Aerodynamic Optimization of Near-future High-wing Aircraft

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This paper discusses aerodynamic optimization of the high-wing configuration to explore fuselage-wing shapes for the high-wing configurations of near-future aircraft, in which it will be possible to install fuel-efficient, ultrahigh-bypass ratio engines, using computational fluid dynamics simulation and the Kriging surrogate-assisted genetic algorithm. First, optimization of the fuselage upper surface is performed, with exploration of the fairing shape suitable for the high-wing configuration. Second, the aircraft nose shape is also optimized, in addition to the fuselage upper surface, to confirm the possibility of generating higher lift by the fuselage itself. Finally, both the fuselage and the wing shape are optimized to improve the lift-to-drag ratio by alleviating the shock wave over the wing, while sustaining the high lift generation of the high-wing configuration. The final optimized configuration achieves not only a lift-to-drag ratio comparable to the DLR-F6, but also a $C_L$ approximately 1.5 times higher than the DLR-F6. These results indicate the possibility of producing high-wing aircraft that not only employ fuel-efficient ultrahigh-bypass ratio engines, but also have much better aerodynamic performance than low-wing configurations.

Key Words: High-wing Configuration, Computational Fluid Dynamics, Multi-objective Optimization

Nomenclature

\[c: \text{ chord length of airfoil}\]
\[C_D: \text{ drag coefficient}\]
\[C_{Df}: \text{ friction drag coefficient}\]
\[C_{dp}: \text{ local pressure drag coefficient}\]
\[C_{dp}: \text{ pressure drag coefficient}\]
\[C_l: \text{ local lift coefficient}\]
\[C_L: \text{ lift coefficient}\]
\[C_p: \text{ pressure coefficient}\]
\[L/D: \text{ lift-to-drag ratio}\]

1. Introduction

With the increase in aircraft traffic and the rise in fuel prices, designing aircraft with high fuel efficiency has become an important goal. Recently, new types of aircraft configurations have been proposed for future fuel-efficient aircraft. In the Environmentally Responsible Aviation N+2 Advanced Vehicle Study,1–4) NASA proposed three unconventional aircraft shapes, including blended-wing-body and box-wing configurations. These are expected to reduce fuel consumption by 50%, exhaust gases by 75%, and noise by 42 dB. These goals will be achieved within a few decades with new technologies. In fact, the N+2 aircraft is supposed to be in service by 2025.

However, the concept of the proposed aircraft is quite different from the conventional low-wing, tube-and-wing (TAW) configuration. Therefore, it will require a long development time and incur high costs for production. Until the appearance of these new concept aircraft, it will be necessary to improve the fuel efficiency of conventional TAW configuration aircraft. With regard to the improvement of fuel consumption for the TAW configuration, one of the key technologies is the development of high-performance engines. The Airbus320neo5) and Boeing737MAX6) were said to cut fuel consumption by about 13% by replacing the engines of existing Airbus320 and Boeing737NG with up-to-date models. These engine design concepts may be a major trend for near-future aircraft until new concept aircraft configurations become feasible. Therefore, to achieve near-future fuel-efficient aircraft, it is advisable to install higher bypass ratio engines. However, it is difficult to install this engine in small- and medium-sized, low-wing aircraft configurations which have 120–169 seats, the delivery demands for which will be greatest in the near future according to aircraft sales forecast,7) due to insufficient clearance between the nacelle and the ground. The engine diameter has been increasing with increases in bypass ratio.

To resolve this problem, a high-wing configuration has been discussed as a near-future aircraft concept based on TAW aircraft configurations. This concept enables the installation of engines with higher bypass ratios, which realizes significant improvements in fuel consumption. In addition, a reduction in interference drag between the wing and the nacelle can be expected because the margin of clearance between the nacelle and the ground increases the degree of freedom in the pylon shape. On the other hand, there is a possibility degrading the aerodynamic performance of high-wing aircraft because the wing unavoidably protrudes from the fuselage upper surface when installed over the fuselage without sacrificing cabin space. Thus, a fairing is required at the wing-fuselage junction to smoothly connect the fuselage and the protruded wing, although it increases...
the frontal projection area of the aircraft and increases aerodynamic drag. It is advisable to consider the fairing shape because the interference between the fuselage and the wing has a significant effect on the aerodynamic performance of the aircraft.

