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AERODYNAMICS AND STRUCTRAL DESIGN STUDIES FOR FUEL CONSUMPTION REDUCTION ON SUBSONIC AIRCRAFT

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Abstract: Studies of the subsonic wing geometry were performed using multidisciplinary design tools to reduc the fuel consumption on a mission flight of 120-pax JAXA technology reference aircraft named TRA2012A. Aerodynamics and wing structural weight were estimated to evaluate the fuel consumption on several load distributions and aspect ratios of the wing on the transonic cruise flight. The drag was obtained using the CFD analysis, and the wing structural weight was obtained by structural sizing process using the FEM analysis. The fuel consumption was estimated using the mission analysis tools included in the aircraft conceptual design phase. The results show that the wing weight is increased with increasing the wing aspect ratio and changing the load distribution from triangle shape to elliptic shape. Lower drag is obtained at higher AR and elliptic and nominal load distributions.

1 INTRODUCTION

Recently, the civil transport aircraft is strongly required of the economic and environmental performance like as cost, CO_2 emission and airport noise [1–3]. Since 2013, Japan Aerospace Exploration Agency (JAXA) has been performed a research for environmental conscious aircraft technology names as “Research for Eco-Wing technology”. The main objective is the reduction of the fuel consumption and airframe noise on the commercial airliners which will be developed from middle of 2020 and 2030 [4]. A 120 pax aircraft such as A319 was set to a technology reference aircraft TRA2012A. Aerodynamics, structures, engine and airframe noise reduction technology are applied to a TRA2022 which can reduce the 30% fuel consumption and 10 dB margin on the ICAO Chapter 14 [5]. Furthermore, the airframe-thrust system integration technology is also focused on further reduce the noise and fuel. For the new aircraft concept, noise simulation and assessment technologies are improved for the design of the TRA203X.

For the TRA2022, a target which imposed on the aerodynamic technology is 7% drag reduction on the cruise flight (5% fuel consumption reduction). Several drag reduction concepts such as natural laminar flow (NLF) wing, riblet coating, hybrid boundary layer control, wing tip device and wing load distribution control technologies have been conducted. These technologies are applied to the TRA2022 geometry using the multidisciplinary design optimization (MDO) technology.

A multidisciplinary design which closely coupled the aerodynamic-structure analysis are constructed to effectively obtain the optimal solutions [6, 7]. The optimal wing load distribution and aspect ratio for reduction of the fuel consumption is a representative issue which closely coupled of aerodynamics and structures performance. Parametric study of the load distribution and aspect ratio using the lifting surface theory [8] and simple structure analysis [9] were conducted. And fuel consumption was obtained by a mission analysis [10]. The concept of the aero-structure coupled design was confirmed and sensitivities of drag and weight reduction were roughly understood from previous study using low fidelity tools [11] (Fig. 1).

In this study, high fidelity simulations are performed for the load distribution and aspect ratio of the wing. Aerodynamics and structure sizing are conducted by CFD and FEM analysis using the TRA2012A geometry. Fuel consumption is derived by mission analysis tools RDS-Pro [12]. Main objective in this study is to understand of the effects of load distribution and aspect ratio obtained by aero-structure coupled design.

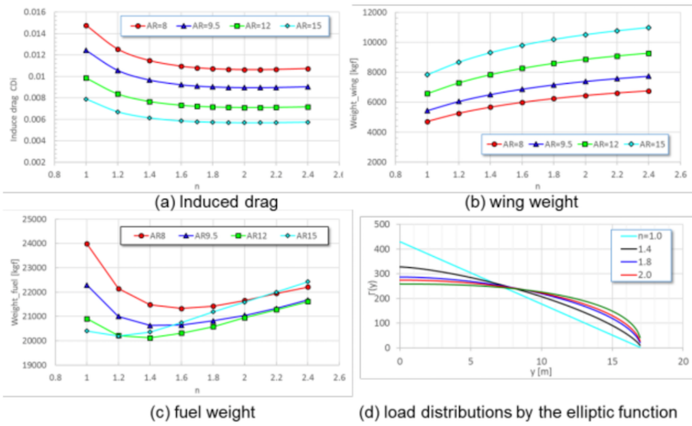

Figure 1: Fuel consumption estimation using low fidelity tools [11]

