Blended-Wing-Body Transonic Aerodynamics: Summary of Ground Tests and Sample Results (Invited)

Melissa B. Carter* and Dan D. Vicroy†
NASA Langley Research Center, Hampton, VA 23681

Dharmendra Patel‡
Boeing Phantom Works, Huntington Beach, CA 92647

The Blended-Wing-Body (BWB) concept has shown substantial performance benefits over conventional aircraft configuration with part of the benefit being derived from the absence of a conventional empennage arrangement. The configuration instead relies upon a bank of trailing edge devices to provide control authority and augment stability. To determine the aerodynamic characteristics of the aircraft, several wind tunnel tests were conducted with a 2% model of Boeing's BWB-450-1L configuration. The tests were conducted in the NASA Langley Research Center's National Transonic Facility and the Arnold Engineering Development Center's 16-Foot Transonic Tunnel. Characteristics of the configuration and the effectiveness of the elevons, drag rudders and winglet rudders were measured at various angles of attack, yaw angles, and Mach numbers (subsonic to transonic speeds). The data from these tests will be used to develop a high fidelity simulation model for flight dynamics analysis and also serve as a reference for CFD comparisons. This paper provides an overview of the wind tunnel tests and examines the effects of Reynolds number, Mach number, pitch-pause versus continuous sweep data acquisition and compares the data from the two wind tunnels.

Nomenclature

C_D	=	drag coefficient
C_L	=	lift coefficient
C_m	=	pitching moment coefficient
Re	=	Reynolds number based on mean aerodynamic chord
α	=	angle of attack, degrees
β	=	sideslip angle, degrees
AEDC 16T	=	Arnold Engineering Development Center 16-Foot Transonic Tunnel
BLI	=	Boundary Layer Ingestion
BWB	=	blended-wing-body
CFD	=	computational fluid dynamics
ESP	=	electronically-scanned pressure
NTF	=	NASA Langley Research Center National Transonic Facility
q/E	=	Dynamic pressure divided by the model material modulus of elasticity

* Aerospace Engineer, Configuration Aerodynamics Branch, M/S 499, AIAA Senior Member.
† Senior Research Engineer, Flight Dynamics Branch, M/S 308, AIAA Associate Fellow.
‡ Aerospace Engineer, Flight Sciences, M/S H045-E407, AIAA Member.

I. Introduction

In the last decade, there has been a growing interest in the Blended-Wing-Body (BWB) concept as a way to deal with the rising cost of fuel and environmental concerns such as emissions and noise. The BWB got its start from a study sponsored by NASA in 1994 to investigate the technical and commercial feasibility of the concept and, in the 2002 AIAA Wright Brothers Lecture[1], Liebeck provides an excellent review of the results of that study. This and other studies[2,3,4] have indicated fuel savings on the order of 30% for the BWB in comparison with other large aircraft (e.g., B747, A380), along with significant reductions in size and weight for a given mission. In addition to the reduced emissions associated with a lower fuel-burn rate, another environmental benefit would be a reduction in the perceived ground level noise. Most of the configurations studied have engines mounted near the trailing edge on the upper surface of the wing, which tends to shield the inlet noise[5] and avoids the issue of exhaust noise reflecting off the lower surface of the wing, as with current large transports.

While these studies indicated some significant benefits for the BWB relative to the conventional "tube and wing" configurations, they also examined a number of challenges that would have to be solved before the aircraft would be technically and economically viable. The elimination of a conventional empennage makes requirements such as trim (at cruise and take-off/landing), low deck angle, and engine-out control more difficult to address. The non-circular fuselage cross-section presents a challenge for handling the pressurized cabin loads and has spawned several new structural approaches that will most likely require composite materials. As Liebeck points out, significant progress has been made on many of the above concerns and research on technologies applicable to a BWB continues within the NASA Fundamental Aeronautics Program, Subsonic Fixed Wing Project.

As mentioned, the aircraft does not have a conventional empennage arrangement so the configuration instead relies upon a bank of trailing edge devices to provide control authority and augment stability. To determine the stability and control characteristics of the aircraft, several wind tunnel investigations were conducted on a 2% model of Boeing's BWB-450-1L configuration. The tests were conducted in the NASA Langley Research Center's National Transonic Facility (NTF) and the Arnold Engineering Development Center's 16-Foot Transonic Tunnel (AEDC 16T). The effectiveness of the trailing edge devices (elevons, drag rudders and winglet rudders) were tested at various angles of attack, sideslip angles, and Mach numbers (subsonic to transonic speeds). These data, along with results from previous tests of this configuration in NASA Langley's 14- by 22-Foot Subsonic Tunnel[6,7] will be used to develop a high fidelity simulation model for flight dynamics analysis and also as a reference for CFD comparisons.

Fig. 1 Pylon mounted nacelles with winglets shown on blade strut.

Fig. 2 **BWB model with boundary layer ingestion nacelles.**

Fig. 3 BWB model with pylon mounted nacelles.

II. BWB Wind Tunnel Model

The 2-percent scale model of the Boeing BWB-450-1L configuration was designed for cryogenic testing in the National Transonic Facility (NTF) wind tunnel (Fig. 1). The goal of the project for which this model was originally built was to verify an improved boundary layer ingestion nacelle integration design. Since the nacelles are on the aft portion of the centerbody, the blade sting interface with the model was designed to minimize the impact on the flow on region of interest[10]. The blade is connected to the balance that is attached to the model via a strut block that can be changed to allow testing at various sideslip angles. The model and mounting sting were both made out of a maraging steel with a model surface finish of 2–4 micro-inches rms. The model included multiple interchangeable parts for testing of various configurations such as wing only (no nacelles or winglets), flow-through boundary layer ingestion nacelles (Fig. 2), or pylon-mounted nacelles (Fig. 3). There are 14 elevons (7 on each side) that can be individually deflected to represent the 18 elevons of the full-scale configuration (Fig. 4). The two outboard split elevons of the 450-1L configuration are combined into a single control segment for the wind tunnel model. This outboard control segment is comprised of upper and lower control surfaces which are capable of being deflected together as elevons or split apart as drag rudders. All the elevons have interchangeable fixed deflections of -10, -2.5, 5, and 10 degrees. There are also two drag rudder parts with deflections of ±10 and ±30 degrees. In addition, the wings tips could accommodate a winglet (with or without rudder deflected) or just a