There have been several studies regarding the fairing design of the low-wing configuration. Vassberg et al. presented two fairing designs for the DLR-F6 wing-body configuration. One of these designs completely removes the side-of-fuselage separation bubble near the wing’s upper surface trailing-edge with its humped shape, and achieves drag reduction. A similar fairing shape analysis based on the DLR-F6 was presented by Li et al. where the properly designed fairing shape increases lift-to-drag ratio \((L/D)\) by alleviating flow separation at the wing-fuselage junction. Peigin and Epstein conducted aerodynamic optimization of a fairing shape. In their paper, the fairing shape was defined by two-parameter Bezier surfaces, and a genetic algorithm (GA) was used in the optimization with full Navier–Stokes evaluation of the wing-body configuration. The optimal solution achieves significant drag reduction due to the decrease in shock strength around the fairing-wing junction. Song and Lv also conducted aerodynamic shape optimization only for the fairing shape. As a result of the optimization, the overall drag is reduced due to significant drag reduction from the wing, although drag contribution from the fairing itself is increased.

These studies indicated that the most important point in fairing design for the low-wing configuration is to avoid flow separation at the side of the fuselage near the wing’s upper surface trailing-edge and alleviate shock strength due to the interference between the fuselage and the wing. However, in the case of the high-wing aircraft configuration, the interference effect between the fuselage and the wing may be different from that of the low-wing aircraft configuration. Therefore, if it is also possible to improve the aerodynamic performance by optimizing the interference effect between the fuselage and the wing of high-wing aircraft, the high-wing configuration will become a potential candidate for near-future, fuel-efficient aircraft.

The present study was performed to explore the fuselage-wing shape for the high-wing configuration as near-future aircraft, into which it will be possible to install fuel-efficient, ultrahigh-bypass ratio engines, through aerodynamic shape optimization using computational fluid dynamics (CFD) simulation and the Kriging surrogate-assisted GA. First, we optimize the fuselage upper surface to explore the fairing shape suitable for high-wing configuration and investigate the interference effect between the fuselage upper surface and the wing. Based on the first optimization results, the geometry definition is modified to increase the degrees of freedom in the fuselage upper surface and the aircraft nose shape, and then a second optimization is conducted to achieve higher lift generated by the fuselage itself. Finally, optimization of the fuselage and the wing shape is conducted to improve \(L/D\) by alleviating the shock wave without adversely affecting the lift generation mechanisms established in the first and second optimizations.

2. Flow Solver and Optimizer

In this research, three-dimensional flow fields are analyzed using an unstructured mesh computational fluid dynamics (CFD) solver, the Tohoku University Aerodynamic Simulation (TAS) code. The compressible Reynolds-averaged Navier–Stokes (RANS) equations are solved using the cell-vertex finite-volume scheme. The numerical flux is computed using the approximate Riemann solver of Harten–Lax–van Leer–Einfeldt–Wada (HLEW). The second-order spatial accuracy is realized using a linear reconstruction of the primitive variables inside the control volume with a Venkatakrishnan’s limiter. The lower/upper symmetric Gauss–Seidel (LU-SGS) implicit method for unstructured meshes is used for time integration. The turbulence model used in this study is the Spalart–Allmaras model. A hybrid volume mesh consisting of tetrahedrons, prisms, and pyramids is used to resolve the boundary layer accurately in unstructured mesh computation. The accuracy of the TAS-code has been validated for various flow problems.

In aerodynamic shape optimizations, a real-coded, multi-objective genetic algorithm (MOGA) is adopted for aerodynamic shape optimization because the non-linearity of the objective functions must be taken into consideration. This is a population-based optimization method simulating the evolutionary process of living organisms, in which the population evolves over generations to minimize or maximize the objective functions using the process of selection, crossover, and mutation. It is well known that GAs requires large computational costs due to those of population-based searches, particularly coupled with expensive CFD solvers. Therefore, the Kriging model is adopted to build approximation models of the objective functions to reduce the computational cost. Pareto-optimal solutions are explored over the approximation model using MOGA.

The flowchart of the current optimization system is shown in Fig. 1. The first sampling points are determined using the Latin hypercube sampling (LHS) method to distribute the points uniformly in the design space. After evaluating the

Fig. 1. Flowchart of the current optimization system.
real objective functions at each sample point using CFD, a Kriging approximation model is constructed based on the sample data. This model estimates the objective functions at any search point in the optimization process. However, it is possible to miss the global optimum in the search space if we rely only on the prediction value of the Kriging model because the model includes uncertainty at the prediction point. For robust exploration of the global optimum point, both the prediction value and its uncertainty should be taken into consideration at the same time. For this reason, the objective function is transformed to the corresponding expected improvement (EI), which indicates the probability of a point being optimum in the design space. By selecting the best EI point calculated on the Kriging model as the additional sample points for the Kriging model iteratively, improving the model and closely exploring the global optimum can be achieved at the same time.