2 MDO CHAIN FOR FUEL CONSUMPTION ESTIMATION

Figure 2 shows a chart of the aero-structure coupled disign process. Initial aerodynamic shape and structural geometry were defined by CATIA. TRA2012A [5] was selected for the baseline configuration in this study, and wing twist angle distribution and aspect ratio were changed to the nine wing geometries (including the baseline geometry).

Aerodynamics were obtained by CFD analysis at three angles of attack for each geometry. Pre-process tools for structure analysis were constructed to re-distribute the aerodynamic static pressure distribution to the structure model [13]. Structure analysis is composed two steps. At first step, structural loads were obtained by the FEM analysis. At second step, the optimization of thickness on structure elements was performed to attain a minimum wing weight where each element satisfied the structure limitation imposed by aerodynamics. At the mission analysis module, the fuel consumption was derived by a mission profile analysis of the consumption was derived by a mission profile analysis of the TRA2012A (Figure 3) using the RDS-Pro software [12]. From this process, the aerodynamics and structure weight can easily assess by the fuel consumption performance. The design tool was also improved by automation of each process and communization for the interface between each module to shortening of the design period.

2.1 Aircraft geometry and design parameters

The wing load distribution is controlled by the spanwise wing twist angle distribution. At first, two load distributions were set from a baseline load distribution obtained from a cruise condition of TRA2012A which called as a "nominal shape" distribution. Comparing with the nominal shape load distribution, the first load distribution had higher load at the inboard wing and lower load at the outboard wing. This load distribution was called as a "triangle shape" distribution. Other is called as "elliptic shape" distribution which has lower load at inboard and higher load at outboard wing than the nominal shape. The total load is same on three load distributions. And then, the twist angle distributions were adjusted which correspond to the load distributions at each spanwise section. Figure 4 show the twist angle distributions on three load distributions.

The aspect ratio of the TRA2012AAA is AR=9.5. Another two aspect ratios were selected AR=8 and 12. These wings have same wing section geometries, twist angle distribution and wing area. However, the taper ratios are different. The location of the engine and trailing edge extension were fixed on same location on three configurations.

