Lateral-Directional Stability Investigation of a Blended-Wing-Body

Paul F. Roysdon[1] and Mahmood Khalid[2]

[1] *Graduate Researcher, Department of Aeronautics and Aerospace, Von Karman Institute for Fluid Dynamics, Chaussee de Waterloo 72, B-1640 Rhode-St-Genese, Belgium.*
[2] *Research Adviser.*

Email: *aerodsnr@gmail.com* [1]

Abstract

Presently at the Von Karman Institute for Fluid Dynamics (VKI), a comprehensive research investigation is being performed on the lateral-directional stability characteristics of a Blended-Wing-Body (BWB). Blended-Wing-Body configurations are based on the concept that the area rule provides a better aerodynamic performance from cross sectional shapes when fuselage, wings, empennage, engine pods, etc., get integrated into a single component resulting in a smooth delta shape wing body configuration. This configuration has been shown to have superior aerodynamic performance - in contrast to their classic wing-and-tube fuselage counterparts - and have reduced sensitivity to aerodynamic flutter as well as potential for increased engine noise abatement. The resulting inner space is demonstrated to cover a larger volume than the classic fuselage supported on cantilevered wings and a crossed T tail. Additionally, when the interior structure of the vehicle can be simplified with a monocoque structure, taking advantage of modern composite materials, it provides superior wing loading and structural strength. Of course without a classic tail elevator to damp the nose up pitching moment, and the vertical tail rudder to damp the yaw and possible rolling aerodynamics, the challenges in lateral roll and yaw stability, as well as pitching moment are not insignificant. The work at VKI will consist of first, designing attempts using lower order methods and vortex lattice based methodology to get a comprehensive understanding of the aerodynamic performance. Later more accurate CFD methods will be used to fine tune the performance. A 1/16th scale model will be tested in the wind tunnel to validate the CFD based modeling strategies.

1 Introduction and Historical Significance

1.1 Historical Case for Aircraft Design

During the first century of flight, the aircraft design evolved from the canard-wing-tail configuration of the Wright Flyer in 1903, to the modern day tube-fuselage wing-tail configuration, first demonstrated with the Boeing B-47 in 1947. Today, 60 years after the B-47, the aircraft design philosophy is relatively unchanged [9] [36]. The modern transport, either Boeing 7-series or the Airbus 3-series, or the smaller variants of the Bombardier or Dassault business-jet-class airplanes, still resemble the tube and wing configuration. While this is a well tested and well understood design, there are significant performance advantages to be gained with the evolution away from this classic design. Instead of gaining performance on the order of fractions of a percent, through the use of a higher performing engines, or the addition of winglets on for example the Boeing 737, it is time for a renaissance in aircraft design philosophy where there exists a potential performance increase greater than 20%.

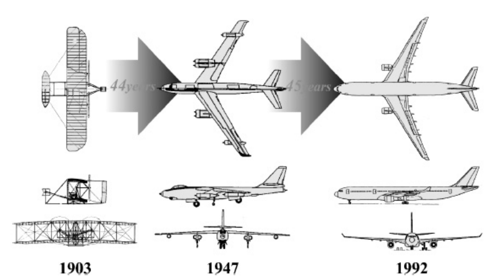

Figure 1: Aircraft evolution during the first century of flight [9].

The flying wing, due to the simplicity of the design and perceived performance advantages, has been a design of interest since man's first flight. Through the 1940s the flying wing received increased interest by the Horten brothers in Germany, and later with Northrop, in America. And it was nearly 40 years before the flying wing emerged as a design in full production, with the B-2 Stealth Bomber, again by Northrop. While flying wing designs have shown promise, their use in industry has been limited, and has lacked the ability to present a strong case for mass transport of personnel or supplies. During the late-1980s and early-1990s, the BWB emerged as a design capable of transporting 400+ passengers [9] with 20% greater efficiency than the classic design. Since then, the BWB has been on the forefront of research and development, with published designs increasing exponentially, (see figure 2).