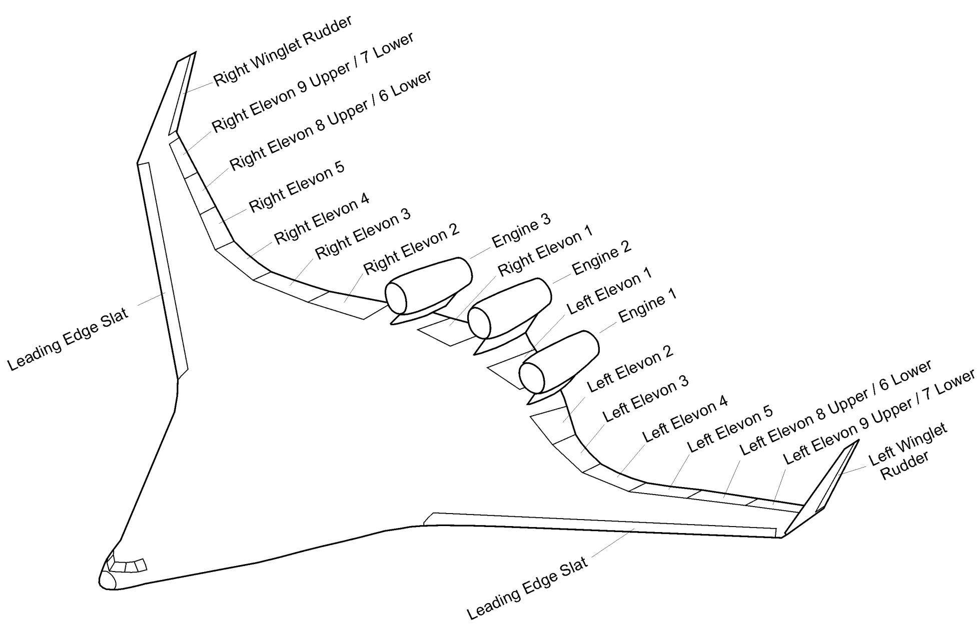

Fig. 4 BWB full scale configuration control surfaces

rounded wing tip. The model, including all the interchangeable parts, had over 400 pressure ports. However, due to limited space within the model only 4 electronically scanned pressure (ESP) modules could be accommodated resulting in only 248 pressure ports monitored at a time. None of the pressure data will be presented in this paper.

III. NTF Tests

A. NTF Facility

Two experimental evaluations of the BWB configuration were conducted in the National Transonic Facility (NTF) at the NASA Langley Research Center.[8] The NTF is a pressurized, cryogenic, fan-driven, closed-circuit, continuous-flow wind-tunnel. The test section's cross-section is 8.2 ft by 8.2 ft, and has a length of 25 ft (Fig. 5). The floor and ceiling of the test section are slotted (6 percent open), while the sidewalls are solid. The facility is able to operate from 90 to 120 °F using dry air, or from -250 to 120 °F using nitrogen gas. The NTF can test at Mach numbers ranging from 0.2 to 1.2, absolute pressures ranging from 15 to 130 psi, and a maximum Reynolds number of $146x10^6$ per foot at Mach 1.0.

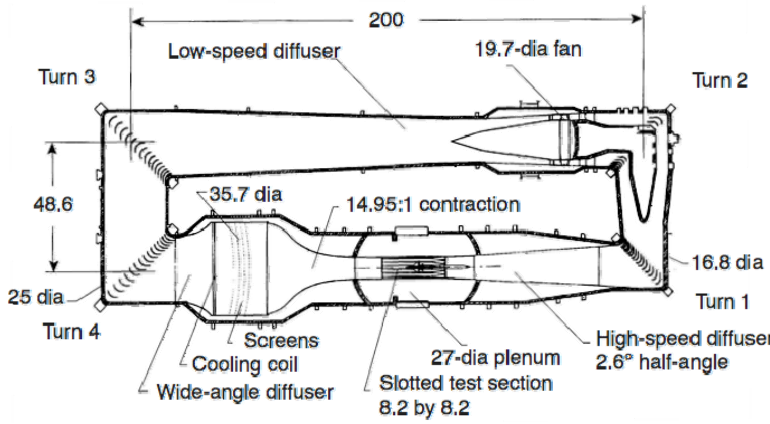

Fig. 5 The National Transonic Facility circuit

B. Boundary Layer Ingested Nacelle Study

The first entry of this BWB model into NTF was conducted in 2004. The project's primary goal was to evaluate CFD design methods for use in propulsion/airframe integration and confirm their effectiveness through a high-Reynolds number wind tunnel test. The study was conducted using flow through boundary layer ingestion (BLI) nacelles. The CFD design work focused on the cruise conditions of M = 0.85 with a Reynolds number of 75 million. Although the study was focused on the design conditions, experimental data were obtained over a range of Reynolds number (2.4 to 75 million) and Mach number (0.2 to 0.88) on four different configurations (no nacelles, pylon-mounted nacelles, BLI nacelles, and redesigned BLI nacelles). A NASA CFD flow solver, USM3D[9], was shown to be sufficiently accurate for use in design, with good correlation demonstrated between its predictions and wind tunnel data from the NTF test. Particularly encouraging was the experimental validation of the CFD prediction of the fairly small changes in drag and local pressures between the baseline and design configurations. The 1.3% reduction in drag due to the redesign of the BLI nacelle region was confirmed with experimental data from the NTF test. The repeatability of the experimental data within the region around the cruise angle of attack was sufficient to validate the predicted drag reduction. Further information concerning this study can be found in references 10 and 11.

C. NTF Transonic Stability and Control Test

The second NTF test of this model was conducted in 2006 and focused on the Stability and Control (S&C) characteristics of the configuration at various Reynolds numbers and Mach numbers, including cruise conditions. Force and pressure data was acquired at 27 different test conditions in air and cryogenic modes. Mach number varied from 0.2 to 0.86 at Reynolds numbers of 3.7, 10, 16, 28, 42 and ~70 million. The intended maximum test Mach number was 0.97, however, increased model dynamics above Mach 0.86 exceeded balance safety thresholds and precluded testing at higher Mach numbers.

Table 1 shows an overview of the completed test plan. The "full configuration" was the wing with pylon mounted nacelles and winglets, and no control surface deflections. Grit was applied at the beginning of the test to the model, pylons, winglets and strut, during the configuration build-up phase. The S&C phase was done with the model transition free. The grit on the strut, which remained on the entire test was

1.25 inches from the leading edge and consisted of a ¼ inch wide strip of #60 grit which had an average height of 0.0175 inches.

To capture both the positive and negative sideslip effects while keeping the model at a fixed sideslip angle, the controls were first deflected on one side only followed by corresponding deflections on the other side only. This effectively allowed the mapping of an asymmetric control deflection to both positive and negative sideslip angles. By deflecting one side at a time only, longitudinal and lateral/directional effects of each deflection are measured. The exception to the use of this technique was the winglet rudder since only one of the winglets was built with nonzero rudder deflections. Therefore, sideslip effects on the winglet rudder deflections were only tested in one direction. All data presented in this report are without control deflections.