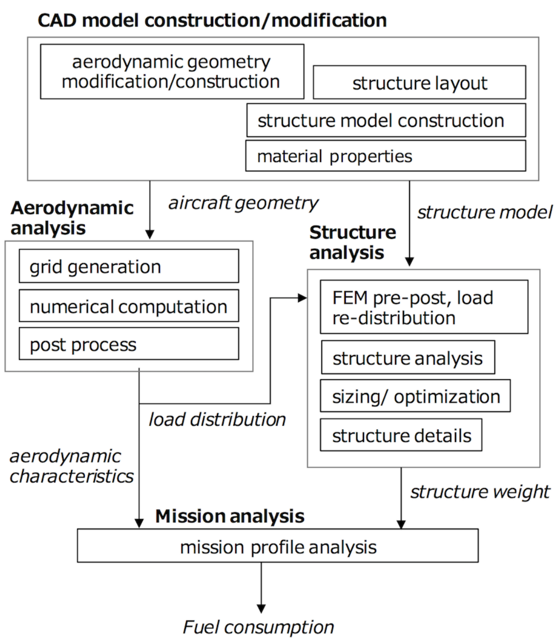

Figure 2: Flowchart of the fuel consumption estimation

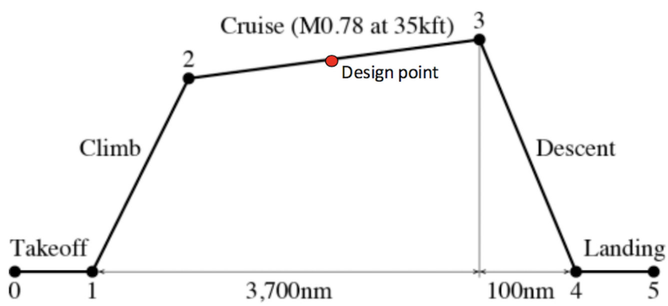

Figure 3: Mission profile for TRA2012A

The analysis cases and flight conditions in this study are summarized in Table 1. A target of this study is set the cruise flight condition, therefore the lift coefficient is $C_L = 0.5194$, the altitude is 35,000 ft and Mach number $M = 0.781$ [5].

baseline geometry	TRA2012A
wing aspect ratio	AR = 8, 9.5, 12
wing twist angle distribution	triangle, nominal, elliptic
Mach number	0.781
angle of attack [deg]	AoA=-0.191, 0.6119, 1.272 at CL=0.5194
altitude [ft]	35,000
Re based on the MAC	24.4×10^6

Table 1: Analysis cases and flow conditions

2.2 Aerodynamic analysis

The aerodynamics were obtained by the RANS CFD analysis. The CFD solver used in this study is FaSTAR (FAST Aerodynamic Routines) which is a JAXA's standard solver. Figure 6 show the grid that is constructed using a commercial software "Pointwise". The grid is unstructured prism and tetra grid, and number of the grid cell points is 11-12 million. Each computation is converged to a solution within 1 hour using JAXA Supercomputer System generation 2 (JSS2).

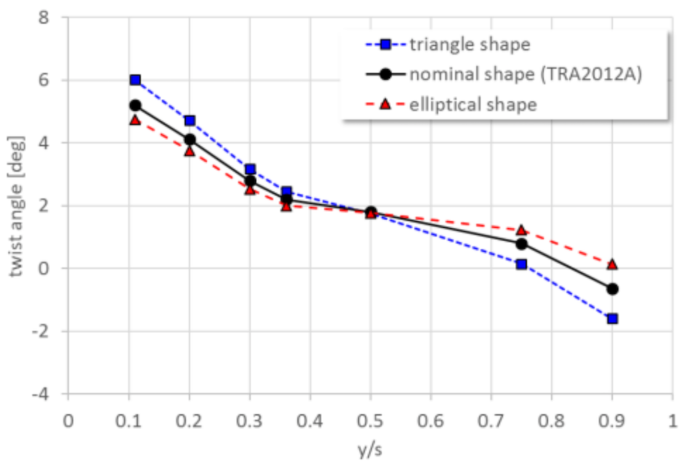

Figure 4: Twist angle distribution on AR=9.5

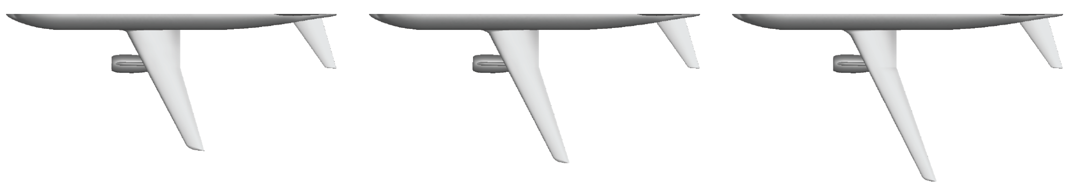

Figure 5: Wing geometries of three aspect ratio

2.3 Structural analysis

The structure analysis and optimal sizing were conducted using the Nastran solver (MSC. NASTRAN2016). Figure 7 shows a layout of the wing structure which was composed by the wing and carry through part. The wing part was constructed by upper and lower skin, forward and rear spars, ribs, and stringers. The shell element use for skin, spar and rib, and the beam element use for stringer. The aerodynamic load, the structure weight of the wing and carry through were impose to the FEM analysis. The engine (including nacelle and pylon) and main landing gear were also considered as concentrated mass. The aerodynamic load factor was set to 3.75 on the aerodynamics on the cruise flight.

