Initial Design and Evaluation of a Novel Concept Regional Aircraft

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Abstract

A type of blended-wing-body (BWB) aircraft is expected to be next generation airliner. While many studies for BWB has been performed for a large scale aircraft, an aircraft which is for regional jet is also expected. Such aircraft would be small (about 100-300 seats). In the development of such aircraft, BWB should be also discussed because it has aerodynamic advantage compared with conventional aircrafts. Therefore, the aerodynamic design optimization for a small size BWB is required for conceptual design. In this study, an initial BWB which has 150 seats configuration is designed using genetic algorithm (GA). Three cross sections are optimized under constraint of elliptic span loading. Three dimensional unstructured Navier-Stokes solver is applied to evaluate the aerodynamic performance of BWB initial design.

Keywords: Blended-Wing-Body; Genetic Algorithm; Computer Fluid Dynamics; Aircraft Design;

1. Introduction

A type of Blended-Wing-Body (BWB) [1] aircraft (Fig.1) has possibility to be a next generation aircraft, because of its highly aerodynamic sophisticated geometry which reduce interference drag. That configuration is very different from the conventional one. Its fuselage is blended to wing surface and its cross section also gain lift. Therefore, BWB has great advantage in aerodynamic performance compared with the conventional aircraft. Many institutes study on BWB for a large aircraft, but ICAO report said that approximately a half of new demand is 100-200 seats aircraft at 2028, because the air traffic demand has been changing from hub-and-spoke to point-to-point. Thus, a small type aircraft should be considered for the next generation.

There are several problems to consider small size BWB. One of the most remarkable problems is that the cabin height has to be about 2.0m. Thus, a small BWB has passenger cabin which height is not so high. The cross section of BWB's fuselage is also same as airfoil. It suggests that small size BWB has relative thick airfoil as shown in Fig.2. Because a general thick airfoil is not ideal for aerodynamic performance, the detail of the geometry include a curvature should be decided for its aerodynamic efficiency.

In this study, design optimization procedure is considered for initial layout with considering of a type of BWB as a Novel-Wing-Body (NWB). Airfoil geometries, which are the span wise cross section of the NWB geometry, are designed using genetic algorithm (GA) [2] with computational fluid dynamics (CFD). Optimum airfoil parameters are selected and applied to the three dimension initial geometry. In three dimension modeling process, NWB's planform is defined with Bezier curve and linear line. Because the inboard, fuselage, planform has to connect outboard wing smoothly, a fuselage center and outboard wing are merged by Bezier curve. The outboard wing planform is similar to a conventional aircraft wing. Then, linear interpolation is conducted. NWB three-dimensional aerodynamic performance is analyzed by unstructured Navier-Stokes flow solver.

Fig.1 Blended-Wing-Body aircraft developed by NASA[1]

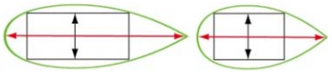

Fig.2 Cabin space in large and small fuselage cross sections

2. Cross Section Design of NWB

2.1. Geometry definition methods

In this study, an airfoil is represented by polynomials. Thickness and camber line is defined by Eqs. (1), and (2), respectively.

$$z_{\text{thickness}} = \sum_{n=1}^{5} a_n \times x^{\frac{2n-1}{2}} \qquad (1)$$

$$z_{\text{camber}} = b_0 \times \sqrt{x} + \sum_{n=1}^{5} b_n \times x^n \qquad (2)$$

where a_n, b_n are decided by airfoil parameters. Here, 11 design variables are defined as shown in Table 1.

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Table 1 Airfoil parameter name

Parameter name	
Leading edge radius	r_{le}
Maximum thickness	x_t
Maximum thickness	z_t
Maximum thickness radius of curvature	z_{xxt}
Trailing edge expansion angle	β_{te}
Camber leading edge radius	r_{le}
Maximum camber location	x_c
Maximum camber	z_c
Maximum camber radius of curvature	z_{xxc}
Camber trailing edge angle	α_{te}
z coordinate of camber trailing edge	z_{te}

2.2. Design Variables

2.2.1 Design Variables for fuselage

The fuselage cross section's leading edge should be cockpit, thus camber leading edge radius is set to zero for the fuselage cross section. The cross section of the proposed NWB fuselage has to be reflected airfoil for aircraft trim balance. To define reflected camber line, the trailing edge gradient has to be negative variables (Fig.3). The fuselage cross section should have sufficient thickness to maintain the cabin volume. Airfoil thickness is set to 15 %. Then, airfoil parameters' ranges are defined as Table 2.