Table 1 BWB stability and control test conditions in NTF

Air Runs	**Re (Millions)**	**Mach**	**α, deg.**	**Grit**	**β, deg.**
Wing	10	0.2 – 0.86	-2 to 16	on	0
Wing and winglets	10	0.2 – 0.86	-2 to 16	on	0
Full configuration	3.7, 10, 16	0.2 – 0.86	-2 to 16	on/off	0
Full configuration with deflections of:					
Elevon 1 (-10, -2.5, 5, 10)	3.7, 10, 16	0.2 – 0.86	-2 to 16	off	0
Elevons 2-5 (-10, -2.5, 5, 10)	10	0.2 – 0.86	-2 to 16	off	-2, 0, 2
Elevon 4 (-2.5, 5)	10	0.2 – 0.86	-2 to 16	on/off	0
Elevons 6-9 (-10, -2.5, 5, 10, ±10, ±30)	10	0.2 – 0.86	-2 to 16	off	-2, 0, 2
Winglet rudder (-10, 5, 10)	3.7, 10, 16	0.2 – 0.86	-2 to 16	off	0, 2
Cryogenic Runs					
Wing	67	0.2 – 0.86	-2 to 10	off	0
Full configuration	42.5, 69.8	0.2 – 0.86	-2 to 16	off	0
Full configuration with deflections of:					
Elevon 4 (-2.5, 5)	69.8	0.5 – 0.86	-2 to 10	off	0
Elevons 6-9 (-10, -2.5, 5, 10, ±10, ±30)	69.8	0.5 – 0.86	-2 to 10	off	0
Winglet rudder (-10, 5, 10)	69.8	0.5 – 0.86	-2 to 10	off	0

D. Reynolds Number Effects with CFD comparison

The BWB configuration represented by this model is part of a generation of designs not previously tested at transonic speeds. All of the wing design, as well as the propulsion airframe integration work, was done using CFD. The NTF BLI test was the first opportunity to validate the results of the CFD codes USM3D and OVERFLOW, which were used by NASA and Boeing in respective order. As previously noted, although the model originated in a program for testing BLI nacelles, modularity allowed the testing of the wing alone configuration as well as the pylon mounted nacelles after which the wind tunnel data may be compared with CFD predictions. Of course, with wind tunnel data, installation effects must be taken into account. The low speed testing had confirmed the expectation that a BWB configuration was particularly sensitive to model support installation effects since there is no part of the body that is non-lifting.[12] As discussed in reference 12, the low speed data obtained with the 3% low speed model had a great deal of interference due to the support system. It also did not match the low speed data acquired on the 2% model at the NTF.

Because of the concern over the installation effects, a quick analysis was conducted prior to the test. It suggested that the NTF installation was indeed an excellent arrangement with minimal interference. After the test, this was followed up by a major effort to quantify the installation effects and create a set of corrections. Presented in the following are a set of comparisons of the CFD and the wind tunnel data at the cruise Mach number. The wind tunnel data is uncorrected for tunnel or installation effects. The CFD data represents the wing and the entire support structure, the latter consisting of the blade, the sting, and the arc sector. It also includes the tunnel walls with porosity to account for the slots and the footprint of the blade on the model surface area.

As can be seen in figure 6, CFD predictions match the wind tunnel data fairly well at the limited conditions examined (note the Fig. 6, and all subsequent data plots in this paper have the scales removed due to the proprietary nature of the data). Lift is slightly underpredicted but drag and pitching moment predictions are better. CFD predictions were within 0.3 counts in drag coefficient, less than 5 counts in pitching moment coefficient, and within 15 counts in lift coefficient. The test data repeatability at this

Reynolds number is within 0.4 counts in drag coefficient, less than 1 count in pitching moment coefficient, and slightly over 2 counts in lift coefficient. The pitching moment coefficient data is resolved around the mid-center of gravity location. The pitching moments show that the characteristics of the BWB-450-1L are comparable to a conventional swept wing transport with a tail. Both are stable at lower angles of attack with a pitch-up in the buffet region. Finally, it should be noted that the 75 million Reynolds number is the maximum possible with the load limits for this balance. However, flight Reynolds number is more than twice that, around 180 million.