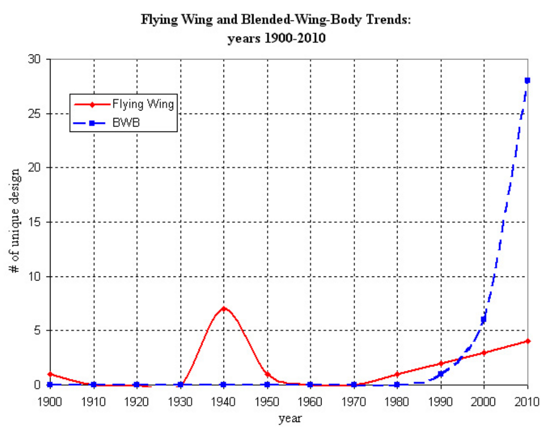

Figure 2: Flying Wing and BWB historical trends.

1.2 The Blended-Wing-Body Argument

The BWB configuration provides several specific design and performance advantages over the common tube and wing designs.

1.2.1 Drag

Drag reduction can be achieved by the elimination of the interference drag, $C_{D\,I}$, caused by the wing-fuselage as well as tail-fuselage intersections. During take off and landing configurations too, it is envisaged that hanging engines with separate tail fuselage and wing configuration the classic shape is prone to larger acoustic signatures compared to the integrated delta shape where interference effects would be minimized from all-in-one blended wing body shape. Also, due to the absence of a vertical tail, the flying wing or BWB requires either artificial lateral stability or winglets. Artificial lateral-directional stability requires control surfaces placed well outboard, and it is common to employ split ailerons which act as both as ailerons for roll-control, and drag rudders for yaw-control. While this is a clean configuration for low-observables, or stealth applications, it still increases the total drag of the system and therefore reduces the potential range performance. Alternatively, in non-stealth configurations, winglets can be used instead of (or in combination with) split-ailerons. The primary advantage of the winglet is the increase in effective wing aspect-ratio, and thus a reduction in induced drag C_{Di}, while simultaneously providing lateral-directional stability. Finally, a by-product of the BWB design is the inherent "area rule" of the vehicle. The "area rule", discovered by Whitcomb [35] during the 1950s, applies the results of cross-sectional area of a vehicle to the effect on transonic drag. Simply put, transonic drag is reduced when a vehicle exhibits a near-to-theoretical circular distribution of cross-sectional area versus fuselage station along the longitudinal axis of the fuselage.

1.2.2 Structure & Payload

The BWB further simplifies the aircraft design by integrating the fuselage into the wing volume, thereby displacing the payload mass over the entire wing. This provides significant design advantages, both structurally and economically. Structurally the wing can can be built of a monocoque structure which is self-contained and self-supporting, without the necessity of transferring the load to another structure—a fuselage for example. This simplifies the both the design and the manufacturing of such a structure. Economically, the wing-box structure has been used for many years for the placement of fuel. This is done such that as the fuel is burned during flight, the resulting impact on center of gravity of the aircraft is minimized, and the aircraft remains stable as a result. While the placement of fuel remains the same for the BWB, the increased volumetric area of the wing, due to the integration of the fuselage volume into the wing, provides greater storage capacity than presently exists in favor of the BWB, and at no extra cost in performance.

1.2.3 Challenges and the Present Investigation

While the argument in favor of the BWB certainly is convincing, there exist significant design challenges which must be overcome. First, the lack of a horizontal and vertical tail requires that the pitch and yaw moments must be managed, at all flight conditions, by a short moment arm. Second, also related to the first, is the requirement of lateral-directional stability throughout the flight regime, most importantly at take-off and landing. At take-off and landing, the high angle of attack conditions make the BWB dangerously susceptible to gust loads which push the local angle of attack to near stall conditions, potentially eliminating control effectiveness of the control surfaces on the trailing edge of the wing.