Fig.3 Airfoil with reflected camber

Table 2 Design space for fuselage definition

Thickness parameters	Minimum value	Maximum value
r_{le}	0.005	0.06
x_t	0.3	0.6
z_t	-	0.15 (const.)
z_{xxt}	-1	0
β_{te}	4	15
Camber parameters	Minimum value	Maximum value
r_{le}	-	0 (const.)
x_c	0.1	0.5
z_c	0	0.05
z_{xxc}	-1	0
α_{te}	*-10*	0
z_{te}	0	0.08

2.2.2 Design Variables for outboard wing

NWB's outboard wing has similar thickness distribution and camber line to the conventional aircraft wing. Therefore, general parameter ranges for a transonic aircraft are set for this design. Thus, design space for the NWB's outboard airfoil is defined in Table 3.

Table 3 Design space for outboard airfoil

Thickness parameters	Minimum value	Maximum value
r_{le}	0.005	0.025
x_t	0.35	0.50
z_t	0.04	0.075
z_{xxt}	-0.6	0.0
	4.4	6.4
Camber parameters	Minimum value	Maximum value
β_{te}	0	0.002
z_c	0.35	0.50
z_{xxc}	0.0	0.04
α_{te}	-0.05	0
z_{te}	3	8

3. Airfoil Evaluation

Aerodynamic performances of airfoils are evaluated Navier-Stokes flow solver expressed as eq. (3).

$$\frac{\partial}{\partial t}\int_{\Omega}\Phi\,dv+\oint_{\partial\Omega}F\cdot d\vec{s}=0 \qquad (3)$$

where Φ is conserved quantity in volume. F is sum of conserved quantity which goes in and out. Baldwin-Lomax model is used as a turbulent model. Space discretization is 191×91 C type structured grid as shown in Fig. 8. This grid is created algebraic method automatically. Lower-upper Symmetric Gauss-Seidel (LU-SGS) implicit method is applied to time integration. Flux is evaluated by third order accurate upwind-discretization with MUSCL method.

4. Optimization Method

To optimize the NWB's cross section, ARDRMOGA (Adaptive Range Divided Range Multi-Objective Genetic Algorithm) is applied [2]. Genetic algorithm (GA) is inspired by the evolution of living organisms with regard to adaptation to the environment and the passing on of genetic information to the next generation (Fig.4). The design problem is defined for fuselage as follows.

$$\begin{cases}\text{Maximize: Moment coefficient } (C_m)\\ \text{Minimize: Drag coefficient } (C_d)\end{cases}$$

The design problem is defined for the outboard wing as follows.

$$\begin{cases}\text{Maximize: Airfoil thickness } (t)\\ \text{Minimize: Drag coefficient } (C_d)\\ \qquad \text{Subject to lift coefficient } (C_l) = \text{target value}\end{cases}$$

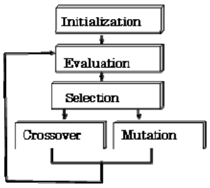

Fig.4 Genetic algorithm applied in this design process;

5. Design Results of Aircraft's Cross Sections

5.1. Fuselage

Fig. 5 illustrates non-dominated solutions between C_d *vs.* C_m. Solutions F-1-3 achieve larger C_m than the solution F-4 on the obtained non-dominated solutions. On the other hand, the solution F-3 achieves minimum C_d among solutions F-1-3. Then F-3 geometry is used for the present NWB root airfoil. Fig.6 shows its pressure distribution and geometry. This airfoil has reflected camber for maintaining the NWB's trim aircraft balance.