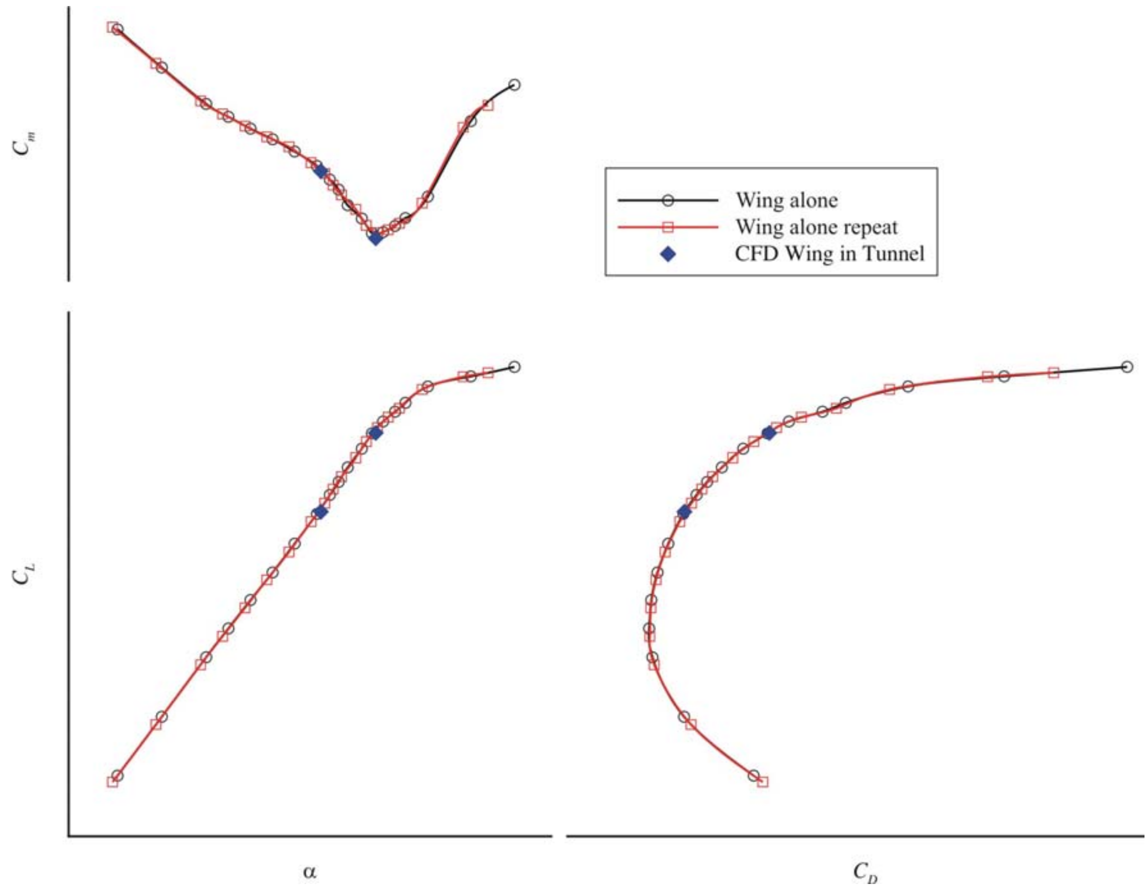

Fig. 6 Wind tunnel to CFD comparison of lift, drag and pitching moment with angle of attack (Re=75 x10^6, Mach=0.85).

While the NTF BLI test was to validate CFD tools and design methodologies, the NTF S&C test was to collect the requisite data for a transonic database. Confidence in the data from the BLI entry was increased by the good match with CFD predictions. The S&C test data was validated by comparisons with the data obtained in the first entry. Test to test repeatability for lift and pitching moment is presented in figure 7. The overall repeatability in cruise region is excellent; within 0.5 counts in drag coefficient, 1 count in pitching moment coefficient, and 2 counts in lift coefficient. However, the problems associated with using grit for transition fixing manifest themselves in the difference near the region of the pitch break at high angles of attack. Grit is notoriously difficult to apply but, because vinyl trip dots were not available in the required height for the 16 million Reynolds number runs, it was decided early in the test program to use grit. The possible unevenness of the grit application is cause for the prominent difference between the pitch break characteristics from the two tests. This issue re-appeared in the AEDC entry as well.

Despite expanding the axial load limit for the NTF S&C entry, data above Mach 0.86 could not be collected due to excessive model dynamics, as noted earlier. To get to the desired Mach 0.97, the model was later installed in the AEDC 16T using the same support hardware and balance used in the NTF entries which remained a good source of data for CFD validations and Reynolds number effects.

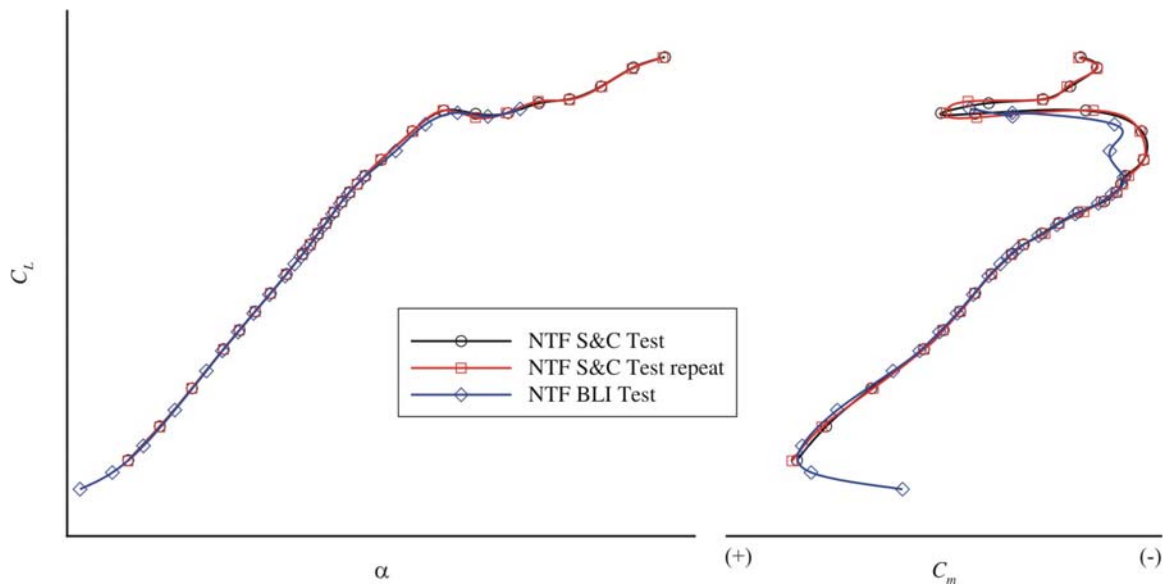

Fig. 7 NTF test to test comparison of wing alone lift and pitching moment with angle of attack (Re=10 x10^6, Mach = 0.85).

