Drag/Weight Reduction Using Split-Tip Winglet for TRA2012A Model

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In this paper, we describe shape optimization of a split-tip winglet (STW) model for the TRA2012A commercial jet aircraft model. The STW configuration is expressed by attaching a small wing under the main winglet. The onboard fuel weight, main wing structure weight and the sum of these weights are objective functions, and are minimized respectively in a fixed aircraft operating range for the present optimization. The onboard fuel weight and main wing structure weight are respectively estimated from the aerodynamic drag obtained using computational fluid dynamics simulations and from an estimation formula based on aerodynamic force acting on the main wing. A Kriging response surface model approach is used as the optimization method. Finally, non-dominated optimal designs obtained using this optimization method are investigated in detail based on the variation in aerodynamic drag and the main wing structure weight. In the STW design having minimum total weight, a reduction in onboard fuel weight and increase in main wing structure weight are observed, and it is found that the reduction in onboard fuel weight per unit volume of STW is the largest.

Key Words: Split-Tip Winglet, Multi-Disciplinary Optimization, Computational Fluid Dynamics

1. Introduction

Aircraft are widespread in the world as means of transporting people and goods. Passenger demand growth is approximately 5% per year on average worldwide, and energy issues such as global warming and the depletion of fossil fuels are drawing worldwide attention. Accordingly, improving the fuel efficiency of aircraft is required. In order to do this, comprehensive improvements such as reducing the aerodynamic drag acting on the aircraft, reducing aircraft weight and improving engine efficiency are required. A drag reduction of 1% can lead to reducing a direct operational cost of approximately 0.2% for a large-sized aircraft, which corresponds to 1.6 tons in terms of operating empty weight or 10 passengers.1) Therefore, it is very important to reduce the aerodynamic drag of aircraft when considering aerodynamic design. The Japan Aerospace Exploration Agency (JAXA) has been performing R&D for an environment-conscious aircraft technology named “Eco-Wing” since 2013.2) The single-aisle aircraft was defined by JAXA as a technology reference aircraft, TRA2012A.3)

Aerodynamic drag can be physically decomposed into wave, profile and induced drag components. The induced drag is a component due to wingtip vortices that cannot be avoided when the aircraft is generating lift force. Reducing the induced drag is required because it accounts for about 25% when cruising and about 60% during takeoff and climb4) among the total aerodynamic drag of the aircraft. It is known that the induced drag is inversely proportional to the radius of the vortex core and the distance between the vortices. The radius and distance can be increased by attaching wingtip de-

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Fig. 1. Various winglets, blended winglet (left), STW (center) and multi-winglet (right).8)
tained by computer fluid dynamics (CFD) simulations, but also the wing structure weight calculated based on the information of force distributions on the main wing have been evaluated and discussed. On the other hand, research focused on aerodynamic performance have been conducted for the STW and multi-winglet, while the weight penalties due to the winglets have not been discussed. The flow field around the STW and force distribution on the main wing are considered to be more complex than that of blended-winglets. Therefore, it is important to obtain knowledge with respect to the complex flow field, force distributions, and STW weight penalty for the practical application of advanced winglets, and this will be important for advanced aircraft development.

In this paper, we focus on a STW, which is obtained by attaching a small wing under a conventional blended-winglet. The objective of this paper is to investigate optimal STW designs for minimizing aircraft total weight, which is defined by the sum of fuel weight and wing structure weight. The present optimization is achieved by attaching the STW on the tip of the main wing of the TRA2012A aircraft after considering the penalty of wing structure weight. Then, the mechanisms of aerodynamic drag reduction and weight penalty of the STW are investigated.

2. Technology Reference Aircraft TRA2012A

In this study, the TRA2012A model is used as the baseline aircraft, shown in Fig. 2. In order to evaluate the effectiveness of technologies for reducing fuel consumption, the TRA2012A was conceptually designed as a 120-passenger class aircraft whose performance is equivalent to that of state-of-the-art aircraft. Its basic layout was designed referring the Airbus A319 and A320 configurations. Its section airfoil shape was designed using a genetic algorithm (GA) to minimize the aerodynamic drag under design conditions (cruise altitude = 35,000 [ft], cruising Mach number = 0.78), keeping the same thickness ratio as that of the A320. The twist angle distribution of the main wing was also optimized to achieve an elliptical load distribution. It has been reported that the elliptical load distribution was not the best for the TRA2012A when aerodynamics and structural mechanics were considered simultaneously. Therefore, in the present optimization considering both aerodynamics and structure of the main wing, there is room for improvement by attaching STW on the TRA2012A model. In this study, it is estimated that the fuel weight consumed by the TRA2012A while cruising is 17,200 [kg], and this is used as the reference weight. Each weight information of the TRA2012A is summarized in Table 1. In this research, nacelle, pylon and tail wings are eliminated to simplify the CFD model.