3. Optimization I

In this section, optimization of the fuselage upper surface, including the fairing, for high-wing aircraft is discussed to maximize the $C_L$ and minimize the $C_D$. This optimization aims to explore the fairing shape suitable for high-wing configurations and investigate the interference effect between the fuselage upper surface and the wing. A high-wing aircraft model is generated based on the original low-wing, DLR-F6 configuration used in the 3rd AIAA Drag Prediction Workshop.

3.1. Geometric definition

The fuselage shape is defined as shown in Fig. 2. The $y$–$z$ cross-sections at different $x$ locations on the fuselage upper surface are defined by the $n$-th order hyper-elliptic functions, which consider the order $n$ as six design variables ($DV_{13}$–$DV_{18}$ in Fig. 2(c)). It is possible to change the $y$–$z$ cross-sectional shape of the fuselage upper surface from circular to rectangular by changing the order $n$ along the $x$ coordinate, which represents the fairing shape around the wing position. The fuselage upper surface at the $x$–$y$ cross-section of the aircraft’s symmetrical plane is defined by the non-uniform rational basis spline (NURBS) curve, which considers the control point coordinates as 12 design variables ($DV_{1}$–$DV_{12}$ in Fig. 2(b)). Thus, the fuselage upper surface, including the fairing, is represented by a total of 18 design variables. In Optimization I, the fuselage lower surface is fixed to that of the original DLR-F6 configuration.

The high-wing aircraft model is generated by merging the original DLR-F6 wing into the fuselage defined above, and then the intersection between the fuselage and the wing is automatically extracted by a Boolean operation as shown in Fig. 3. Note that only the dihedral angle is changed from the DLR-F6 configuration, which is set to $0^\circ$.

The computational mesh is generated using Mixed-Element Grid Generator in 3 Dimensions (MEGG3D). The total number of grid points, including the surface grid and the volume grid, is about seven millions.

3.2. Flow and optimization conditions

The freestream Mach number is 0.7 and the Reynolds number based on the mean aerodynamic chord (MAC) is $6.9 \times 10^7$.

The objective functions are as follows.

Objective 1: Maximize $C_L$
Objective 2: Minimize $C_D$

3.3. Results of Optimization I

The initial Kriging models for each objective function are constructed using 70 sample points obtained using the LHS. The Kriging models are updated 12 times, and 163 sample points are evaluated in total. The sample points are plotted in the objective function space in Fig. 4. The calculation result of the DLR-F6 configuration is also plotted as a cross mark in Fig. 4, and its shape using the surface $C_p$ distribution with the shock wave depicted in a gray isosurface and the chordwise $C_p$ distributions at 0, 10, and 14% semispan sections are shown in Figs. 5 and 6, respectively. In Fig. 4,
compared to the DLR-F6, a few sample points have a lower value for $C_D$, while most have a higher value for $C_L$. This is due to the ranges of the design variables, which allow the volume of the fuselage to become larger than that of the DLR-F6. In this optimization, therefore, it is important to confirm whether increasing the volume of the fuselage can generate lift while preventing an increase in drag. In Fig. 6, the gray and black areas indicate the lift and downforces, respectively. As a result of Optimization I, three optimal solutions are explored: the maximum $C_L$ configuration ($\text{OPT}_1$), the minimum $C_D$ configuration ($\text{OPT}_2$) and the maximum $L/D$ configuration ($\text{OPT}_3$). Here, the features of $\text{OPT}_1$ and $\text{OPT}_3$ are investigated in detail.

For $\text{OPT}_1$, the shape with the surface $C_p$ distribution, spanwise lift distributions (compared to the DLR-F6 configuration) and chordwise $C_p$ distributions at 0, 10 and 14% semispan sections are shown in Figs. 7–9, respectively. As a result of maximizing $C_L$, $\text{OPT}_1$ has an inflated part in the fuselage upper surface around the wing position as shown in Fig. 7. The flow acceleration is caused by this inflated part of the fuselage (Fig. 9(b)), and $\text{OPT}_1$ increases lift significantly around the wing-fuselage junction as compared to that of the DLR-F6 in Fig. 8. In addition, lift generated over the wing is also increased because the flow over the wing is also significantly accelerated (Fig. 9(c)) due to the interference effect between the fuselage upper surface and the wing, even though the wing shape is the same as that for the DLR-F6. However, lift does not increase near the symmetrical plane of the aircraft, because strong downforces act on the fore and aft areas of the inflated part of the fuselage (Fig. 9(a)), which reduces the generation of lift in this section. Furthermore, shock waves occur extensively over both the fuselage and the wing due to the rapid flow acceleration caused by the inflated part of the fuselage. Thus, comparing Figs. 6 and 9, the significant increase in overall lift resulting from the interference effect between the fuselage upper surface and the wing is one of the aerodynamic characteristics of the high-wing configuration.