The present investigation is centered around a 6 seat, business-jet-class airplane, similar to the Lear 23: see figures 3 and 4. This configuration was selected because of publically available data [23] from which to make a comparison of the aircraft stability and performance. This paper presents the original design of a BWB configuration which exhibits favorable stability characteristics, as well as significant drag reduction and increased range performance. Particular attention will be addressed in control actuators which restore lateral-directional stability, as well as pitch stability, in the take-off and landing flight regimes.

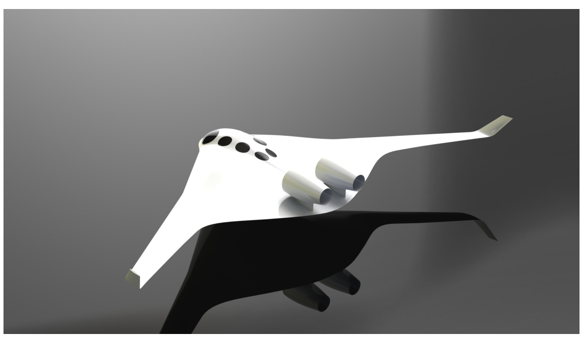

Figure 3: The Roysdon BWB.

Figure 4: Overlay of the BWB with a Lear 23.

2 MODELING STRATEGIES

The Roysdon BWB design philosophy was influenced by the aircraft designs of Burt Rutan [21] as well as the carbon-composite manufacturing capabilities of companies like Composite Engineering Inc.[3]. The initial investigation into the BWB design was first to determine a planform which was statically-stable, with aerodynamic characteristics similar to literature([2], [11] thru [16], and [28] thru [30]) and applying the literature results as a basis from which to start a multidisciplinary-optimization, varying: inboard-to-outboard planform area, wing-sweep, wing-twist, airfoil-family, airfoil-thickness and chord length. Upon obtaining a preliminary design, a study was performed on the entire angle-of-attack (α) and angle-of-side-slip (β) envelope, with special interest in the lateral-directional stability characteristics. Comparing the stability coefficient results to literature data available in stability and control ([1], [6], [8], [10], and [17] thru [20]), further investigation was made, and an initial 6DOF non-linear simulator was developed in MatLab & Simulink. By employing a basic attitude hold autopilot block and performing simple pitch-up maneuvers and roll maneuvers, the non-linear simulation provided a benchmark from which to test the vehicle dynamics for further optimization. Later, tuning of these results would be obtained with higher-order methods, and wind tunnel analysis.

2.1 Low-Order Methods

The initial investigation managed the pitch moment in two ways; first by creating pitch stability through wing sweep, and second by applying reflexed airfoils on the inboard regions of the BWB and cambered airfoil sections on the outboard regions of the BWB. The reflexed airfoil creates pitch-trim on the inboard section of the BWB, while the cambered airfoil creates two things. First, the restoring pitch-moment common to cambered profiles, creates pitch stability. And second, the cambered profile, when combined with proper wing twist and airfoil thickness, creates the optimal lift distribution over the wing.

The pitch stability and lift distribution was obtained by applying a gradient-based multi-disciplinary optimization (MDO) routine, coupling MatLab with Athena Vortex Lattice (AVL) [4], a vortex-lattice-method code. The MatLab-AVL optimization obtained a compromise of airfoil-family selection, airfoil thickness, wing sweep and wing twist, and ultimately the MDO results compare well with the findings of [11] thru

[16], and [28] thru [30]. Figure 6 presents the final version of the VLM model, with the control surface highlighted for visual clarity. All but the "belly-flap" control surfaces were used in the initial stability and control study, afterwhich the control surfaces were assumed "locked" at zero degrees deflection, and the effectiveness of the "belly-flap" was investigated.

By applying the MatLab-AVL routine in a batch-mode, an analysis was performed throughout the flight envelope with sweeps of the angle-of-attack (α) and angle-of-side-slip (β) envelope at various velocities. The result is a complete 6DOF aero-database for the non-linear simulation, as well as a series of plots which provide a quick-look reference of the aircraft stability coefficients.