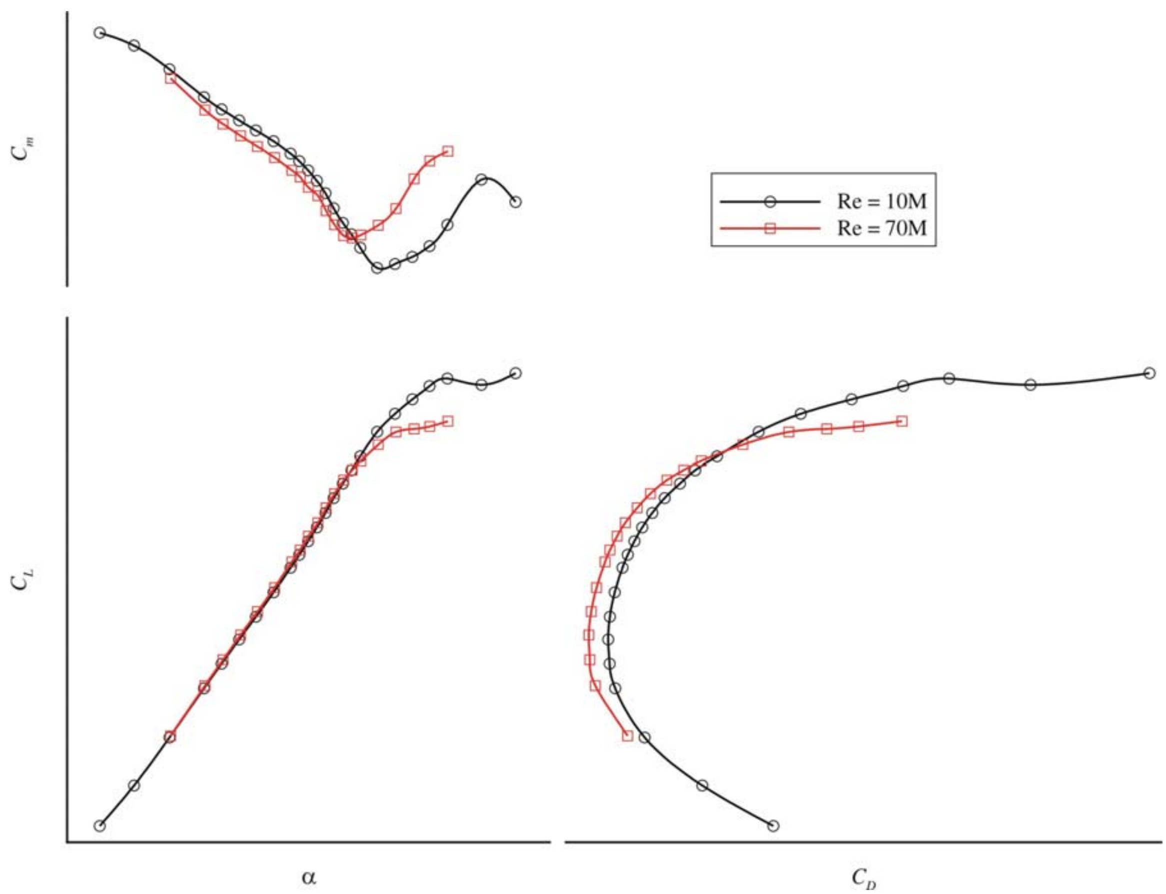

Fig. 8 Reynolds number effects on lift, drag and pitching moment with angle of attack (Full Configuration, Mach = 0.85).

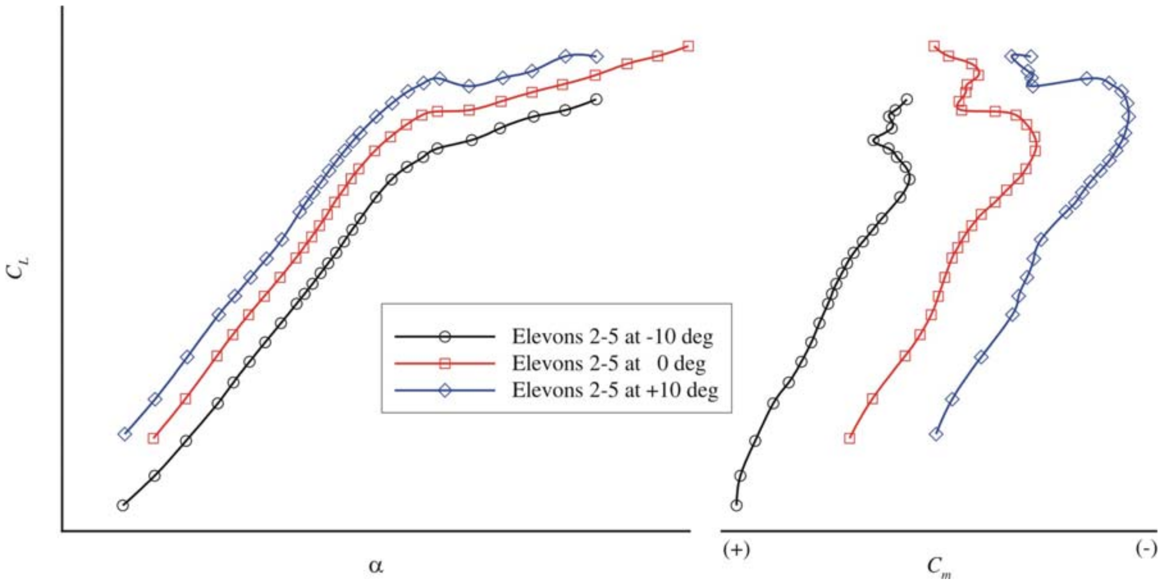

Fig. 9 Effects of elevons 2-5 on lift and pitching moment (Full configuration, Mach = 0.85, transition free).

Figure 8 shows the changes in lift, drag and pitching moment due to Reynolds number. It compares data at 10 million Reynolds number with fixed transition to data at 70 million. There is a significant change in the drag and pitching moment in the linear lift region but the most dramatic difference is in the location of the pitch break and lift roundover. Both the 10 million and the 70 million data were taken at a constant q/E, a way of isolating the Reynolds number effects from the aeroelastic effects, so the change in the pitch break is an adverse consequence of the increase in Reynolds number. The data taken at 16 million Reynolds number was not at the same q/E and aeroelastic corrections would have to be implemented before it can be used in further defining the Reynolds number effects.

As mentioned earlier, the basic characteristics of the BWB are similar to a conventional swept wing transport with a tail. The BWB relies upon trailing edge elevons for control authority and figure 9 is a chart showing the effects of deflection of elevons 2 through 5 on one side up to 10 degrees trailing edge up and down. It can be seen that the elevons remain effective throughout the angle of attack range and no reversals are present.

Fig. 10 Installation of 2% BWB model in AEDC 16T (Wing only configuration).

IV. AEDC 16T Test

A. AEDC 16T Facility

The 16-foot transonic tunnel at the Arnold Engineering Development Center is a closed-loop, continuous flow, variable density tunnel.[13] The tunnel is capable of testing at Mach numbers from 0.06 to 1.60 with a stagnation pressure range of 120 to 4,000 psfa. The facility can obtain Reynolds numbers from approximately 0.03 to 7.3 million per foot. The test section, which is a removable test cart, is a 40-foot long with a 16-ft square cross-section. The walls are a fixed 6 percent porosity with 0.75-inch diameter holes. The test section is enclosed in a plenum chamber, which is evacuated at transonic and supersonic conditions to remove the tunnel wall's boundary layer through the test section wall porosity.

B. AEDC 16T Transonic Stability and Control Test

The BWB wind tunnel test in AEDC 16T was conducted in 2007 and focused on the Mach effect on the stability and control characteristics of the aircraft (Fig. 10). Force and moment, as well as pressure data were acquired at 25 different test conditions. Mach number varied from 0.5 to 0.97 at chord Reynolds numbers of 5 and 10 million, respectively.

Table 2 shows an overview of the completed test plan. As before, the "full configuration" consisted of the wing with pylon mounted nacelles and winglets, and no control surface deflections Grit was applied at the beginning of the test to the model, pylons, winglets and strut as was the case for the NTF test. The configuration build-up was done with transition fixed while the full configuration was run with transition both fixed and free. All control surface deflected runs were done transition free. As with the NTF test, all of the deflections were conducted on only one side of the model in order to isolate the lateral/directional effects of each deflection in addition to the longitudinal effects.