3. Computational Methodologies

3.1. CFD approach

Three-dimensional transonic viscous flows are analyzed using a CFD solver code of Tohoku University Aerodynamic Simulation (TAS). The TAS code is an unstructured mesh CFD solver based on a finite-volume cell-vertex scheme. Unstructured meshes are generated by Mixed-Element Grid Generator in 3 Dimensions (MEGG3D). Governing equations are compressible Reynolds-averaged Navier-Stokes equations. The LU-SGS implicit method for unstructured meshes is used for time integration. The turbulence model utilized is the SA-noft2-R (Crot = 1). The validity of the SA-noft2-R (Crot = 1) model for transonic conventional aircraft configurations has been demonstrated in Yamamoto et al. and Vassberg et al.

3.2. Estimation of fuel weight

The variation in onboard fuel weight $\Delta W_F$ due to the change in the aerodynamic drag is estimated using the following simple formula,

$$\Delta W_F = \frac{W_F}{C_{D_{base}}} \cdot \Delta C_D$$

where, $W_F$, $C_{D_{base}}$, and $\Delta C_D$ are respectively the reference fuel weight, aerodynamic drag coefficient of the TRA2012A without STW and the variation in aerodynamic drag coefficient due to modifying the winglet shape.

3.3. Estimation of wing structure weight

In this study, an analytical approach is used to estimate the wing structure weight from the distribution of fluid force on the main wing. The wing structure weight is calculated using a design load set to 3.75 times the load when cruising (limit load 2.5 x safety factor 1.5). The wing structure of the TRA2012A is shown in Fig. 3, where $C_{FSR} = 2.63$ [m] is the chord length of the carry-through. $b_3 = 15.68$ [m] is a wing structural semi-span length, which is defined through the center of each wing box from the fuselage to the 95% semi-span section. The structural strength required for the main wing is estimated from shear force and bending moment acting on the wing box structure and the carry-through structure, and from torque acting on the carry-through structure. Then, the main wing structure weight can be estimated analytically. The bending moment, shear force and torque

![Fig. 2. Three-directional view of the TRA2012A model.](image)
acting on the wing are given from the CFD results in this study.

When the wing box is divided into \( N \) along the spanwise direction, the bending moment weight per unit semi-span length \( W_{\text{BEND}} \) in each segment of the wing box structure is calculated using the following formula,

\[
W_{\text{BEND}} = \varepsilon \left( \frac{M}{Z_{st}^2 E} \right) \rho Z_{st} \quad (2)
\]

where, \( \varepsilon, e, M, Z_s, t, E \) and \( \rho \) are respectively shell buckling efficiency, buckling index of wing, bending moment acting on this segment, wing box width, wing box height, Young’s modulus and structural material density. \( \varepsilon, e, E \) and \( \rho \) are constants determined from the outer wrapping of the main wing and the web structure as \( \varepsilon = 2.21 \) [—], \( e = 0.556 \) [—], \( E = 69.0 \) [GPa], and \( \rho = 2.8 \times 10^3 \) [kg/m\(^3\)]. The rotation center of \( M \) is at the center of the wing box in the \( x \)-axis direction. The shear force weight per unit semi-span length \( W'_{\text{SHEAR}} \) in each segment of the wing box structure is calculated using the following formula,

\[
W'_{\text{SHEAR}} = \frac{\rho F_s}{\sigma_s} \quad (3)
\]

where, \( F_s \) and \( \sigma_s = 33.1 \) [MPa] are respectively the shear force and allowable shear stress. The shear force is defined as positive when it is in the \(+z\)-axis direction. \( E, \rho \) and \( \sigma_s \) are defined as material properties of aluminum alloy 7075-T6/7651. The wing box structure weight \( W_{\text{Box}} \) is calculated using the following formula.

\[
W_{\text{Box}} = 2b_s \times \sum_{i=1}^{N} \left( W'_{\text{BEND}} + W'_{\text{SHEAR}} \right) \quad (4)
\]