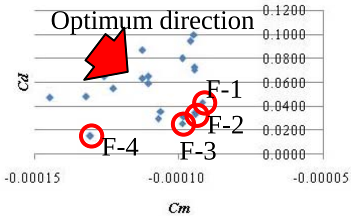

Fig.5 Fuselage section airfoil solution C_d-C_m (t/c = 0.15)

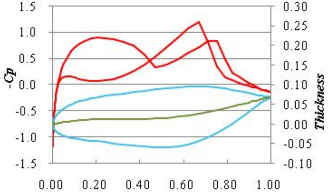

Fig.6 F-3 pressure distribution

5.2. Outboard airfoil (Mid-span)

To decide the outboard wing for the initial NWB concept, airfoils at the mid-span and wing tip are designed individually. Each target C_l is decided according to the ideal span loading. To design mid-span airfoil which connects fuselage and outboard wing, target C_l is set to 0.27. Figure 12 shows non-dominated solutions between C_d *vs.* t. Investigating non-dominated solutions, solution M-3 has minimum C_d, but t is not so large. On the other hand, the solution M-2 has moderate t, while it also achieves small C_d. Then, it is best for the mid-span airfoil in these solutions. Fig.7 illustrates its pressure distribution and geometry.

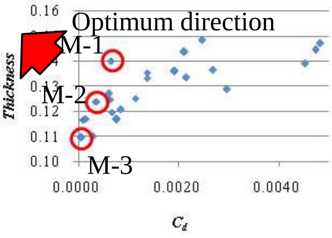

Fig.7. Mid-span section airfoil solution C_d-t (C_l=0.27)

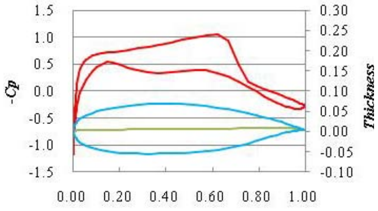

Fig.8 M-2 cruise *Cp* (AoA=1.1 deg.)

5.3. Outboard airfoil (Tip)

Conventional subsonic airliner tip airfoil's thickness is about 10% and its ideal C_l is zero to reduce the induced drag. According to the result of MOGA whose target C_l=0, T-1 and T-2 have nearly 10 % thickness and small C_d. Here, T-1 is chosen for the tip airfoil in these solutions. Fig. 15 illustrates T-1 pressure distribution and its geometry.

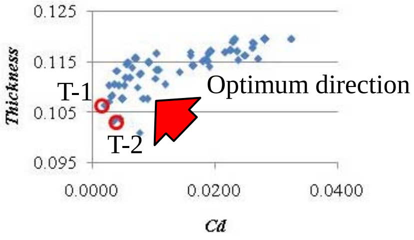

Fig.9 Tip section airfoil solution C_d-t (C_l=0.0)

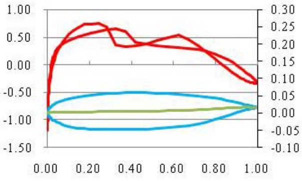

Fig.10. M-2 cruise *Cp* (AoA=0.6 deg.)

6. Three-dimension Evaluation

6.1. Definition of Initial Geometry

Figure 11 illustrates the definition of the NWB's planform. Three cross sections which defined for NWB geometry discussed in Section 5. Here, at the cross section of the fuselage center is designed in 5.1.

The cross section between the fuselage and the outboard wing, and the wing tip are designed in 5.2 and 5.3. The three dimensional geometry of outboard wing (the connection between the fuselage and the wing tip) is linearly interpolated. The three dimensional geometry between the fuselage and the wing is interpolated by a Bezier curve. At the fuselage center, the curve is vertical to the aircraft center line. C1 continuous condition is considered to connect the inboard wing and the outboard wing.

Inboard and outboard wing has three and four parameters respectively. To define the inboard wing planform there are three parameter the connect airfoil span position and Bezier control points span position. Outboard wing has four design variables, which are sweep back, taper ratio and aspect ratio. The parameters for initial planform are shown in Table 4. Here, the planform parameters of the NWB developed by NASA [1] are followed. The cabin is composed by the surface.

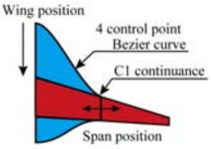

Fig.11 Planform definition

Table 4 Initial planform parameter

Parameter	Inboard Bezier control point for C1 continuance		mid-span airfoil position
unit	span %		span %
	0.15	0.35	0.55

Parameter	Outboard Wing LE position	Aspect ratio	Taper ratio	Sweep
unit	m	-	-	deg.
	8.75	9.4	0.2	25

4.2. Aerodynamic Evaluation

Aerodynamic performance of NWB is evaluated using TAS code (Tohoku university Aerodynamic Simulation code)[3, 4], an unstructured grid flow solver. Computational grid is shown in Fig.12. Compressive Navier-Stokes equation is solved while angles of attack are changed. Free stream Mach number is set on 0.80.