Table 2 BWB stability and control test conditions in AEDC 16T.

Configurations:	Re (Millions)	Mach	α, deg.	Grit
Wing	10	0.6-0.90	-3 to 10	on
Wing and winglets	10	0.6-0.90	-3 to 10	on
Full configuration	5, 10	0.5-0.97	-3 to 10	on/off
Full configuration with deflections of:				
Elevon 1(-10, -2.5,5,10)	5	0.5-0.97	-3 to 10	off
Elevons 2-5 (-10, -2.5, 5,10)	5	0.5-0.97	-3 to 10	off
Elevons 6-9 (-10, -2.5, 5, 10, ±10, ±30)	5	0.5-0.97	-3 to 10	off
Winglet rudder (-10, 5, 10)	5	0.5-0.97	-3 to 10	off

C. Pitch-Pause versus Continuous Sweep

The AEDC 16T normally uses a continuous sweep method for obtaining data at different angles of attack. This differs from the NTF pitch-pause method where the model is moved to the desired angle of attack and paused for a set period of time while a time averaged data measurement is recorded. The continuous sweep method can provide more data in shorter time but may not provide repeatable data in unsteady flow regions. To ensure that the data obtained using the continuous sweep method would be as robust as the pitch-pause data obtained from NTF, both methods were used at the beginning of the AEDC test for the wing alone configuration. The continuous sweep was conducted at a rate of 1.0 degree per second. Figure 11 shows a comparison of the lift, drag and pitching moment data using both methods. In general there is little difference between the data with the largest differences occurring at the highest lift coefficients where the flow is less steady. The ability to quickly acquire the data was critical to completing the test plan within budget. Therefore, the remainder of the AEDC test was conducted using the continuous sweep data acquisition method.

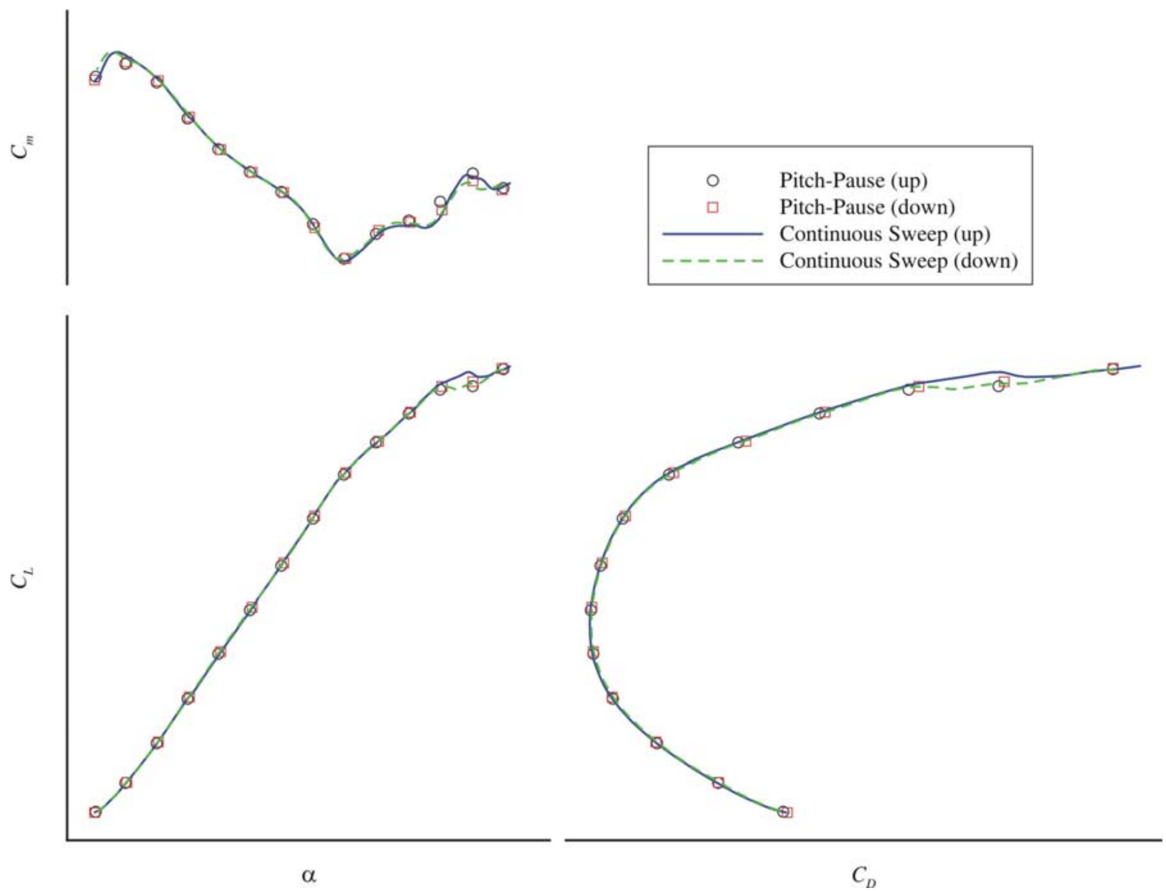

Fig. 11 Lift, drag and pitching moment comparison of pitch-pause and continuous sweep methods for the wing alone configuration (Re=10x10^6, Mach = 0.85, grit applied).

D. Mach Effect

Characterizing the effect of Mach number was the primary purpose for the BWB test in AEDC 16T. Figure 12 shows the drag rise and pitch break with increased Mach number from both wind tunnel tests at a constant lift coefficient of 0.2 and a Reynolds number of 10 million. The data from the AEDC test provided a clear definition of the drag rise and good agreement with the NTF data at Mach 0.85. The pitching moment agreement with NTF diminishes at the lower Mach numbers. The AEDC pitching moment data showed the anticipated reduction in pitching moment with increased Mach but was then followed with an unanticipated large increase. Figure 13 shows the pitch effectiveness derived from the large deflections (+10 and -10 degrees) of elevons 2 through 5. While the effectiveness does vary with Mach number it does not reverse throughout the Mach range. CFD studies are currently ongoing to provide insight into the flow physics driving the higher Mach pitch change. Once a transonic simulation has been developed, studies can be undertaken to determine the impact of the pitch variation to handling qualities.