In this study, \( N \) is set to 24 and the spanwise length of each wing box is about 656 [mm] on average. The fluid force and bending moment acting on the region over the 95% semi-span and on STW are considered to affect the segment adjacent to the 95% semi-span location. The bending moment weight of the carry-through structure \( W_{\text{BEND}} \) is calculated using the following formula,

\[
W_{\text{BEND}} = \varepsilon \left( \frac{M_0 \cos(A_S)}{l_0^2 C_{SR} E} \right) \rho C_{SR} l_0 b_c \quad (5)
\]

where, \( A_S = 24.3 \) [deg], \( b_c = 3.71 \) [m] and \( l_0 = 0.768 \) [m] are respectively the sweepback angle of the centerline of the wing box, the width of the carry-through structure in the \( y \)-axis direction and the height of the carry-through structure. The subscript 0 indicates values at \( y = 0 \). The shear force weight of the carry-through structure \( W_{\text{SHEAR}} \) is calculated using the following formula.

\[
W_{\text{SHEAR}} = \frac{\rho F_s}{\sigma_s} b_c \quad (6)
\]

Torque acting on the carry-through structure is calculated using the following formula.

\[
T = M_0 \sin(A_S) \quad (7)
\]

The torsional weight of the carry-through structure \( W_{\text{TORSION}} \) is calculated using the following formula.

\[
W_{\text{TORSION}} = \frac{\rho T(l_0 + C_{SR}) b_c}{l_0 C_{SR} \sigma_s} \quad (8)
\]

Then, the total structural weight of the carry-through structure, \( W_C \) is calculated as

\[
W_C = W_{\text{BEND}} + W_{\text{SHEAR}} + W_{\text{TORSION}} \quad (9)
\]

Finally, the total wing structure weight \( W_W \) is calculated using

\[
W_W = K(W_{\text{Box}} + W_C) \quad (10)
\]

where, \( K = 2.0138 \) is an empirical coefficient that complements the difference between the total wing structure weight calculated using the estimation formulas and the actual weight of TRA2012A.

3.4. Kriging response surface model approach

In this study, the variation in onboard fuel weight \( \Delta W_F \), total wing structure weight \( \Delta W_W \) and the sum of these values \( \Delta W_{TO} \) from the TRA2012A model without a STW are objective functions. \( \Delta W_{TO} \) is adopted as the main objective function. \( \Delta W_W \) and \( \Delta W_F \) are adopted secondarily because we want to obtain detailed design knowledge of the STW by investigating the shapes with minimal \( \Delta W_W \) and \( \Delta W_F \). An optimization method applying the Kriging method\(^{21,22} \), which is one of the response surface methods, is used for the present optimization. In this method, performance evaluations for initial designs generated using the Latin hypercube sampling method\(^{23} \) in the design variables space are performed first. Then, approximate models of the performance functions in the design variables space are constructed. Global optimal solutions are explored using a GA with the functional evaluations on the approximate models. This exploration can be performed in detail because the evaluation cost of the approximate model is much smaller than the CFD evaluation. In this study, the approximate models for three objective functions are constructed respectively. Performance evaluations using CFD are performed on three approximate optimal designs where the expected improvement (EI)\(^{21} \) is maximal (for each objective function), and then the approximate models are updated. These three approximate optimal designs are expected to minimize \( \Delta W_F, \Delta W_W \) and \( \Delta W_{TO} \), and are added iteratively. By iterating these processes, global optimal solutions can be explored with a small number of performance evaluations using CFD.
4. Definition of Optimization Problem

4.1. Design conditions

The main winglet is attached at the 95% semi-span section of the main wing of the TRA2012A in this study. The STW is expressed by attaching a small wing under the main winglet. The sectional shapes of the main winglet and the small wing are fixed to the NACA0010. Due to the definitions of the design variables, local angles of attack of the sectional airfoil of the main winglet/small wing can be positive and negative values. It is difficult to determine whether we should adopt a positive or negative camber airfoil for the STW in advance. Therefore, a symmetrical NACA0010 airfoil is used for this study. The main winglet has a trailing-edge thickness, while the small wing has no trailing-edge thickness. The TRA2012A with a STW is shown in Fig. 4. The STW configuration is shown in Fig. 5 and its configuration is defined using 13 design variables, as shown in Table 2. The distance in the Y-axis direction from the root of the main winglet to the main winglet tip is defined as the span length of the small wing.