The structural models are made by following steps. The number of grid points and elements of the baseline model are 454 and 1076.

- The structural layout made on CATIA. The stringer pitch and the rib pitch are decided to referred to other existing aircraft.
- The intersections of stringer and rib are exported IGES format.
- The grid points and the elements are made by use the points of the previous step and exported as Nastran input file format.
- The pressure data of th previous section is interpolated to grid points [13] and exported as Nastran input file format.

The structural sizing are conducted by Nastran SOL200. The objective function is to minimize

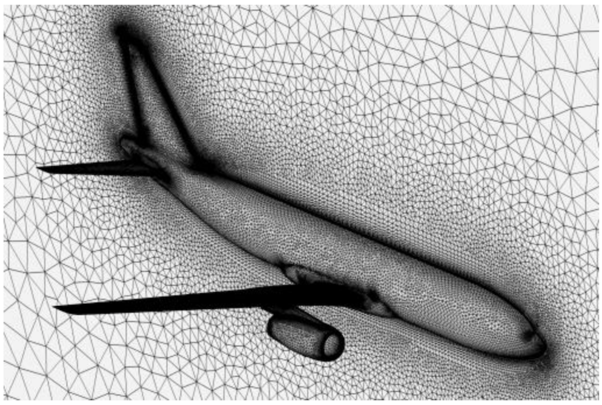

Figure 6: Computational grid for CFD analysis

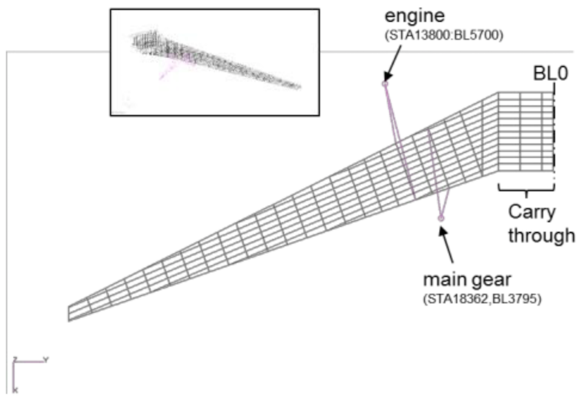

Figure 7: Structural model layout (AR = 9.5)

to weight of wing box. The design variables are thickness of skin, spar, rib and DIM1-4 of stringer and spar-cap. The constraints are stress of elements.

To derive the total weight of the wing, the weight of leading and trailing part of wing, control surface system (high lift devices, aileron) and etc. should be additionally estimated. The total wing weight was derived by taking 1.7372 times in the structural weight which was empirical value referred by previous aircraft [9].

2.4 Fuel consumption estimation

The conceptual design of TRA2012A was conducted with RDS-Pro [5]. The fuel consumption of TRA2012A along the mission profile in Figure 3 was estimated in the mission analysis. In RDS-Pro, aerodynamic performances and component weights are usually computed with empirical equations and statistical equations, respectively [10]. In this study, however, the aerodynamic performances at cruise and the wing weight have been replaced with the CFD results and the FEM results, respectively. Then, the fuel consumption of the several wing geometries has been re-estimated.

3 RESULTS AND DISCUSSION

3.1 Aerodynamics

Figure 8 show the spanwise load distributions at $C_L = 0.52$ on AR=9.5. The load distribution curves divided three parts which corresponding to the wing, fuselage and horizontal tail plane (HTP). Comparing with the "nominal shape" at the wing, the "triangle shape" is higher load at the inboard wing, and lower load at the outboard wing. However, the "elliptic shape" has higher load at the outboard wing, because the local geometric incidence angles at outboard wing are higher than the nominal shape. It means that three wings with different twist angle distributions were obtained according load distributions to aim of this study. Even though the wing twist angle is only changed, the load distribution at fuselage and horizontal tail plane (HTP) are also changed. The load distribution at the fuselage are changed by the interaction with load at the inboard wing. And the loads at the HTP are influenced by the down-wash flow from the inboard wing which also depended on the load distribution.