For $\text{OPT}_3$, the shape with the surface $C_p$ distribution and spanwise lift and pressure drag distributions (compared to the DLR-F6 configuration) are shown in Figs. 10–12, respectively. In $\text{OPT}_3$, the fuselage upper surface around the wing position is slightly inflated as shown in Fig. 10. As a result, $\text{OPT}_3$ increases lift around the wing-fuselage junction, because the flow of the wing’s upper surface is acceler-
ated due to the interference effect between this slightly inflated part of the fuselage upper surface and wing, as in OPT1. In addition, lift near the symmetrical plane of the aircraft is also increased slightly, as shown in Fig. 11. This is because the downforces acting on the fore and aft areas of the inflated part of the fuselage upper surface are alleviated. These factors contribute to increasing the $C_L$ of OPT3 as compared to that of DLR-F6 configuration.

The $C_{D_l}$ and the $C_{D_p}$ generated by each component for the DLR-F6 configuration and OPT3 are shown in Figs. 13 and 14, respectively. In Fig. 13, OPT3 increases the friction drag by four counts compared to that of DLR-F6 due to increasing the area of the fuselage upper surface. As shown in Fig. 12, OPT3 reduces pressure drag around the wing-fuselage junction compared to DLR-F6. Although the pressure drag caused by the fuselage itself increases drag by 18 counts, the total pressure drag is reduced by two counts due to a significant reduction by the wing, as shown in Fig. 14. As a result, the overall drag of OPT3 is comparable to that of DLR-F6 as the result of pressure drag reduction, which partly compensates for the increase in friction drag.

Therefore, it is possible that OPT3 has a higher $L/D$ than that of the DLR-F6 configuration. This result suggests that a high-wing aircraft has improved aerodynamic performance even when having a fuselage with a large fairing, which seems disadvantageous for drag.
4. Optimization II

In the previous section, it was confirmed that the high-wing configuration generates much higher lift around the wing-fuselage junction than a low-wing aircraft configuration (DLR-F6) due to the interference effect between the fuselage upper surface and the wing. However, even with significant lift generation around the junction of the wing-fuselage, the lift near the symmetrical plane of the aircraft is hardly increased. To take further advantage of the high-wing configuration, the geometry definition should be modified to increase the degrees of freedom in the fuselage shape.

Based on the results of Optimization I, the aircraft nose shape is also optimized, together with the fuselage upper surface, to achieve greater lift generation over the whole fuselage in this section.

### 4.1. Geometric definition

For the fuselage upper surface, the same geometric definition is used as in Optimization I. In addition, for the fuselage nose shape, new design variables are introduced as shown in Fig. 15. The aircraft nose position is defined by one design variable ($DV_{19}$ in Fig. 15) representing vertical movement. The aircraft nose lower surface at the $x$–$y$ cross-section on the aircraft symmetrical plane is defined using the NURBS curve, which considers the control point coordinates as five design variables ($DV_{20}$–$DV_{24}$ in Fig. 15). The total number of design variables is 24 in Optimization II.

### 4.2. Flow and optimization conditions

The freestream Mach number is 0.7 and the Reynolds number based on the MAC is $6.9 \times 10^7$.

The objective functions are as follows.

Objective 1: Maximize of $C_L$

Objective 2: Minimize of $C_D$

#### 4.3. Results of Optimization II

The initial Kriging models for each objective function are constructed using 100 sample points obtained using the LHS. The Kriging models are updated 11 times, and 205 sample points are evaluated in total. The sample points of Optimizations I and II are plotted in the objective function space in Fig. 16. From this figure, the $C_L$ and $C_D$ are significantly improved compared to the results of Optimization I by allowing modification of the aircraft nose shape. As a result of Optimization II, three optimal solutions, the maximum $C_L$ configuration ($OPT_4$), minimum $C_D$ configuration ($OPT_5$) and maximum $L/D$ configuration ($OPT_6$), were explored. Here, the aerodynamic features of $OPT_4$ will be discussed in detail.