Based on the VLM results, a 3D CAD model was created for CFD analysis and the preparation of a wind tunnel model. Using the CAD model, the "area-rule" of this design was also verified. Figure 5 compares the BWB to the theoretical area-rule, as well as to the reverse-engineered area-rule of the Lear 23 (performed by generating a representative 3D model from a 3-view drawing of a Lear 23).

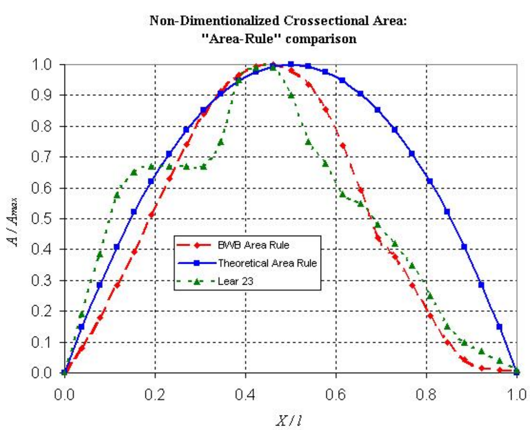

Figure 5: Area-Rule comparison.

2.2 High-Order Methods

2.2.1 Mesh

A systematic approach was taken for the investigation of the BWB using CFD, first to determine grid dependencies on the results, and second to provide the "tuning" values needed for the Low-Order database. A full model was used, because of the need to model yaw-moment, and an initial mesh was created using engineering experience in CD-Adapco STAR-CCM+ for aircraft profiles of similar size. For modeling simplicity, the engine nacelles and pylons were eventually removed from the CFD model, and based on based on [2], [14] and [16], this is a good first order approach until the engine inlet and exit velocities can be modeled with reliable data. Figure 7 depicts the mesh density and surface total pressure at Mach 0.500. This figure validates the removal of the engine nacelle and pylon from the domain, based on resulting increased pressure on the wing upper surface and subsequent adverse effect on the pitch stability of the vehicle.

The initial mesh resulted in a structured-mesh domain which contained 15.4 million elements, followed by progressively coarser domains with 11.4, 9.2 and 5.4 million elements. To capture the boundary layer, six prismatic layered cells were used, and were varied in thickness throughout the grid dependency study. Ultimately, the study revealed that a domain of 9.2 million cells provided nearly equal accuracy, similar convergence and with good computational time, when compared to the finer mesh domains. At low α and β, Lift, Pitch Moment, Yaw Moment and Roll Moment were within 5-10% of the Low-Order method results. Convergence of the mass, momentum and energy equations typically occured within 1000-1500 iterations, with all residuals flat-linning at or below 1E-5.

2.2.2 Physics

Based on previous experience in aircraft studies using STAR-CCM+, the physics was modeled using a Reynolds Averaged Navier Stokes (RANS) solver, with a 2^{nd} order segregated flow model (convection/ diffusion). A two-equation turbulence model was applied with the assumption that the flow characteristics to be modeled were of similar Mach Number, Altitude and surface roughness (thereby imposing a critical Reynolds Number) for the operating conditions of the vehicle. An SST (Menter) $k-\omega$ model was applied, with compressibility correction and all y+ wall treatment. Both, previous studies, and available literature, reveal that the SST model was more appropriate for this aerospace application as it blends the near-wall turbulence $k-\omega$ model with the transition region captured by the $k-\varepsilon$ model. Based on standard day atmospheric conditions, the model was run at: Mach 0.183 at Sea-Level (Takeoff and Landing), Mach 0.500 at 5 km (Climb), and Mach 0.738 at 10 km (Cruise), for α and β combinations of [0, 4, 8, 12] and [0, 2, 6] degrees, respectively.