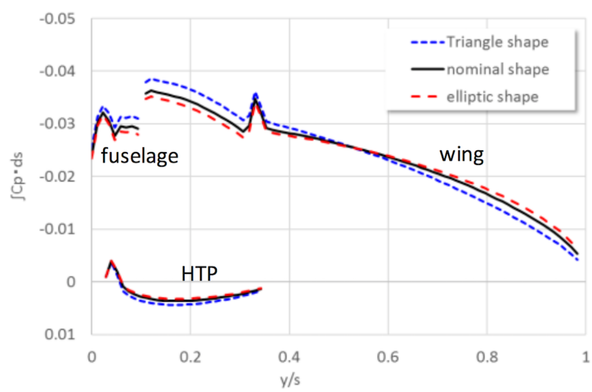

Figure 8: Wing load distributions at $C_L = 0.5194$ on AR = 9.5

Figure 9 show the lift C_L, drag C_D and pitching moment coefficient C_m characteristics. On the wing with AR = 8 and AR = 9.5, linear C_L curves are obtained on three twist angle distributions. Comparing with the C_L on three AR, high C_L is obtained on the wing with high AR (AR = 12).

The C_D on AR = 12 are higher than the AR = 9.5 and AR = 8. Comparing the C_D on AR = 12, the triangle shape is the highest value, and the elliptic shape is the lowest value. The highest C_D on triangle shape are also observed on AR = 9.5 and AR = 8. On the C_m curves on three load distribution, similar trend is observed on three AR. The triangle shape has highest C_m, and the elliptical shape has lowest C_m. Higher load at the inboard wing on the triangle shape induces strong down wash at trailing edge, then the load at the HTP is decreased and the C_m is increased.

Figure 10 show the C_L-C_D curves on three load distributions. When the load distribution changes from triangle shape to elliptical shape, the curves are shifted to the left-hand direction. It means the reduction of C_D as a same C_L. This trend is clearly observed on higher AR. On the AR = 8, reduction of the C_D is not obtained between the normal shape and elliptic shape.