Table 2. Design variables definitions.

| Details                                      | Range                  |
|----------------------------------------------|------------------------|
| 1. Span length of main winglet (\(l_w\))     | 5–10% semi-span length of main wing |
| 2. Curve coefficient A                        | -3.6E-04 to +4.4E-04   |
| 3. Curve coefficient B                        | -3.0E-02 to +2.4E-02   |
| 4. Taper ratio of main winglet                | 0.3–1.0                |
| 5. Twist angle of main winglet                | -10° to +10° [deg]     |
| 6. Sweepback angle of main winglet           | -60° to +60° [deg]     |
| 7. Span length of small wing (\(l_w\))        | 0.5–2.0 times of chord-length of small wing |
| 8. Curve coefficient A’                       | -2.4E-05 to +4.4E-05   |
| 9. Curve coefficient B’                       | -3.3E-03 to +1.3E-03   |
| 10. Taper ratio of small wing                 | 0.3–1.0                |
| 11. Twist angle of small wing                 | -10° to +10° [deg]     |
| 12. Sweepback angle of small wing             | -60° to +60° [deg]     |
| 13. Attachment position of small wing         | 25–50% of \(l_w\)      |

where, \(Z\) is the attachment angle of the main winglet at the root of the main winglet, and the \(Z\) is fixed to 3.85 [deg]. The shape of the main winglet is shown in Fig. 6 when the curve coefficient \(B\) is changed from its minimum to maximum value (curve coefficient \(A\) is fixed to 0). The twisting region of the main winglet is from the attachment position of the small wing to the tip of the main winglet. The design variables of \(\circ\) and \(\circ\) define the twist angles at the tips of the main winglet and of the small wing. The centers of twist are set at the 50% chordwise locations of the main winglet and of the small wing. The twist angle changes linearly toward the tips of the main winglet and of the small wing. The distance in the y-axis direction from the 95% semi-span position of the main wing to the root of the small wing is defined as the attachment position of the small wing (\(\circ\)). To avoid complicated connection around the regions of the leading/trailing-edges of the main winglet, the chord length of the small wing at the root position is set to a moderate value (\(= 80%\)) with respect to the chord length of the main winglet at the attachment position. The taper ratios and sweepback angles of the main winglet and small wing (\(\circ\), \(\circ\), \(\circ\)), respectively using third-order polynomials as follows (\(\circ\), \(\circ\), \(\circ\), \(\circ\)).
are also defined as design variables. In the present optimization, a geometrical constraint is set for the most distal position in the y-axis direction ($y_{\text{max}}$) of the STW, and $y_{\text{max}}$ has to be at the inward side of the 105% semi-span location of the original main wing: depending on the design variable settings, the y-coordinate for the tip of the small wing can exceed the 105% semi-span location.

4.2. CFD conditions

In CFD computations, the freestream Mach number is set to 0.78 and Reynolds number is set to $2 \times 10^{8}$ (representative length = fuselage length). The target lift coefficient is set to 0.542, which corresponds to the cruise conditions of the TRA2012A at an angle of attack of 0.61 [deg]. The angle of attack of the TRA2012A with a STW is adjusted to match the target lift coefficient. The number of grid points is approximately $6.4 \times 10^{6}$ and the averaged value of $y+$ on the model is approximately 0.64. We performed a mesh dependency study to determine the present grid resolution. The number of final steps for CFD analysis is $5 \times 10^{4}$, which enabled convergence of the drag coefficient value within $1 \times 10^{-5}$. In the present CFD computation, a local time stepping strategy is used in which the maximum CFL number is about 20.

4.3. Summary of optimization problem

In the present optimization, 30 initial STW designs are generated, and then 84 additional designs are iteratively selected and evaluated. The number of design variables is 13, as shown in Table 2. Three promising designs with respect to minimizing $\Delta W_F$, $\Delta W_W$ and $\Delta W_{FD}$ are selected and evaluated in the optimization process. The geometrical constraint is set for the most distal position in the y-axis direction ($y_{\text{max}}$) of STW and $y_{\text{max}}$ has to be at the inward side of the 105% semi-span location of the original main wing.