2.2.3 Initial Results

The Mach 0.500 test cases were important to this study because the lower-order results were obtained using an in incompressible solver. Once a good correlation was obtained between the lower-order method and the CFD, a full test matrix was examined. Examining first the higher Mach numbers, at the optimized cruise condition, Mach 0.73. Followed by more computationally expensive, low Mach numbers, Mach 0.183, where a low-Reynolds number correction model was applied. In this flight regime, the BWB is prone to lateral-instabilities due to high angles-of-attack combined with asymmetric gust loads or cross-wind. Cases were investigated in the $\alpha = 10^o - 16^o$, and $\alpha = 30^o - 40^o$ deep-stall range, see figure 8. Initial results of pitch-moment and yaw-moment are presented in figures 9 & 10, respectively. Both figures reveal good correlation of the VLM results compared to the CFD results. The linearity of the VLM results is attributed to the inability of the vortex lattice model to predict and solve for flow separation and asymmetry. In contrast, the CFD results display non-linear trends as expected, demonstrating the effects of flow separation and angularity as the angle-of-attack and angle-of-side-slip are increased. Both, the pitch-moment and the yaw-moment are stable and compare well with similar size aircraft coefficients available in literature [13] and [18], namely the Lear-23. As expected, the initial results indicate that the BWB is marginally stable at higher off-zero conditions, and the need for stability augmentation is apparent.

2.3 Lateral-Directional Control

Following the initial investigation of α and β combination sweeps, a differential control actuator was investigated based on the research by Staelens ([24], [25], [26] and [37]) investigating the pitch-moment stability created by belly-mounted flaps. While Staelens research focused on the longitudinal stability with simultaneous, *symmetric*, deployment of various belly-flap configurations, this investigation is in the *asymmetric* deployment of similar belly-flaps for lateral-directional control. This design is common to model-airplane enthusiasts, and has appeared in published literature as early as the late-1980s [7] & [27], for slope-soar flying wing gliders. However, at the present, no literature exists on the differential deployment of belly-flaps on the BWB configuration. Initial CFD analysis was performed on the differential; belly-flaps located at 60% of the root chord, a flap chord length equal to 5% of the mean-aerodynamic-chord (MAC), with 30% span of the total vehicle wing span, and at 90 degree deflection angles — based on the work done by Staelens.

In addition to the belly-flap, an outboard wing flap, similar to the spoiler-slot-deflector [5] shown in figure 11 was also investigated. In this design the flap is deployed from the bottom wing surface, with a through-slot to the top wing surface. This slotted flap, when deployed at high angle-of-attack, allows the airflow on the bottom wing surface to enter the flow on the top surface, thereby energizing the boundary layer and ultimately restoring the effectiveness of the control surface. This flap was not modeled in the low-order analysis for obvious thru-flow modeling reasons. However, in the initial CFD results, this slotted flap has shown promise of restored aileron roll control at high angle-of-attack.

3 CONCLUDING REMARKS

The present investigation into the lateral-directional stability of the BWB configuration, reveals that higher-order methods confirm the findings, with increased accuracy, compared with the lower-order methods. Initial results reveal that the present configuration is statically stable, however with 25-40% reduced stability when compared with the BizJet coefficients [23], [13],[18]. Initial belly-flap analysis improves this stability delta to a range of 10-18%. CFD analysis is presently continuing to validate the use of belly-flap control surfaces for lateral-directional control, and the results will be presented in a future report.

Both the advantages and challenges were presented with the original design of a BizJet class BWB configuration, with potential design advantages which could be incorporated into future industrial applications of the BWB design. This is a first level attempt to prove the results of the first order method using more accurate CFD based results. Further confidence in the design will be achieved when the computed results in hand are validated through wind tunnel testing.

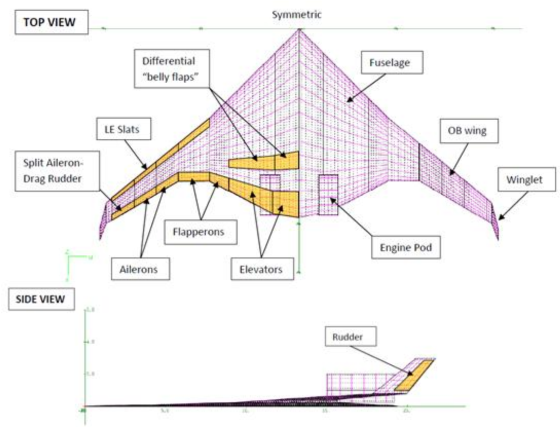

Figure 6: BWB vortex lattice model control surfaces.

