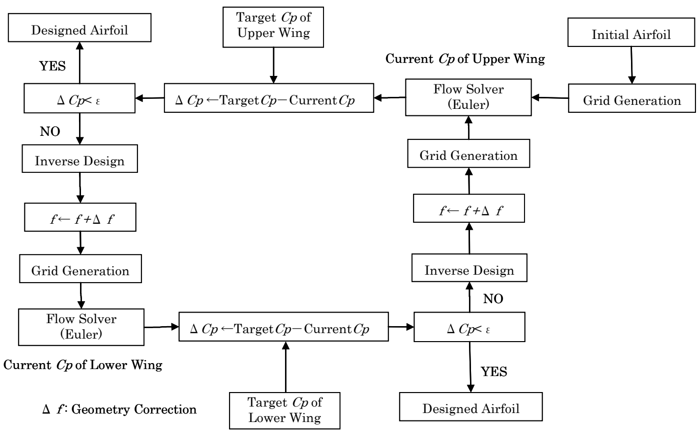


Figure 5: Design cycle of inverse problem method

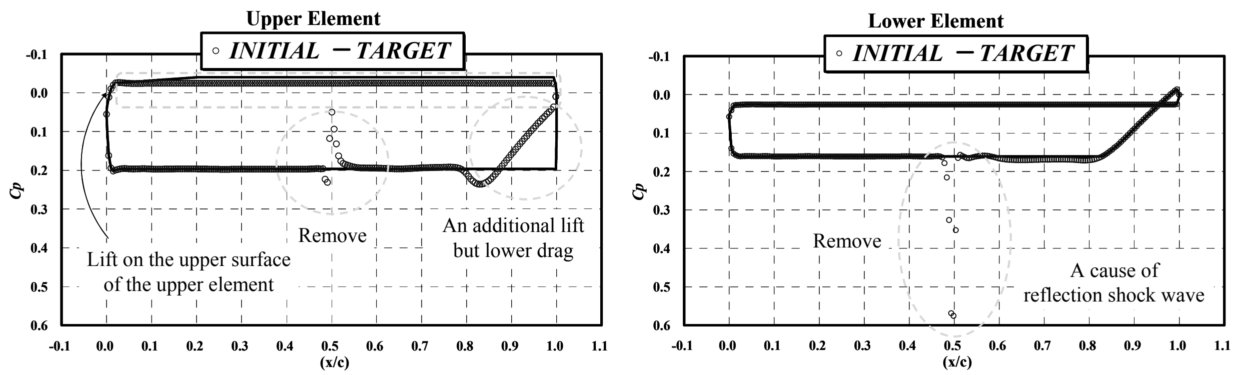


Figure 6: Target and intial (Licher biplane, α=1deg.) C_p distributions

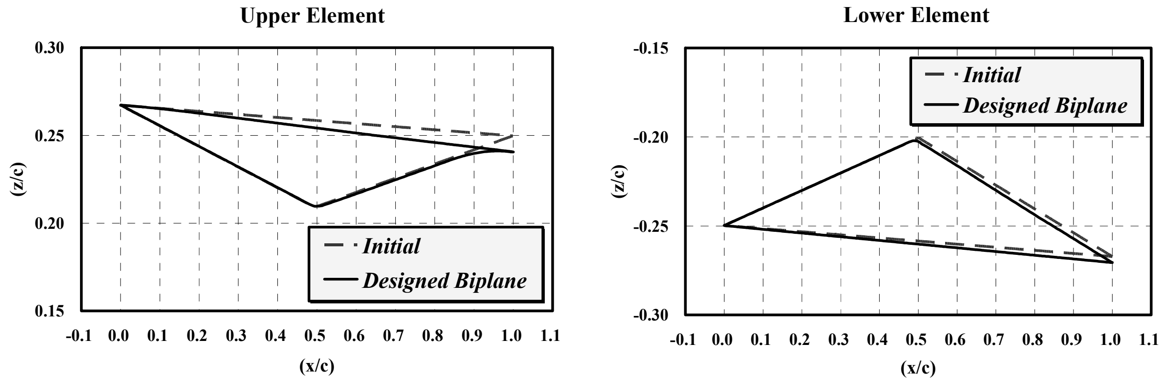
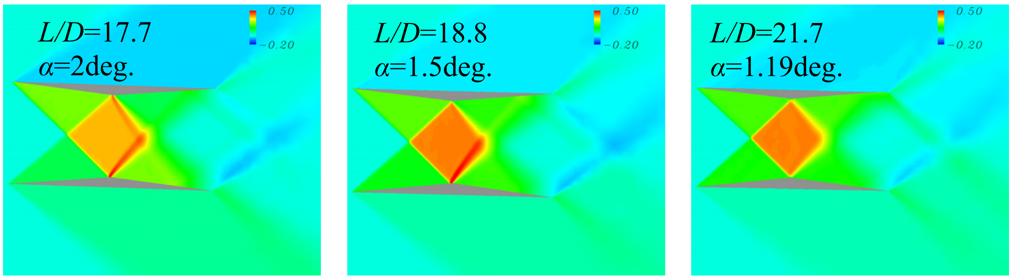


Figure 7: Airfoil geometries of the initial (Licher biplane, α=1deg.) and designed biplane configuration (t/c=0.102)



Busemann biplane (α=2deg.) Licher biplane (α=1.5deg.) Designed biplane (α=1.19deg.)

Figure 8: C_p visualizations of Busemann biplane and designed biplane at the same lift conditions ($C_l \cong 0.11$)

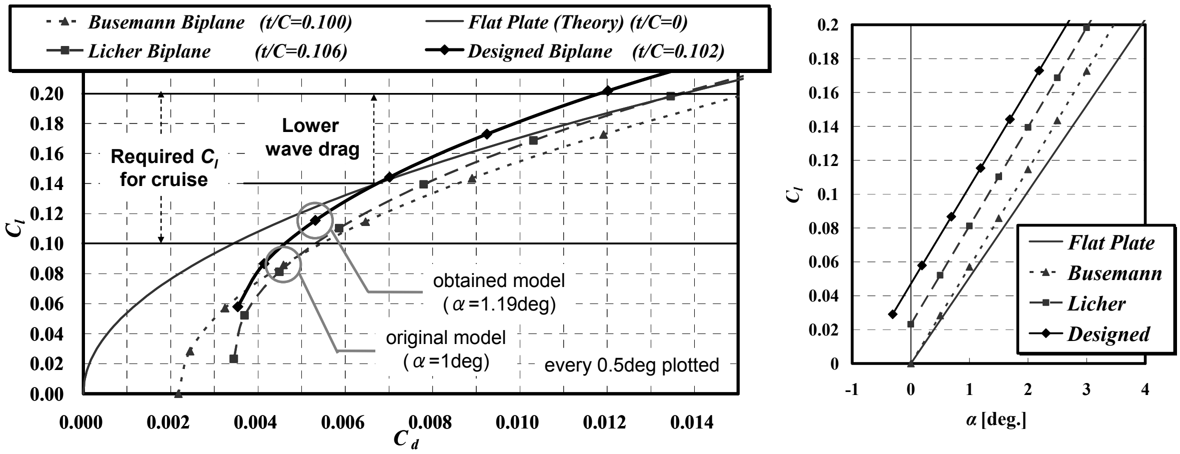


Figure 9: Drag polar diagrams of various biplanes at M_∞=1.7

3.2 Aerodynamic analysis and design at off-design conditions

As mentioned in section 2.3, choking and its hysteresis are problems that are desired to be avoided. A way to avoid choking will be shown. On the condition of M_∞<1, the outlet section area should be modified to reduce the strength of shock waves located at a downstream location of the throat by the use of flaps. On the condition of M_∞>1, choking and its hysteresis occur and choking is continued to be kept to Mach numbers greater than the cruise Mach number, that is, un-starting on intake diffuser continues. This phenomenon can be explained by some theory of starting-unstarting on intake diffusers. According to the theory of one-dimensional flow on intake diffuser, the Mach number of starting can be reduced by increasing the ratio of the surface area of the inlet to the throat. Hinged slats equipped with the leading edges are used to control the surface area ratio.