For $OPT_4$, the shape with the surface $C_p$ distribution, the spanwise lift distributions (compared to the DLR-F6 configuration and $OPT_1$), and chordwise $C_p$ distributions at the 0% semispan section (compared to that of $OPT_1$) are shown in Figs. 17–19, respectively. From Fig. 18, it can be seen that $OPT_4$ increases lift near the aircraft’s symmetrical plane compared to $OPT_1$. There are two reasons for this: $OPT_4$ has an upward-facing aircraft nose, and the inflated part of the fuselage upper surface is larger than that of $OPT_1$. Thus, the inflated fuselage upper surface around the wing position leads to the generation of lift around the wing-fuselage junction and the upward-facing aircraft nose generates lift near the aircraft’s symmetrical plane.

Although $OPT_6$ achieves a $L/D$ comparable to that of $OPT_3$, it is not easy to improve the $L/D$ by changing the shape of the aircraft nose. This indicates that the $L/D$ of
the high-wing configuration is not markedly improved by changing the aircraft nose shape, although $C_L$ and $C_D$ are significantly improved. Especially for the objective of maximizing $C_L$, OPT4 increases the overall lift as the result of the lift generated by the fuselage itself, in addition to the interference effect between the fuselage upper surface and the wing, although its $L/D$ is lower than that of OPT1.

Figure 20 shows the sample points used in Optimizations I and II plotted in the $C_L$ and $L/D$ space. From this figure, it can be seen that the shapes with relatively higher $C_L$ tend to reduce the $L/D$ due to the extensive shock wave generated over the wing. Therefore, the wing shape should also be optimized to improve the $L/D$ of the high-wing configuration, which is expected to have a much higher $C_L$ than the DLR-F6 configuration.

5. Optimization III

In this section, the optimization of the fuselage and wing shape is conducted to improve the $L/D$ by alleviating the shock wave over the wing, while sustaining the lift induced using the interference effect between the fuselage upper surface and the wing, as well as the lift generated by the fuselage itself.

5.1. Geometric definition

Optimization III employs the same geometric definition of the fuselage shape as Optimization II and newly considers the wing shape, which is defined by 27 design variables to control three airfoil shapes at the root, tip, and kink, as shown in Fig. 21. Each airfoil is defined by nine design variables ($DV_{25} - DV_{33}$, $DV_{34} - DV_{42}$, and $DV_{43} - DV_{51}$ in Fig. 21) with PARSEC parameterization. The wing sections between these sections are represented by linear interpolation. In this wing shape definition, the planform of the wing is fixed to that of the original DLR-F6 configuration. The total number of design variables in Optimization III is 51.

5.2. Flow and optimization conditions

The freestream Mach number is 0.7 and the Reynolds number based on the MAC is $6.9 \times 10^7$.

To sustain the high lift generation induced by the interference effect between the fuselage upper surface and the wing as well as the lift generated by the fuselage itself, the targeted elliptic lift distribution is determined as shown in Fig. 22. The lift at the root is set based on that of OPT4 and the targeted elliptic lift distribution corresponds to the total $C_L$ of 0.804. Then the difference between the targeted elliptic lift distribution and the real lift distribution ($DBTR$), which is defined by Eq. (1), is minimized as Objective 1.

$$DBTR = \sum (C_l \cdot c_{target,i} - C_l \cdot c_{real,i})^2$$ (1)
In addition, the minimization of $C_D$ is considered as Objective 2 to reduce drag, which is expected to increase significantly when shock waves occur extensively over the wing as in OPT1 and OPT4.

As described above, the objective functions are as follows.

Objective 1: Minimize of $DBTR$

Objective 2: Minimize of $C_D$ at the angle of attack $\alpha = 0$

5.3. Results of Optimization III

The initial Kriging models for each objective function are constructed using 120 sample points obtained using the LHS. The Kriging models are updated five times, and 158 sample points are evaluated in total. The sample points are plotted in the objective function space in Fig. 23. We select the shape that achieves a relatively small $DBTR$ by reducing the shock wave as the optimal solution (named OPT7). For OPT7, the shape with the surface $C_p$ distribution, spanwise lift distributions (compared to those of the DLR-F6 configuration, OPT4, and the target) and chordwise $C_p$ distributions at 0, 10, 13, 41, and 63% semispan sections (compared to those of OPT4) are shown in Figs. 24–27, respectively.