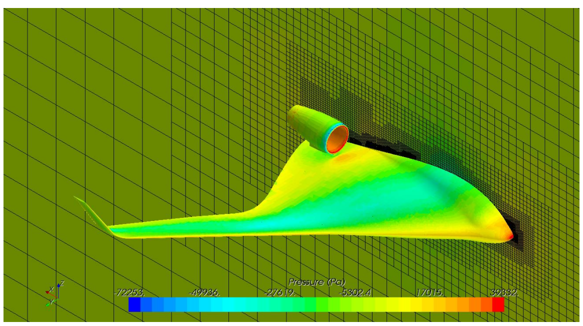

Figure 7: BWB CFD model: mesh and surface pressure.

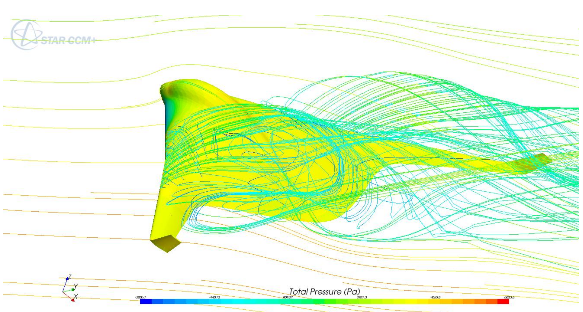

Figure 8: Deep-stall stability: Back view.

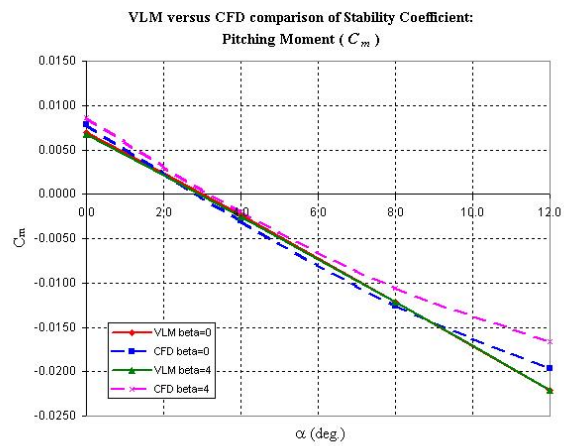

Figure 9: Pitch Moment Coefficient Comparison.

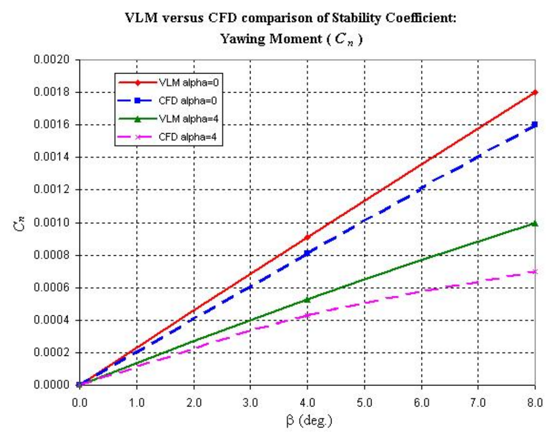

Figure 10: Yaw Moment Coefficient Comparison.

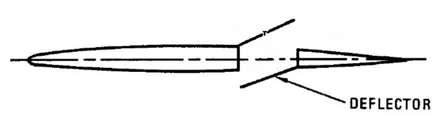

Figure 11: Spoiler Slot Deflector.

REFERENCES

[1] J.M. Buffington, "Tailless Aircraft Control Allocation", AIAA-97-3605.

