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The aerodynamic design evaluation of a blended-wing-body configuration

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Inherent aerodynamic potential and environmental benefits of the blended-wing-body configuration make it an appropriate candidate for the future airliners. This article studies an initial scaled blended-wing-body airframe using computational analyses in early conceptual design stage. Then, a modified airframe is developed based on evaluation of the initial airframe. Eventually, a full-scaled high-capacity blended-wing-body configuration is proposed for a long-range mission. In assessment of the initial airframe, its aerodynamic coefficients are obtained for a range of angle of attacks based on Reynolds-Averaged Navier–Stokes simulations. The second airframe is designed using conceptual design approach with a typical mission profile, and it is modified based on evaluation of the first airframe. The sequential aerodynamic investigation of the airframes with emphasizing on geometric parameters facilitates the design methodology at its early stage. In the second airframe, the appropriate space for 800 passengers is provided, and geometric parameters are changed according to the mission profile. The current design philosophy allows utilization of maximum aerodynamic potential for designing a blended-wing-body configuration.

1. Introduction

The first blended-wing-body airliner, called the Stout Batwing, was designed by William Bushnell Stout in 1926 [35]. He was promoting his design with an unorthodox configuration. Furthermore, the Junkers G38 super jumbo was flying with capacity of 34 passengers in its central body in 1926. Another example of such a configuration was the Ford Trimotor airliner which was flying with 9-passenger capacity at the same time [11]. In early 1940, the X Minor was designed as a research model for studying combination of wing and body in a large airliner [3]. Following this further, the Burnelli CBY-3 with its airfoil liked central body flied in 1944. It was designed with a twin boom for improving the stability in flight [30]. At the end of the World War II, Horton brothers designed the Ho 229, which was a true flying wing configuration [23]. Later, Jack Northrop developed the YB-49 [34]. Nowadays, NASA and the Boeing Company are developing the blended-wing-body configuration as a commercial transports for the future [16].

After emergence of rectangular-shaped body and then tube-shaped body, wings and cylindrical body have become two main characters of commercial flights since early 20th century. Aircraft manufactures remained loyal to them, and passengers, more or less, entered the cylindrical body to travel around the world. At the time of designing the B747, it has been believed a typical configuration with cylindrical body has reached its maximum performance, and further development for commercial transport could be a challenge [15]. However, the Boeing Company came up with an innovative idea which was a practical substitute for addressing real requirements of the future commercial transport in 1998, in a conference in Reno, Nevada. Accordingly, the blended-wing-body configuration officially came into existence for the future generation [17]. In general, aircraft configurations are classified according to conventional, blended wing body, hybrid flying wing, and true flying wing. In comparison with flying wing configuration with no central body also known as tailless fixed wing, in the BWB configuration, passenger cabins, cargo, and equipment are located in central structure of the wings and body. In other words, the BWB configuration combines features of the conventional configuration with the flying wing configuration. It has advantages in terms of performance, and construction in comparison with the conventional configuration. This configuration exploits thick airfoil-liked body in the center, and it accommodates cargo and passengers

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Nomenclature

t/c	thickness-to-chord ratio	
C_{D_0}	minimum drag coefficient	
$C_{L_{max}}$	maximum lift coefficient	
C_{α_0}	zero-angle-of-attack lift coefficient	
b	wing span	m
AR_w	wetted aspect ratio (S_{wet}/S_{ref})	
Y	mean aerodynamic chord location	m
i	angle of incidence	°
C_R	root chord	m
x, y, z	streamwise, spanwise, and vertical coordinates	
C_L	lift coefficient	
C_D	drag coefficient	
C_M	pitching moment coefficient	
L/D	lift-to-drag ratio	
S_{wet}	wetted area	m^2
C_{L_α}	lift coefficient curve slope	rad^{-1}
S_{ref}	reference wing area	m^2
$S_{exposed}$	exposed wing area	m^2
F	fuselage lift factor	
C_{D_0}	parasite drag coefficient	
C_p	pressure coefficient	
K	induced drag factor	