5. Results and Discussion

5.1. Outline of optimization results

The optimization results of STW are summarized in Fig. 7. The vertical and horizontal axes respectively indicate the differences of fuel weight and of wing structure weight from that of the TRA2012A model without STW. The 105% span extension model is defined by smoothly extending the main wing to the 105% span location. $\Delta W_F$ decreases as $\Delta W_W$ increases, and we can observe the tradeoff relationship between $\Delta W_F$ and $\Delta W_W$. The variation in fuel weight is larger than the variation in the wing structure weight. In this problem, it is therefore more effective to reduce total weight by reducing the fuel weight, which can be achieved by reducing aerodynamic drag. Arrows in Fig. 7 indicate non-dominated optimal designs obtained in this study. Most of the non-dominated optimal designs consist of additional samples obtained in the optimization process. $\Delta W_F$-1-5 and $\Delta W_F$-1-11, shown in Fig. 8, are non-dominated optimal designs that reduce wing structure and fuel weights, respectively. $\Delta W_W$-5, $\Delta W_F$-11 and $\Delta W_F$-8 are the designs for minimum wing structure weight, minimum fuel weight and minimum total weight, respectively. Each weight component

Fig. 7. Optimization results: Upper, overview; Lower, enlarged view.

Fig. 8. Non-dominated optimal designs.
of the representative designs is summarized in Table 3. Compared to the 105% span extension model, winglet design \( \Delta W_{F-8} \) reduces more fuel weight, and its penalty in terms of wing structure weight is also lower, thereby resulting in a larger reduction in the total weight. Although the lift required for cruise of each design is different, its variation can be ignored in this study because the variation in total weight relative to the maximum takeoff weight is less than 3% (= 1855/74,185).

\( \Delta W_{F-5} \) has a downward forward-swept main winglet with a small wing bent in the main wing root direction. The shapes of \( \Delta W_{F-2-4} \) are similar to the shape of \( \Delta W_{F-5} \). \( \Delta W_{F-8} \) and \( \Delta W_{F-11} \) have upward sweptback main winglets. Most of the other non-dominated optimal designs that reduce fuel weight have upward sweptback main winglets.

5.2. Aerodynamic effects of STW

The aerodynamic performance of the representative designs is shown in Tables 4 and 5. \( \Delta C_D, \Delta C_{DP}, \Delta C_{DF} \) and \( \Delta \alpha_{OA} \) are respectively the variations in total drag coefficient, pressure drag coefficient, friction drag coefficient and angle of attack compared to that of the TRA2012A model without STW. \( \Delta C_{D_{ind}}, \Delta C_{D_{wav}} \) and \( \Delta C_{D_{pro}} \) are respectively the variation in induced, wave and profile drag components that are evaluated using a drag breakdown approach.\(^{14} \)

\( \Delta C_{D_{pro}} \) corresponds to the sum of the variations in three physical drag components (referred to as pure drag in Yamazaki et al.\(^{14} \)). The drag coefficient of 0.0001 corresponds to 1.0 drag count (dct). In the designs of the 105% span extension model, \( \Delta W_{F-8} \) and \( \Delta W_{F-11} \), reductions in \( \Delta \alpha_{OA}, \Delta C_{D_{ind}}, \Delta C_{D_{wav}}, \Delta C_{D} \) and \( \Delta C_{DP} \) are observed. On the other hand, an increase in these values is observed in winglet design \( \Delta W_{F-5} \). The variation in each drag component of the non-dominated optimal designs is summarized in Fig. 9. \( \Delta C_{DF}, \Delta C_{D_{ind}}, \Delta C_{D_{wav}} \) and \( \Delta \alpha_{OA} \) decrease with the reduction of \( \Delta W_F \). It can be seen that winglet design \( \Delta W_{F-8} \) reduces \( \Delta C_{D_{ind}} \) and \( \Delta C_{DF} \) with a very small increase in \( \Delta C_{D_{DF}} \) and \( \Delta C_{D_{pro}} \) as compared to the other optimal designs.

To clarify the mechanisms for reducing aerodynamic drag, the flow field around the representative designs is visualized. The vorticity and induced drag source on a near-wake surface of the winglet are visualized in Figs. 10 and 11, respectively. The induced drag source distribution can be obtained using the drag breakdown approach. In Fig. 12, the shock wave generation regions around the wingtips are visualized based on a shock wave function.\(^{24} \) In Fig. 10, the clockwise vortex (red-colored area) locates at the tip of the main wing for the TRA2012A model and 105% span extension model.