[2] M.B. Carter, *et.al.*, "Blended-Wing-Body Transonic Aerodynamics: Summary of Ground Tests and Sample Results (Invited)", A47th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, 5-8 January 2009, Orlando, Florida. AIAA-2009-935.

[3] Composite Engineering, Inc., *BQM-167 Aerial Target*, <http://www.compositeeng.com>.

[4] M. Drela, H. Youngren, AVL 3.26 User Primer. MIT Aero & Astro. 29 Apr 2006.<http://web.mit.edu/drela/Public/web/avl/>.

[5] D.E Hoak *et.al.*, USAF Stability & Control DATCOM, Flight Control Division, Air Force Flight Dynamics Laboratory, Wright Patterson Air Force Base, Ohio, Vol 1-3., April 1979, AFFDL-TR-79-3032.

[6] A. Iniguez de Heredia, H. Frichmelt, "GN&C Concepts for a Blended Wing Body", AIAA Guidance, Navigation, and Control Comference, 15-18 August 2005, San Francisco, California. AIAA-2005-6351.

[7] B. Kuhlman and B. Kuhlman, "On the 'Wing... the book", vol. 1-4, B^2Streamlines, Washington, 1993-2004.

[8] T. Leman, *et.al.*, "λ_1 Adaptive Control Augentation System for the X-48B Aircraft", AIAA Guidance, Navigation, and Control Comference, 10-13 August 2009, Chicago, Illinois. AIAA-2009-5619.

[9] R.H. Liebeck, *Design of the Blended Wing Body Subsonic Transport*, AIAA Journal of Aircraft, Vol. 41, No. 1, January-February 2004. AIAA-9084-368.

[10] P.D. McKeehen, "Genesis Non-Realtime Simulation of a Tailless Aircraft", AIAA-98-4159.

[11] B. Mialon, T.Fol, and C. Bonnaud, "Aerodynamic Optimisation of Subsonic Flying Wing Configurations", 20th AIAA Applied Aerodynamics Conference, 24-26 June 2002, St. Louis, Missouri. AIAA-2002-2931.

[12] A.M. Morris, C.B. Allen, T.C.S. Rendall, "Aerodynamic Optimisation of Modern Transport Wing using Efficient Variable Fidelity Shape Parameterisation", 47th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, 5-8 January 2009, AIAA-2009-1277.

[13] R. Nelson, *Flight Stability and Automatic Control*, McGraw-Hill, 2nd ed., 1997.

[14] S. Peigin, *et.al.*, *Computational Fluid Dynamics Driven Optimisation of a Blended-Wing-Body Aircraft*, AIAA Journal, Vol. 44, No. 11, November 2006. AIAA-19757-954.

[15] N. Qin, *et.al.*, *Spanwise Lift Distribution for a Blended Wing Body Aircraft*, AIAA Journal of Aircraft, Vol. 42, No. 2, March-April 2005. AIAA-4229-140.

[16] N. Qin, "Aerodynamic Studies for Blended Wing Body Aircraft", 9th AIAA/ISSMO Symposium on Multidisciplinary Analysis and Optimisation, 4-6 September 2002, Atlanta, Georgia. AIAA-2002-5448.

[17] C.D. Regan, "In-Flight Stabilty Analysis of the X-48B Aircraft", AIAA Atmospheric Flight Mechanics Conference and Exhibit, 18-21 August 2008, Honolulu, Hawaii. AIAA-2008-6571.

[18] J. Roskam and C.E. Lan, *Airplane Flight Dynamics and Automatic Flight Controls*, Darcorporation, Vol.1-2, 2003.

[19] T. Risch, *et.al.*, "X-48 Flight-Test Progress Overview", A47th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, 5-8 January 2009, Orlando, Florida. AIAA-2009-934.

[20] S. Saephan, C.P. van Dam, *Determination of Wing-Only Aircraft Tumbling Characteristics Through Computational Fluid Dynamics*, AIAA journal of Aircraft, Vol. 45, No. 3, May-June 2008, AIAA-33730-763.