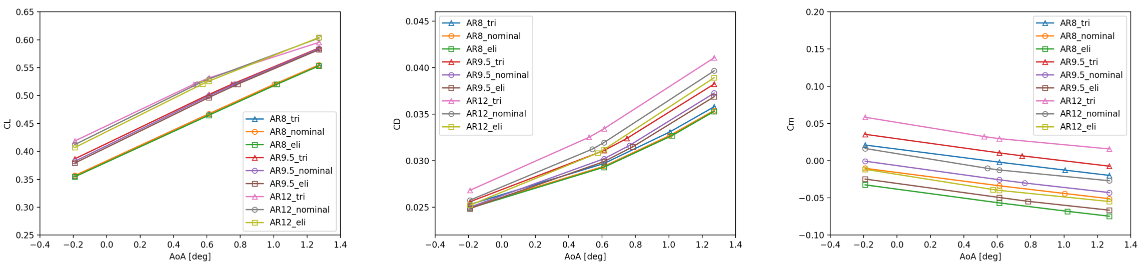

Figure 9: Aerodynamic characteristics on several wing geometries

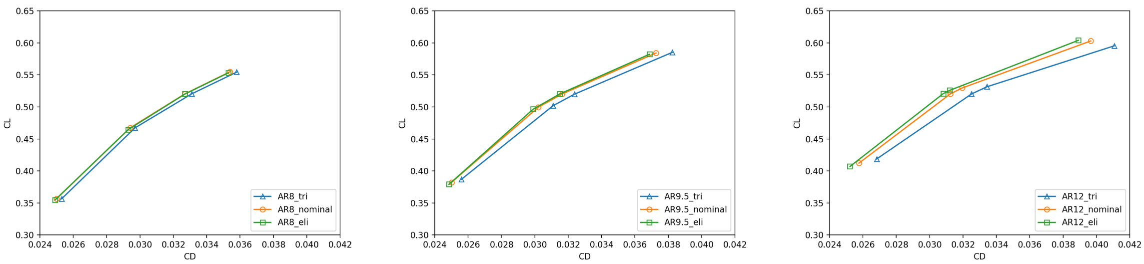

Figure 10: $C_L - C_D$ curves on several wing geometries

3.2 Structural weight

Figure 11 shows the optimal results obtained by the structure sizing process on three aspect ratio. With increasing the AR, the thickness on overall wing area are increased. The higher load at outboard wing increases the thickness of the structure elements, then induces the increment of the wing structure weight. As a same manner, the wing weight becomes heavy with increasing the angles of attack. Comparing with the AR, the heavy wing weight was needed at high AR, because the wing span is increased by the increment of AR even though the wing area is constant. The sensitivity of the wing weight by the load distribution were depended on the AR. The difference of the weight between each load distribution on AR = 12 is largest on the three AR when compared on the same C_L (Figure 15).

3.3 Fuel consumption

The fuel consumption for the nine wing geometries on the range of 3800 nm was estimated by the mission analysis using RDS-Pro. At first, the take-off gross weight including the wing weight obtained above was re-estimated using the weight and mission analysis loop. Because the aerodynamic performances and the wing weight were changed from the original RDS-Pro results to the analytical ones. Figure 13 shows the fuel weights consumed for the mission profile. On the wings with AR=9.5, the maximum fuel is needed in case of the triangle shape, while the minimum fuel is needed in case of the nominal shape. Though the C_D of the nominal shape is the same as the elliptic shape, the wing weight of the nominal shape is lighter than the elliptic shape (Fig. 12). On the other hand, the maximum fuel of the triangle shape was caused by the poor aerodynamic performances in spite of the lightest wing weight among the three. The effects of the load distributions on AR = 8 are similar to AR=9.5. However, the difference of the fuel consumption among the three load distributions in case of AR = 8 is smaller than AR = 9.5. It means that the sensitivity of the load distribution on AR = 8 is lower than AR = 9.5.

In case of AR = 12, no solutions were obtained with all three shapes. Because their heavy weights need higher lift on the cruise flight, where the drag is significantly increased. Therefore, all case of AR = 12 can not satisfy the range of 3800 nm.

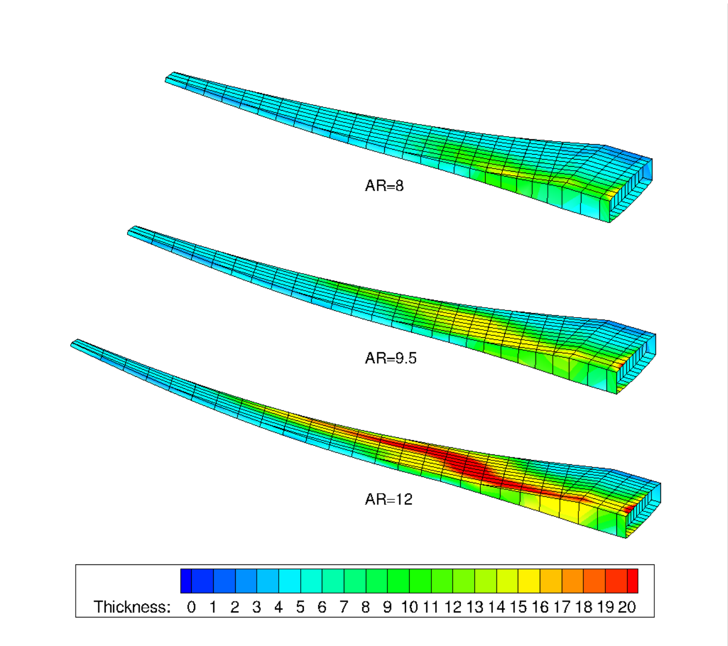

Figure 11: Optimal results of the thickness distribution of the wing structure part (nominal shape, $C_L = 0.5194$)