As a result of Optimization III, OPT7 yields a spanwise lift distribution much closer to the targeted elliptic lift distribution than OPT4 by markedly increasing lift not only over the wing, but also near the symmetrical plane of the aircraft as shown in Fig. 25. This is because OPT7 generates lift near the aircraft symmetrical plane of not due to a largely inflated part in the fuselage upper surface like OPT4, but due to flow acceleration from the wing as shown in Fig. 26(a). As a result, there is no downforce acting on the aft area of the fuselage upper surface and OPT7 realizes much higher lift near the aircraft symmetrical plane than any other shape reported to date. Therefore, improving the $L/D$ of the high-wing configuration while obtaining much higher $C_L$ than the DLR-F6 configuration requires a fuselage shape without the inflated part on its upper surface.

With respect to the optimized wing shape, it can be seen that OPT7 makes flow acceleration from the leading-edge much milder than OPT4 at three airfoil sections as shown in Figs. 27(a)–(c). As a result, the shock wave generated over the wing of OPT7 is significantly alleviated compared to that of OPT4. This indicates that the ideal wing has a large camber to obtain lift, which is generated not only over the wing but also over the whole fuselage and a small leading-edge radius to avoid flow acceleration, which leads to shock wave generation.

The most significant difference between the targeted elliptic lift distribution and OPT7 appears at the 10% semispan section, where the lift generation of OPT7 drops drastically. This is because the local peak of negative pressure is caused by flow acceleration due to the large curvature of the fuselage lower surface, which is inevitable due to the upward-facing aircraft nose. In addition, OPT7 no longer generates lift from the aircraft nose at the 10% semispan section as shown in Fig. 26(b).

Figure 28 shows the sample points used in Optimizations I, II, and III plotted in the $C_L$ and $C_D$ space. In this figure, the
dotted line indicates a $L/D$ of 20, and the enclosed area indicates the sample points of Optimizations I and II employing the DLR-F6 wing. After optimization of the fuselage and wing shape, we obtain the fuselage-wing shape, which achieves a $L/D$ not only comparable to the DLR-F6 configuration by alleviating the shock wave over the wing, but also a $C_L$ as high as approximately 1.5 times that of the DLR-F6 configuration by considering the lift generation mechanisms established in this paper.

6. Conclusion

The aerodynamic optimization of a high-wing configuration was conducted using computational fluid dynamics simulation and a Kriging surrogate-assisted genetic algorithm to investigate the feasibility of a high-performance high-wing configuration suitable for installing fuel-efficient, ultrahigh-bypass ratio engines.

First, the fuselage upper surface, including the fairing, was optimized to explore the fairing shape suitable for the high-wing configuration. The maximum $L/D$ configuration achieved a $L/D$ of 21.15, which is higher than that of the low-wing DLR-F6 configuration. This improvement in $L/D$ was mainly due to the interference effect between the fuselage upper surface and the wing. This result suggested that a high-wing aircraft would show improved aerodynamic performance even if the fuselage has a large fairing, which seems disadvantageous for drag.

Second, the aircraft nose shape was optimized in addition to the fuselage upper surface to determine the benefits of optimizing the aircraft nose in generating lift for the fuselage. The $C_L$ and $C_D$ of the high-wing configuration were significantly improved, although deformation of the aircraft nose shape did not have a significant influence on the aerodynamic performance of the high-wing configuration. In terms of maximizing $C_L$ especially, we obtained an optimized shape

Fig. 26. The chordwise $C_p$ distributions of OPT4 and OPT7.

Fig. 27. The chordwise $C_p$ distributions of OPT4 and OPT7.

Fig. 28. Design summary.
that achieved higher lift generation resulting from not only the interference effect between the fuselage upper surface and the wing, but also from the fuselage itself. However, the shapes with relatively high $C_L$ had a tendency to reduce the $L/D$ due to the extensive shock wave generated over the wing.

Finally, both the fuselage and wing shapes were optimized to improve $L/D$ by alleviating the shock wave over the wing while sustaining the lift generated from the interference effect and fuselage itself. The final optimized configuration not only has a $L/D$ comparable to the DLR-F6 configuration as the result of reducing the shock wave, but also a $C_L$ of 0.742, which was much higher than that of the DLR-F6 configuration.

These results suggest the possibility of producing high-wing aircraft that will enable not only the use of fuel-efficient ultrahigh-bypass ratio engines, but also have a much higher $C_L$ than low-wing configurations by utilizing the lift generation mechanisms established in this paper, while achieving a drag comparable to that of the low-wing configuration.

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