Figure 10 shows the countermeasure of choking and its hysteresis in which a Busemann biplane is equipped with hinged slats and flaps to control the inlet and outlet areas respectively, and a graph of intake diffusers. The inner surfaces of the hinged slats and flaps of the two elements of the biplane are set to be parallel to the free-stream direction. The ratio of the sections of the inlet to the throat is 0.91 (that of a Busemann biplane is 0.80.).

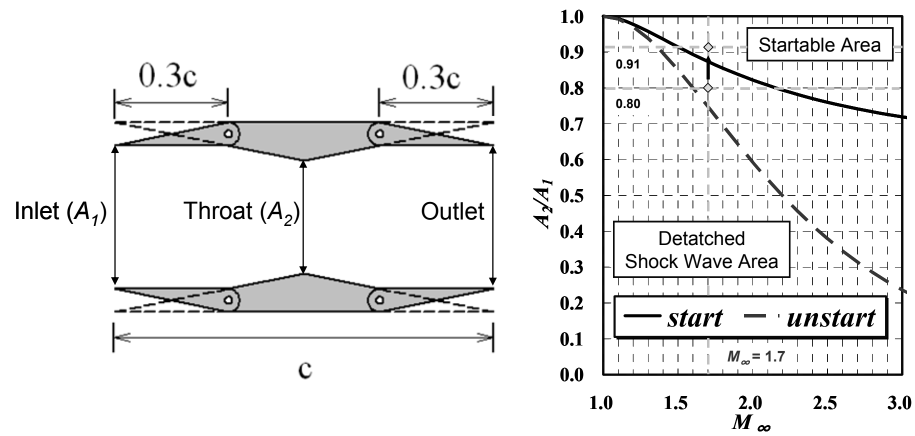


Figure 10: Simple diagram of the Busemann biplane equipped with hinged slats and flaps and application to characteristics of intake diffusers

Figure 11 shows the biplane to avoid high drag form from take-off to the cruise state by utilizing the hinged slat and flaps and its C_l and C_d characteristics. The primary biplane is the designed biplane show in section 3.1. We equipped the biplane with hinged slats and flaps to control section area ratio. Here, 'Sufficient C_l' in Fig. 11 is theoretical line obtained by simple assumption that lift and other parameters are constant over changes of free stream Mach numbers. The value of lift is set to satisfy a condition C_l =0.4 at M_∞=0.85.

Sufficient aerodynamic performance will be secured by using the hinged slats and flaps as high-lift device on take-off. In subsonic flight, it is necessary to use the flaps as mentioned in the previous paragraph. It is possible to have some angle of attack because there are few worries about sonic boom in this domain. Thus, the biplane equipped with hinged slats and flaps flies with about 1.5 degree angle of attack in subsonic flight. Then, it needs to have the hinded slats to avoid high C_d and hysteresis of choking in supersonic flight. When the flaps are returned to their original positions, a biplane equipped with only hinged slats flies with no additional angle of attack. Thus, the biplane is reconfigured back to the form of a traditional biplane in order to produce good aerodynamic performance at the cruise condition (M_∞=1.7), at which Mach number hysteresis of choking disappears at around 1.56 of free-stream Mach numbers.