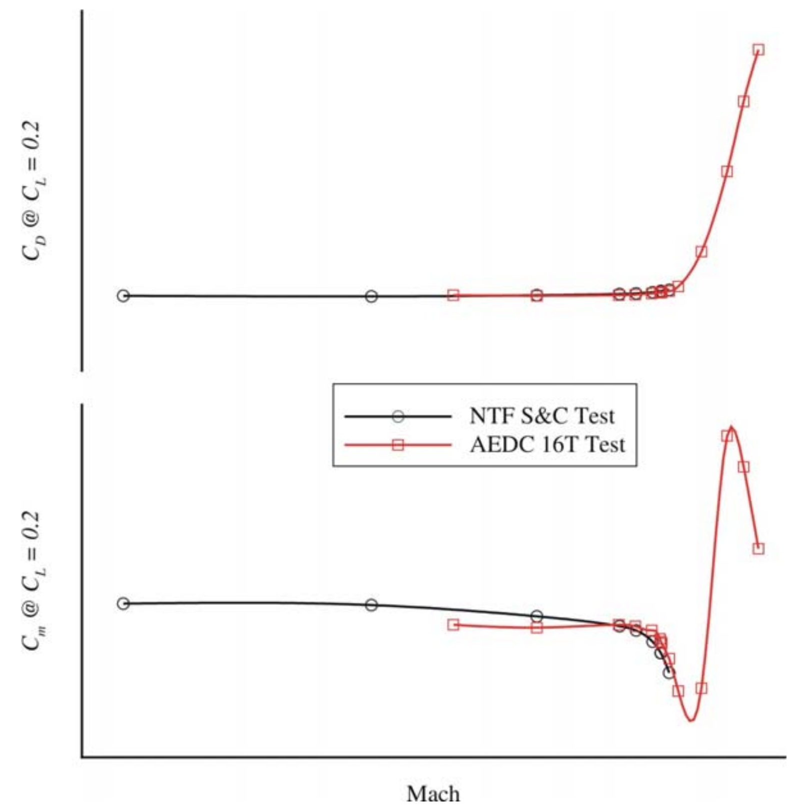

Fig. 12 Effect of Mach number on drag and pitching moment of BWB full configuration at C_L=0.2 (Re=10 x10^6).

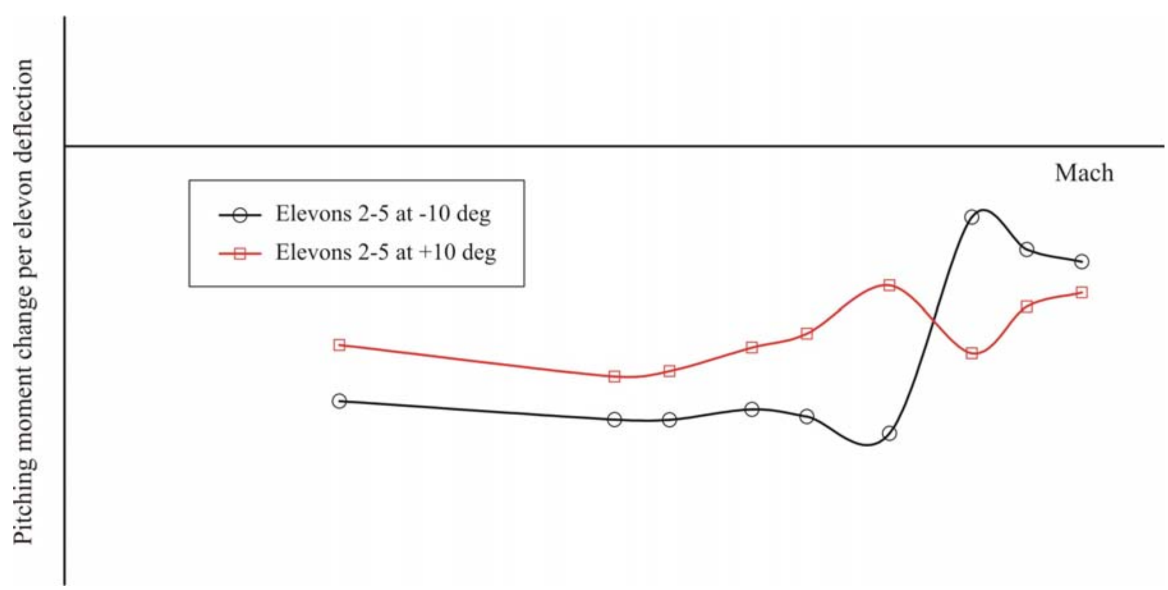

Fig. 13 Effect of Mach number on pitch effectiveness of elevons 2 through 5 in AEDC 16T (Re = 5 x10^6, full configuration, no grit)

V. NTF and AEDC 16T Data Comparison

Initial results from the AEDC test of the wing alone data at 10 million Reynolds number showed significant differences in the pitching moment at the higher angles of attack. Despite great care in applying the grit for transition fixing, it seemed certain that the application was not even and led to the differences in high angle of attack data. Figure 14 shows the lift and pitching moment coefficient plots comparing the NTF and the AEDC data. The variation in the pitch break of the AEDC data was similar to the NTF BLI test data and the possibility that this is a valid characteristic was considered.

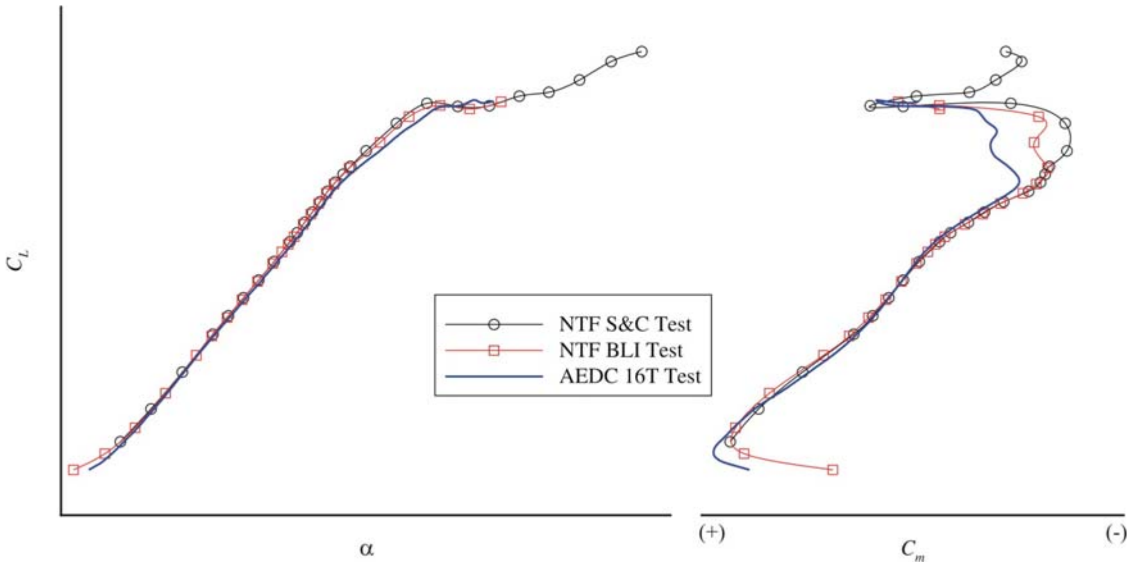

Fig. 14 NTF and AEDC 16T data comparison of wing alone lift and pitching moment with angle of attack (Re=10x10^6, Mach = 0.85, grit applied).