### Table 3. Weight components of representative designs.

| Design                        | \( \Delta W_F \) [kg] | \( \Delta W_W \) [kg] | \( \Delta W_{FD} \) [kg] |
|-------------------------------|-----------------------|-----------------------|------------------------|
| 105% span extension model     | -440.53               | 229.17                | -211.36                |
| \( \Delta W_{F-5} \)          | 2242.28               | -387.22               | 1855.06                |
| \( \Delta W_{F-8} \)          | -480.90               | 179.50                | -301.40                |
| \( \Delta W_{F-11} \)         | -607.09               | 317.60                | -289.49                |
| \( \Delta W_{F-8} \) w/o      | -441.27               | 158.07                | -283.20                |

### Table 4. Aerodynamic performance obtained using the surface integral method and angle of attack of representative designs.

| Design                        | \( \Delta C_D \) [dct] | \( \Delta C_{DF} \) [dct] | \( \Delta C_{DP} \) [dct] | \( \Delta \alpha_{OA} \) [deg] |
|-------------------------------|-----------------------|--------------------------|--------------------------|-------------------------------|
| 105% span extension model     | -8.82                 | 1.46                     | -7.36                    | -0.09                         |
| \( \Delta W_{F-5} \)          | 14.41                 | 7.33                     | 14.35                    | 36.09                         |
| \( \Delta W_{F-8} \)          | -11.03                | -2.41                    | 0.10                     | -13.54                        |
| \( \Delta W_{F-11} \)         | -13.75                | -4.26                    | 2.07                     | -15.94                        |
| \( \Delta W_{F-8} \) w/o      | -7.61                 | -1.90                    | -0.90                    | -10.41                        |

### Table 5. Aerodynamic performance obtained using the drag breakdown approach for representative designs.

| Design                        | \( \Delta C_{D_{ind}} \) [dct] | \( \Delta C_{D_{wav}} \) [dct] | \( \Delta C_{D_{pro}} \) [dct] | \( \Delta C_{D_{DF}} \) [dct] |
|-------------------------------|-----------------------------|-----------------------------|--------------------------------|-----------------------------|
| 105% span extension model     | -6.14                       | -2.36                       | -0.71                          | -9.21                       |
| \( \Delta W_{F-5} \)          | 14.41                       | 7.33                        | 14.35                          | 36.09                       |
| \( \Delta W_{F-8} \)          | -11.03                      | -2.41                       | 0.10                           | -13.54                      |
| \( \Delta W_{F-11} \)         | -13.75                      | -4.26                       | 2.07                           | -15.94                      |
| \( \Delta W_{F-8} \) w/o      | -7.61                       | -1.90                       | -0.90                          | -10.41                      |

In winglet design \( \Delta W_{F-5} \), the clockwise vortex is located at a position further inside, near the fuselage, as compared to the TRA2012A model. It is estimated that the large forward-swept main winglet and small wing cannot suppress swirling flows from the lower side to the upper side of the main wing, and the clockwise vortex occurs around the root of the main winglet. In winglet design \( \Delta W_{F-5} \), the counter-clockwise vortex (blue-colored area) at the tip of the main wing.
winglet is also observed. This is because the pressure on the upper surface of the tip of the main winglet is higher than the lower surface, and the airflow from the upper side to the lower side occurs at the tip. On the other hand, in winglet designs /C1WF -8 and /C1WF -11, clockwise vorticity areas at the tips of the main winglet and small wing are observed, and the vortices are located at positions further away from the main wing. It is estimated that the influence of the downwash induced by the vortices becomes weaker since the vortices move, thereby reducing the induced drag. In addition, it is observed that the strong induced drag source areas are located at positions where vortices exist. The strong induced drag source areas become smaller compared to the TRA2012A model, which results in reducing the induced drag. In the results of shock visualization, shock waves are generated on the upper surface of the main wing. In winglet design /C1WF -11, shock waves on the upper surface of the root of the main winglet can be observed, while $\Delta C_{D_{\text{wav}}}$ is smaller than that for the TRA2012A model. This is because the shock wave strength on the main wing and wave drag decrease since $\alpha_{0}$ becomes smaller than that of TRA2012A model. The reduction of $\Delta C_{D_{\text{wav}}}$ is observed in representative winglet designs /C1WF -11. It is considered that these winglet designs achieve a reduction in $\Delta C_{F}$ by decreasing these drag components.