Acronyms

AEROPP	aerodynamic research on passenger plane
CFD	computation fluid dynamics
RANS	Reynolds-Averaged Navier–Stokes
SA	Spalart–Almaras
AR	aspect ratio
MAC	mean aerodynamic chord
AoA	angle of attack

Re	Reynolds number
GPS	global positioning system
ANT	antenna
c.g.	centre of gravity
FAR	federal aviation regulation

Greek symbols

α	angle of attack	°
α_{0_L}	zero-lift angle of attack	°
Λ_{LE}	leading-edge wing sweep angle	°
$\Lambda_{0.25C}$	quarter-chord wing sweep angle	°
$\Lambda_{0.5C}$	half-chord wing sweep angle	°
θ	twist angle	°
Γ	dihedral angle	°
λ	taper ratio	
Λ_{maxle}	sweep angle in maximum t/c location	°
η	airfoil efficiency	
β	Mach number parameter	

Super-/subscripts

L	lift
D	drag
M	pitching moment
0	zero angle of attack
w	wetted
R	root
C	chord
ref	reference
LE	leading edge
maxle	maximum t/c location from leading edge

in the center with low compressibility drag. Meanwhile, it reduces total drag comparing with the conventional configurations because its airfoil-liked body with no tail is blended smoothly with outboard wings. Consequently, it increases lift-to-drag ratio and decreases fuel consumption for a long-range high-capacity missions [17]. Moreover, those advantages are expanding on economical fuel consumption, reliability, maintenance period, and low cost for large-scale production [2].

There are several technical advantages in the BWB configuration. Among them, effective spanwise lift distribution is intended to be obtained by using a wide airfoil-liked body. Therefore, entire airframe in this configuration play an effective role in lift generation that improves economical fuel consumption. Meanwhile, this configuration decreases aerodynamic load on outboard wings because of big central chord that bears major part of the span loading [31]. In addition, because of the biggest chord in central body, it needs low lift coefficient to bear an elliptical spanwise load distribution. Therefore, central spanwise location can be thicken to acquire required space for accommodating passengers and cargo without large compressibility drag penalty. In this configuration, most trapezoidal area of planform is covered by the wings, which decreases wing area, and consequently the skin friction drag. Furthermore, shape of the airframe relatively weakens shock waves over the wings and body, and also subsonic flow region behind the shock waves provides appropriate area for engine installation. Besides, its low and effective load coefficient eliminates needs for complex high lift devices because of trim effect. Therefore, it only needs leading edge slots in outboard wings and simple fowler flap along with elevons, which combines functionalities of elevator and aileron.

In central body of this configuration, usable space accommodates passenger cabins, galleys, equipped restrooms. The least possible wetted area for this volume is obtained in shape of sphere. However, the sphere is not aerodynamically appropriate. It is only usable when it flattens out to a disk. Therefore, disk-liked body decreases total wetted area in this configuration, which has low compressibility drag in cruise flight condition [15]. Further, blending the body with the wings in addition of adding an elliptical nose in front of the configuration completes a commercial transport BWB configuration. Meanwhile, engines are connected to the aft portion of central body. Therefore, because of their vertical distance from neutral point, they need to be considered in balancing the configuration around the lateral axis.

Several researchers around the globe are investigating the blended-wing-body configuration from different points of view. Among them, Liebeck et al. introduced the BWB configuration as a subsonic commercial transport in 1998. They compared it with conventional configuration, studied its advantages as the future airliner, and performed a multidisciplinary planform optimization for improving its aerodynamic performance [14–17,25]. Roman et al. [31] aerodynamically studied the BWB configuration. They used a multidisciplinary design and optimization technique on its planform for increasing its cruise speed. Kuntawala et al. [13] performed a series of aerodynamic shape optimizations for improving spanwise lift distribution on a BWB configuration with a short range mission. In addition, Reist and Zingg [29] investigated a series of multipoint shape optimizations on a BWB configuration using Euler and RANS simulations. Wakayama et al. [37–41] reconfigured a BWB aircraft using a multidisciplinary design and optimization technique. Lyu and Martins [18,19] studied a BWB