However, when the grit was removed from the full configuration for the start of the database testing, the pitch break variation disappeared. It had remained through the build-up from wing alone to full configuration with nacelle/pylons and winglets but was not evident when the grit was removed. Figure 15 shows the excellent agreement between NTF and AEDC in lift and pitching moment coefficients of the full configuration.

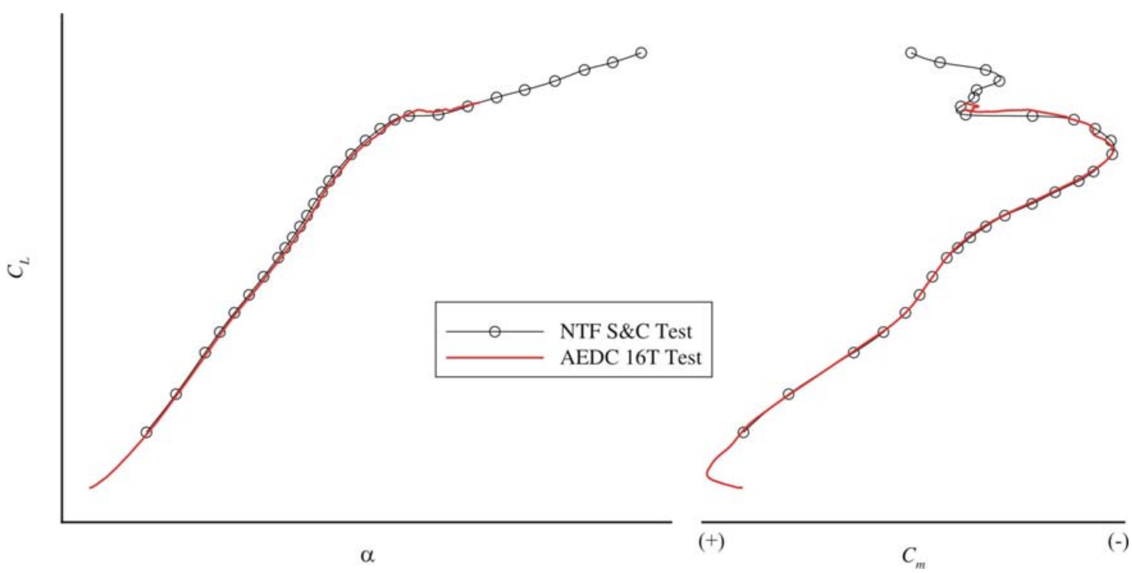

Fig. 15 NTF and AEDC 16T data comparison of full configuration lift and pitching moment with angle of attack (Re=10x10^6, Mach = 0.85, no grit).

VI. Conclusions

The AEDC and NTF transonic wind tunnel tests of the 2-percent scale BWB model have provided a high fidelity transonic aerodynamic data set suitable for simulation development and CFD design tool validation. The test-to-test and tunnel-to-tunnel comparisons of the data have shown overall good agreement and provided added confidence in the data set. The limited CFD comparisons have also agreed well. The data from the AEDC test provided a clear definition of the drag rise with Mach number. The corresponding pitching moment data showed the anticipated reduction in pitching moment with increased Mach but was followed with an unanticipated large increase. Additional CFD comparisons as well as simulation analysis of the stability and control and handling quality characteristics of the configuration remains to be completed.

References

[1]Liebeck, R, "Design of the Blended-Wing-Body Subsonic Transport," AIAA-2002-0002, January 2002.

[2]Daggett, David L., Kawai, Ron, and Friedman, Doug, "Blended Wing Body Systems Studies: Boundary Layer Ingestion Inlets with Active Flow Control," NASA CR-2003-212670, December 2003.

[3]Roman, D., Allen, J. B., and Liebeck, R. H., "Aerodynamic Design Challenges of the Blended-Wing-Body Subsonic Transport," AIAA-2000-4335, August 2000.

[4]Holmes, Stanley, "The Battle over a Radical New Plane," Business Week, Vol. 145, November 25, 2002, pp. 106-108.

[5]Clark, Lorenzo R., and Gerhold, Carl H., "Inlet Noise Reduction by Shielding for the Blended-Wing-Body Airplane," AIAA-99-1937, May 1999.

[6]Vicroy, Dan D.; Murri, Daniel G.; and Abeyounis, William K.; "Low-speed Aerodynamic Characteristics of a Subsonic Blended-Wing-Body Tri-jet Configuration," NASA TM-2006-214309, May 2006.

[7]Vicroy, Dan D.; Murri, Daniel G.; and Grafton, Sue B.; "Low-speed, Large Angle Wind Tunnel Investigation of a Subsonic Blended-Wing-Body Tri-jet Configuration," NASA CDTM-10044, 2004.

[8]Wahls, R. A., "The National Transonic Facility: A Research Retrospective." 39th Aerospace Sciences Meeting and Exhibit, Reno, NV, January 8-11, 2001. AIAA-2001-0754.

[9]Frink, Neal T., "Assessment of an Unstructured-Grid Method for Predicting 3-D Turbulent Viscous Flows." 34th Aerospace Sciences Meeting and Exhibit, Reno, NV, January 15-18, 1996. AIAA-1996-292.

[10]Campbell, Richard L., Carter, Melissa B., et al, "Design and Testing of a Blended Wing Body with Boundary Layer Ingestion Nacelles at High Reynolds Numbers (Invited)," AIAA-2005-0459, January 2005.

[11]Carter, M., Campbell, R., Pendergraft, O., Friedman, D., and Serrano, L., "Design and Testing a Blended Wing Body with Boundary-Layer Ingestion Nacelles," Journal of Aircraft , Vol. 43, No 5, pages 1479-1489, September-October 2006.

[12]Vicroy, Dan D., "Blended-Wing-Body Low-Speed Flight Dynamics: Summary of Ground Tests and Sample Results (Invited)." 47th AIAA Aerospace Sciences Meeting and Exhibit, Orlando, Florida, January 5-8, 2009. AIAA 2009-0933 (to be published).

[13]"Arnold Engineering Development Center 2008 Test Facility Guide," Arnold Engineering Development Center, www.arnold.af.mil, 2008.