5.3. Wing structure weight analysis

The variation in the wing structure weight components of the non-dominated optimal designs is shown in Fig. 13. Both $\Delta W_{C}$ and $\Delta W_{\text{Box}}$ decrease with the reduction in $\Delta W_{W}$. Most of the weight variation of the carry-through is due to the torsion acting on the carry-through. With respect to the weight variation of the wing box, the effects of shear force and bending moment are almost the same degree. The load distributions acting on the STW and main wing are compared in Fig. 14. The shear force and bending moment on a wing box, indicated in Fig. 15, are calculated from aerodynamic loads acting on
more outward (wingtip side) wing boxes. Accordingly, the shear force and bending moment on the 95% semi-span location (the most outward one) cannot be defined in Fig. 15. In the design of $\Delta W_{F}-5$, the load becomes negative at the wingtip regions (98–102% semi-span). The shear force and bending moment are also smaller than those of the TRA2012A model. In the design of $\Delta W_{F}-11$, the load increases at the outer side, from 98% semi-span section, because the small wing generates a certain amount of lift force. In winglet designs $\Delta W_{F}-8$ and $\Delta W_{F}-11$, the load, shear force and bending moment at the wingtip regions are larger than those of the TRA2012A model.

The lift coefficients acting on the main winglet and small wing for the representative designs are shown in Fig. 16. The vertical axis indicates $\Delta C_{L}$, which is the difference of the lift coefficient from that of the TRA2012A model without STW. The difference of the lift coefficient on the main winglet component indicates a variation in the lift coefficient acting on the region outward from the 95% semi-span. It can be observed that $\Delta W_{F}$ is reduced, with smaller lift coefficient acting on STW. It is considered that the generation of negative lift force on the STW can reduce the shear force and bending moment acting on the wing box structure, thereby enabling the wing structure weight to be reduced.

5.4. Investigation of important design parameter influence

The relationship between shape characteristics and weight components is investigated in this section. An analysis of variance (ANOVA)\(^{21}\) is performed and the results are shown in Fig. 17. The ANOVA is performed on the response surface models, including the information of 114 designs. Here, ANOVA was performed for 11 variables space, including the heights of the main winglet and of small wing (excluding four curve coefficients) to obtain a more intuitive understanding of the effect of shape parameters. The heights are indicated in Fig. 5. The height of the main winglet can be calculated using $l_{w}$ (\(\textcircled{1}\)), and the curve coefficients $A$ (\(\textcircled{2}\)) and $B$ (\(\textcircled{3}\)). The height of the small wing, which is defined as the distance in the $Z'$-axis direction from the reference position to the tip of the small wing, can be calculated from $l_{s}$ (\(\textcircled{7}\)), and the curve coefficients $A'$ (\(\textcircled{8}\)) and $B'$ (\(\textcircled{9}\)). The results indicate that the design variables for the main winglet have a stronger influence on each weight component. In particular, the sweepback angle and height of the main winglet have a larger influence than the other design variables. The effective span length of STW is considered to be determined by the interaction between the main winglet and small wing. Even if the span length of the main wing is relatively short, the induced drag can be reduced with larger span length of the small wing. Therefore, it can be supposed that the effect of span length of the main winglet is not apparent in the ANOVA results.

Figures 18 and 19 show the effect of the sweepback angle and height of the main winglet on the weight components. The height is defined when the fuselage length is set as a unit. In both figures, the performance of all 114 designs is indicated. The reduction in $\Delta W_{F}$ and $\Delta W_{TO}$, and the increase in $\Delta W_{W}$, are observed with a larger sweepback angle as well as a larger height of the main winglet. Main winglets with larger height generate wingtip vortices at positions far from the main wing, thereby reducing the induced drag, which results in the reduction of $\Delta W_{F}$. These trends of the main winglet shapes are also observed in the non-dominated optimal designs shown in Fig. 8.