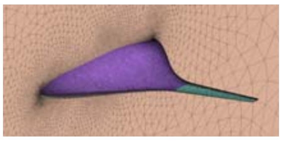

Fig.12 Computational grid

4.3. Result

Fig.13 shows angle of attack *vs.* C_L, and Fig.14 shows C_L *vs.* C_D, Fig.15 shows angle of attack *vs.* *L/D*. According to Fig.15, this aircraft has maximum *L/D* at angle of attack of two degrees. Fig.16 illustrates the pressure contour and the stream line at angle of attack of two degrees. From this picture, the span-wise flow from the fuselage to the outboard wing can be observed. Additionally, two compressive points as shown by dotted line is also observed. In a transonic wing, only one compressive area conventionally appears, that is local shock wave. Designed airfoils discussed in section five also have one local shock around 0.70. This result suggests that such two compressive points appear by three-dimensional effect which means the aerodynamic interaction between thick fuselage and outboard wing. This interaction also affects the aerodynamic phenomena on the outboard wing. Therefore, the final aircraft geometry should be proposed by the three dimensional optimization in consideration of the interaction between the fuselage and the outboard.

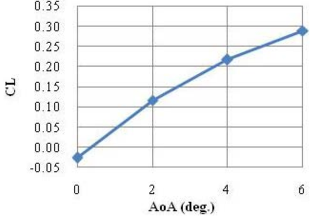

Fig.13 Initial NWB C_L-AoA

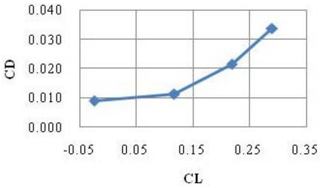

Fig.14 Initial NWB C_L- C_D

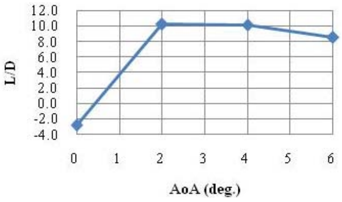

Fig.15 Initial NWB AoA-L/D

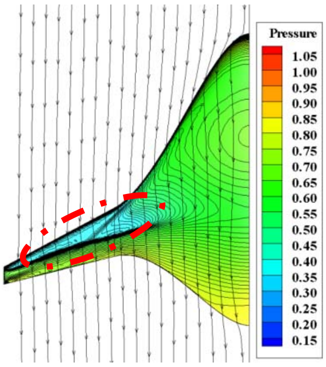

Fig.16 Upper surface pressure contour and stream line at angle of attack 4 deg.

3. Conclusion

In this study, the conceptual design and the aerodynamic design optimization is carried out to propose the initial geometry is the blended-wing-body as a small size aircraft, that is NWB. Airfoils at the fuselage and the outboard wing are separately designed by MOGA. In MOGA process, the distributed scheme is employed with the range adaptation algorithm. Every individual's aerodynamic performances are evaluated using Navier-Stockes solver. Non-dominated solutions are obtained and airfoil designs are selected for the fuselage section and the outboard wing section. For the fuselage, a reflected camber airfoil is selected because the fuselage has to gain the negative lift around the trailing edge to maintain the trim balance. For the outboard wing, the design which achieves the most adequate shape among the non-dominated solutions is selected. It was similar to conventional transonic airfoil. As their result, three dimensional geometry could be designed using these airfoils and its aerodynamic performance is also investigated using unstructured Navier-Stockes solver. This result suggests that the shock wave interaction is severe problem in the design of the small size NWB.

References

[1] http://www.dfrc.nasa.gov/ (last accessed in July, 2010.)

[2] Kanazaki, M., Yokokawa, Y., Murayama, M., Ito, T., Jeong, S., and Yamamoto, K., "Nacelle Chine Installation Based on Wind Tunnel Test Using Efficient Design Exploration," *Transaction of JSASS*, Vol 51, No. 173, Nov. 2008.

[3] Ito, Y., and Nakahashi, K., "Direct Surface Triangulation Using Stereolithography Data," *AIAA Journal*, Vol. 40, No. 3, pp. 490-496, May, 2002.

[4] 3) Ito, Y. and Nakahashi, K., "Surface Triangulation for Polygonal Models Based on CAD Data," *International Journal for Numerical Methods in Fluids*, Vol. 39, Issue 1, pp. 75-96, May, 2002.