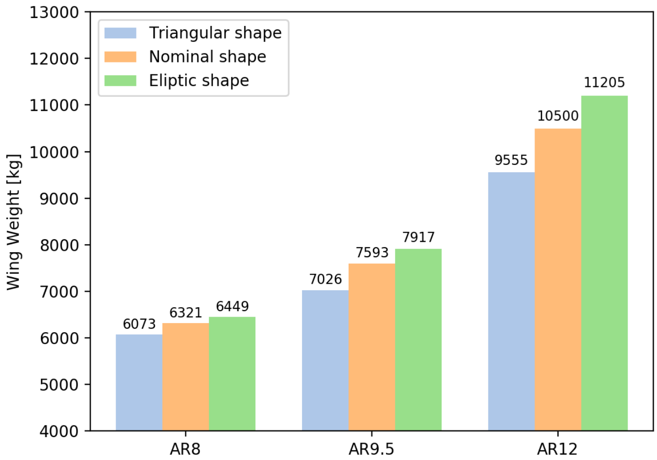

Figure 12: Wing weight estimation at the design point

4 CONCLUSION

Studies of the subsonic wing geometry were performed using multidisciplinary design tools to reduce the fuel consumption on a mission flight with TRA2012. The aerodynamics and structure weight were obtained by the CFD and FEM analyses on nine wing geometries comprising three aspect ratios (AR = 8, 9.5, 12) and three load distributions (triangle, nominal, elliptic shapes). The fuel consumption was estimated by the mission analysis using RDS-Pro.

- Concerning the load distribution, the C_D of the nominal shape and the elliptic shape are lower than that of the triangle shape in case of AR = 8, 9.5. On the other hand, the elliptic shape has the lowest C_D on AR = 12. With increasing the AR, the reduction of the C_D is observed on AR = 8, 9.5, while the increment of the C_D is observed on AR = 12. Even if only the geometry of the wing is changed, the loads on the fuselage and the HTP are also changed by the interaction of the flow past the inboard wing.
- The wing weights are increased with increasing the wing aspect ratio because the wing span length is increased in case of higher AR. With changing the load distribution from triangle shape to elliptic one, the wing weight increases due to the higher load on the outboard wing.
- In case of AR = 8, 9.5, the minimum fuel consumption is obtained on the nominal shape load distribution, and the benefit of the light wing weight on the triangle shape is cancelled by poor aerodynamics. On the other hand, the heavy wing weight of the elliptic shape causes the increment of the fuel consumption. In case of AR = 12, no solutions are obtained on the mission flight. Because the heavy wing weight results in the significant increase of the drag at cruise, the range of the mission is shortened.

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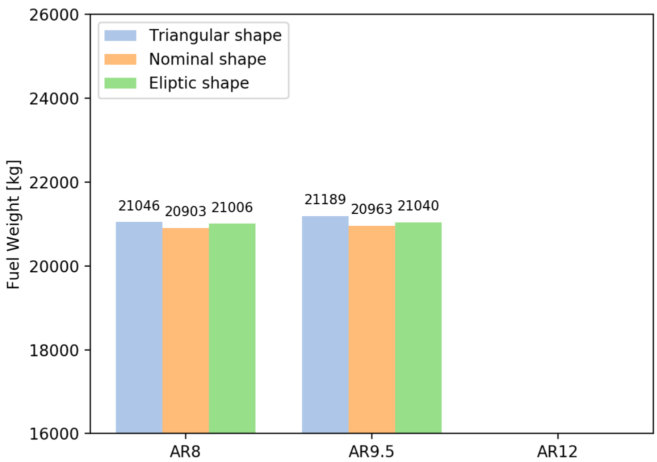

Figure 13: Fuel consumption estimation at the design point

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