The structure of STW is more complicated than conventional winglet configurations. In addition, the shapes of STW are intricately changed by the 13 design variables used in this study. Therefore, it is difficult to take into account the weight of STW as a part of the objective function. Here, the post-process for the weight of STW is performed by assuming that the weight of STW is proportional to the volume of
STW (vol). (This assumption of the proportional relation is not accurate, which should be noted as the limitation of the present post-process.) The volume of STW is calculated when the fuselage length of the TRA2012A model is set to 37.6 [m].\(^{11}\) The relationship between \(\Delta W_{TO}\) and \(\Delta W_{F/\text{vol}}\) (\(\Delta W_F\) per unit volume of STW) is shown in Fig. 20. \(\Delta W_{F/\text{vol}}\) decreases when \(\Delta W_{TO}\) is reduced. In winglet design \(\Delta W_F-8\), \(\Delta W_{F/\text{vol}}\) is minimized, which means that winglet design \(\Delta W_F-8\) effectively reduces aerodynamic drag using a small-sized STW. To discuss the reduction in \(\Delta W_{F/\text{vol}}\), ANOVA is performed for \(\Delta W_{F/\text{vol}}\) and the results are shown in Fig. 17. It is observed that the influence of the sweepback angle of the main winglet is the greatest. The relationships between the height and sweepback angle of the main winglet and \(\Delta W_{F/\text{vol}}\) are also shown in Figs. 18 and 19. \(\Delta W_{F/\text{vol}}\) decreases as the height and sweepback angle of the main winglet are increased. In addition, it is observed that there is an appropriate value for the height of the main winglet that minimizes \(\Delta W_{F/\text{vol}}\).

In summary, the present STW shape optimization to minimize the total weight of the aircraft without considering the weight of STW gave an optimal STW design (= \(\Delta W_F-8\)) with a minimum \(\Delta W_{F/\text{vol}}\). Winglet design \(\Delta W_F-8\) is not the largest within the present design space. Therefore, even in the case of the present STW optimization without considering the weight of STW, it is possible to obtain the optimal STW shape that is not simply the largest STW. This can be considered due to the effect of the wing structure weight which becomes heavier with larger STW shapes.

5.5. Effect of small wing

To investigate the effect of the small wing, winglet design \(\Delta W_F-8\) without the small wing (= \(\Delta W_F-8\) w/o) is analyzed. The results of \(\Delta W_F-8\) w/o are included in Tables 3–5 and Figs. 10–12. Compared to the winglet design \(\Delta W_F-8\), \(\Delta C_{D\text{pro}}\) and \(\Delta C_{DF}\) are smaller, while \(\Delta C_{D\text{par}}, \Delta C_{D\text{ind}}, \Delta C_{D\text{wav}}, \Delta C_D\) and \(\Delta C_{DP}\) are larger in winglet design \(\Delta W_F-8\) w/o. As a result, in winglet design \(\Delta W_F-8\), \(\Delta F\) and \(\Delta W_{TO}\) are smaller than in \(\Delta W_F-8\) w/o. It is observed from the visualization results that strong vorticity areas around the main winglet are divided into two areas at the tips of the main winglet and of the small wing in winglet design \(\Delta W_F-8\). In addition, the source of induced drag around the small wing is reduced by attaching the small wing. It is estimated that the vortices are diffused faster by dividing the wingtip vortices, which results in reducing induced drag. Similar discussions can be found in the previous studies.\(^{8,25}\)

In winglet design \(\Delta W_F-8\), an increase of approximately 21 [kg] in \(\Delta W_w\) is observed due to the effect of aerodynamic force acting on the small wing, while more decrease in \(\Delta F\) is observed by larger drag reduction. This result indicates the effectiveness of the optimal STW design derived.

Among non-dominated optimal designs to reduce \(\Delta W_F\), there are peculiar designs such as winglet designs \(\Delta W_F-6\) and \(\Delta W_F-11\). These have sweepback angles for the main winglet and sweepforward angles for the small wing, as shown in Fig. 8. The distance between the tips of the main winglet and of the small wing increases in these designs. Therefore, the relationship between the distance and \(\Delta F\) is investigated and shown in Fig. 21. The distance is defined as the distance between 50% chord positions of the tips of the main winglet and of the small wing. Designs similar to winglet designs \(\Delta W_w-1\)–5 are selected from the values of design variables and defined as “exceptional designs” in Fig. 21. Winglet designs \(\Delta W_w-1\) and \(\Delta W_w-1\)–5 belong to the exceptional designs among the non-dominated optimal designs derived. As confirmed in Fig. 7, there is little or no reduction in \(\Delta W_{TO}\) for the designs \(\Delta W_F-1\) and \(\Delta W_w-1\)–5, so these exceptional designs are omitted from the following discussion. In Fig. 21, without the exceptional designs, it can be confirmed that there is a trend of decreasing \(\Delta F\) as the distance between the wingtips increases. In winglet designs \(\Delta W_F-6\)
These findings obtained here are effective only for the present design condition as well as for the TRA2012A model at present. We will perform further investigations to determine whether or not these findings are effective for different conditions and different models. In addition, optimizations considering the structural weight of STW will be performed to evaluate aircraft weight more realistically in our future works.

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