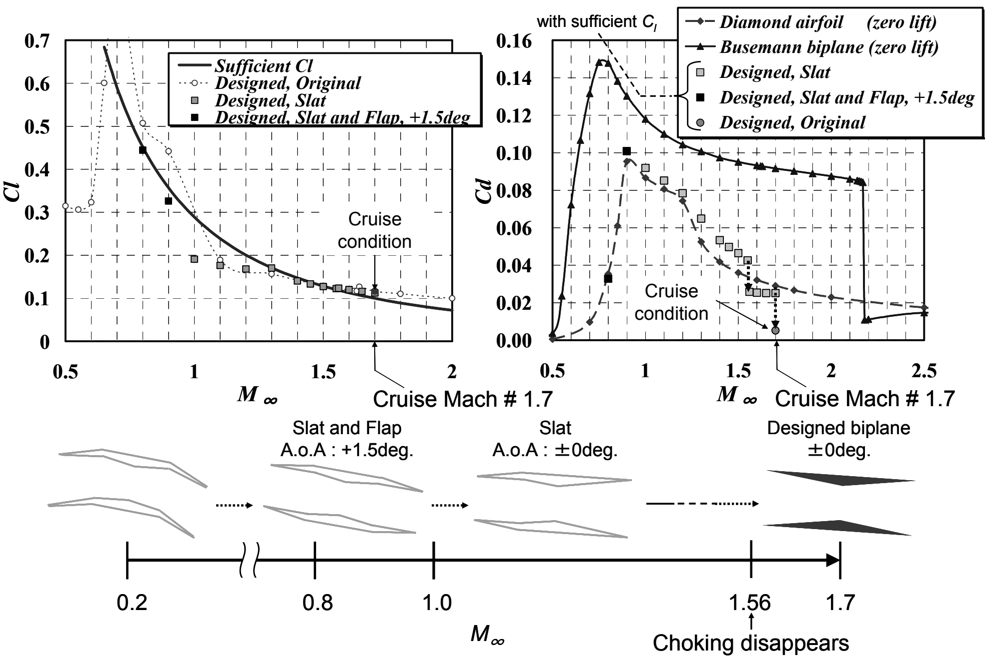


Figure 11: Wing form utilizing hinged slats and flaps from take-off to cruise state and C_l-M_∞, C_d-M_∞ graph

Other ways to improve the performance are morphing. Figures 12 shows a simple diagram of the Busemann biplane with additonal morphing mechanism. A section area around the throat become larger by folding surfaces around the throat as shown in Fig. 12. In order to lower wave drag, the leading edges and trailing edges are also modified by utilizing the abobe-mentioned hinged slats and flaps. The morphing also alters the area ratio of the inlet area to the throat, which is similar to the effect by hinged slats and flaps discussed in the previous paragraph. Moreover with the morphing strategy, additional reduction in wave drag is expected, due to the reduction of airfoil thickness. For example, the thickness-chord ratio (*t/c*) is changed from 0.05 to 0.03 on each element in Fig. 12. Figure 13 shows analysis results of further improvement to avoid high drag form from take-off to the cruise state by utilizing the morphing mechanism in addition to the hinged slats and flaps and its C_l and C_d characteristics. Conditions such as 'Sufficient C_l' are the same as those in Fig. 11. At the take-off state, sufficient aerodynamic performance will be secured by using only the hinged slats and flaps in the same way as Fig. 11. In subsonic flgiht, the surfaces around the throat are folded and the leading edges and trailing edges are moved to the center positions of the wing thickness direction, and the wing shoul have some angle of attack (a range from 0 to 1deg.). This form is named as 'morphing1' in Fig. 13. Then, in supersonic flight, the surfaces aroud the throat are kept to be folded, and the positions of leading edges and trailing edges are moved up and down respectively to have some canber (as 'morphing2' in Fig. 13). Hysteresis of choking disappears at around 1.51 of free-stream Mach numbers. Around 0.04 or less C_d were achieved by applying the morphing mechanism.