[21] Scaled Composites, <http://www.scaled.com>.

[22] O. Schrenk, "A simple approximation method for obtaining the spanwise lift distribution", National Advisory Committee for Aeronautics, April 1940, NACA-TN-948.

[23] P. Soderman and T. Aiken, "Full-Scale Wind-Tunnel Tests of a Small Unpowered Jet Aircraft With a T-Tail", NASA Ames Research Center, November 1971, NASA-TN-D-6573.

[24] Y.D. Staelens, R.F. Blackwelder and M.A. Page, "Novel Pitch Control Effectors for a Blended-Wing-Body Airplane in Takeoff and Landing Configuration", January 2007, AIAA-2007-68-229.

[25] Y.D. Staelens, R.F. Blackwelder and M.A. Page, "Study of Belly-flaps to Enhance the Lift and Pitching Moment Coefficient of a Blended-Wing-Body Airplane , June 2007, AIAA-2007-4176.

[26] Y.D. Staelens, "Study of belly-flaps to Enhance the Lift and Pitching Moment Coefficient of a Blended-Wing-Body Airplane in Landing and Takeoff Configuration", Ph.D. Dissertation, Aerospace and Mechanical Engineering Dept., Viterbi School of Engineering, University of Southern California, Los Angeles, California, December 2007.

[27] H.A. Stokely, *et.al.*, "Soar-Tech", vol. 1-10, Herk Stokely (Editor), SoarTech Journal, Virginia, 1982-1993.

[28] A. Valiyff, M. Arjomandi, "An Investigation into the Aerodynamic Efficiency of a Tailess Aircraft", 47th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, 5-8 January 2009, Orlando, Florida. AIAA-2009-1436.

[29] D.D. Vicroy, "Blended-Wing-Body Low-Speed Flight Dynamics: Summary of Ground Tests and Sample Results (invited)", 47th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, 5-8 January 2009, Orlando, Florida. AIAA-2009-933.

[30] S. Wakayama, "Multidisciplinary Optimization of the Blended-Wing-Body", 7th AIAA Symposium on Multidisciplinary Analysis and Optimization, St Louis, MO, September 1998, pp. 1771-1779, AIAA-98-4938.

[31] S. Wakayama, I. Kroo, "The Challenge and Promise of the Blended-Wing-Body Optimisation", 7th AIAA Symposium on Multidisciplinary Analysis and Optimization, St Louis, MO, September 1998, pp. 239-250, AIAA-98-4736.

[32] S. Wakayama, I. Kroo, *Subsonic Wing Planform Design Using Multidisciplinary Optimization*, Journal of Aircraft, Vol. 32, No. 4, Jul.-Aug. 1995, pp.746-753.

[33] S. Wakayama, M. Page and R. Liebeck, "Multidisciplinary Optimization on an Advanced Composite Wing", 6th AIAA Symposium on Multidisciplinary Analysis and Optimization, Bellevue, WA, September 4-6, 1996, AIAA-96-4003.

[34] S. Wakayama, K. Willcox, *Simultaneous Optimisation of a Multiple-Aircraft Family*, AIAA Journal of Aircraft, Vol.40, No. 4, July-August 2003, AIAA-2002-1423.

[35] R.T. Whitcomb, "A Study of the Zero-Lift Drag-Rise Characteristics of Wing-Body Combinations Near the Speed of Sound", National Advisory Committee for Aeronautics, 1952. NACA-RM-L52H08.

[36] R.M. Wood and S.X.S. Bauer, "Flying Wings/Flying Fuselages", 39th AIAA Aerospace Sciences Meeting & Exhibit, Reno, Nevada, 8-11 January 2001, AIAA-2001-0311.

[37] D.S. Yann, *et.al.*, "Computer Simulation of Landing, Takeoff and Go-around of a Blended-Wing-Body Airplane with Belly-Flaps", AIAA Conference, 7-10 January 2008, Reno, Nevada, AIAA-2008-297.