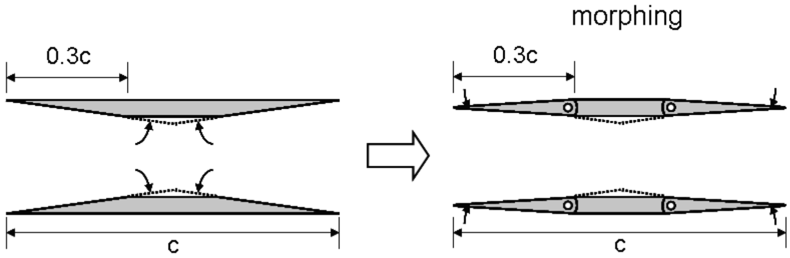


Figure 12: Simple diagram of the Busemann biplane with additional morphing mechanism

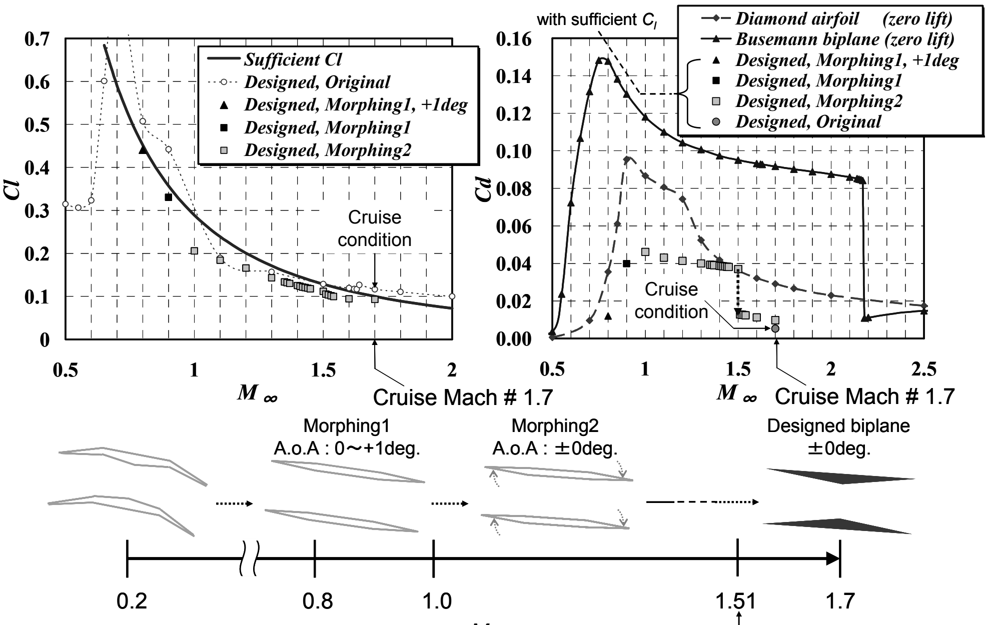


Figure 13: Wing form utilizing additional morphing from take-off to cruise state and C_l-M_∞, C_d-M_∞ graph

4. Conclusion

For the purpose of realizing low-boom and low-drag supersonic transport, we examined aerodynamics performance of a Busemann biplane and Licher biplane. On comparison of the Busemann biplane and the diamond airfoil having the same thickness-chord ratio, more than 90% reduction of C_d (wave drag coefficient) was confirmed at a design Mach number (M_∞=1.7). However, it was also found that there were high drag domains of free-stream Mach numbers on supersonic biplanes although they had desirable performance at their design Mach numbers. Concerning wing designs, we focused on achieving lower wave drag supersonic biplanes with a sufficient lift at the cruise Mach number and also on avoiding choked flow and hysteresis at their off-design conditions.

On the cruise condition (M_∞=1.7), lower wave drag two-dimensional biplane wing configuration than the zero thickness single flat plate at the sufficient lift condition (C_l>0.14) was successfully designed by using the inverse design method. At off-design conditions, by applying the hinged slat and flaps used as high-lift device on take-off and landing conditions, the biplane achieved the same C_d as the diamond airfoil over a wide range of flight Mach numbers. Furthermore, the C_d was reduced to around 0.04 or less by using the mechanism of morphing.

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