Blended-Wing-Body Low-Speed Flight Dynamics: Summary of Ground Tests and Sample Results (Invited)

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A series of low-speed wind tunnel tests of a Blended-Wing-Body tri-jet configuration to evaluate the low-speed static and dynamic stability and control characteristics over the full envelope of angle of attack and sideslip are summarized. These data were collected for use in simulation studies of the edge-of-the-envelope and potential out-of-control flight characteristics. Some selected results with lessons learned are presented.

Nomenclature

b	=	span
l	=	length
V	=	velocity
C_L	=	lift coefficient
C_m	=	pitching-moment coefficient
q	=	dynamic pressure
α	=	angle of attack
ΔC_L	=	lift coefficient increment
δ_{e1-5}	=	deflection of left and right elevons 1 through 5, (+ trailing edge down)
Ω	=	rotation rate about the velocity vector
BWB	=	Blended-Wing-Body
cg	=	center of gravity
LFST	=	Langley Full-Scale Tunnel
VST	=	20-Foot Vertical Spin Tunnel

I. Introduction

THE Blended-Wing-Body (BWB) concept evolved though a series of NASA funded design studies conducted by the McDonnell Douglas Corporation (later Boeing) during the early 1990's.[1,2] The concept has shown potential for improved efficiency over the classic tube and wing transport configuration with reductions in both takeoff weight and fuel burn.[2] A summary of the BWB design evolution is well documented in reference 2.

Early in the BWB concept development there were two critical technology challenges identified. One was the development of light weight structural concepts for the non-cylindrical pressurized center body payload section. The recent progress in BWB composite structural concepts is documented in reference 3. The other BWB technology challenge was the flight controls. To address the flight controls challenge, a series of wind tunnel tests was conducted leading to the development of the two subscale low-speed X-48B flight test vehicles. These wind tunnel tests in conjunction with the flight tests were focused on addressing the following flight dynamics research goals:

- Explore the stability & control characteristics of a BWB class vehicle.
    - Assess stability and controllability about each axis at a range of flight conditions.
    - Characterize departure onset.
    - Characterize post-departure and out-of-control modes of motion.
    - Assess dynamic interaction of control surfaces.
    - Assess asymmetric-thrust control requirements.

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- Develop and evaluate flight control algorithms designed to provide desired flight characteristics.
    - Assess control surface allocation and blending.
    - Assess edge of envelope protection schemes.
    - Advance the state-of-the-art in control theory.

- Evaluate prediction and test methods for BWB class vehicles.
    - Correlate flight measurements with ground-based predictions and measurements.

This paper will provide a brief review of the battery of low-speed wind tunnel tests presented in chronological order and a summary of the lessons learned. An abbreviated discussion of some of these wind tunnel tests was previously published in reference 4. A review of the high speed wind tunnel tests is provided in reference 5 with the flight tests covered in reference 6.

A. BWB Configuration

All the wind tunnel models discussed in this paper were scale versions of the same Boeing BWB proprietary geometry. This BWB configuration (Fig. 1) was designed in the late 1990's following a series of government sponsored studies of a much larger BWB configuration.[2] This smaller BWB configuration was designed to satisfy airport compatibility constraints (e.g. wing span) and provided a more direct comparison with existing commercial aircraft. Although there have been many BWB designs and improvements developed since this design, it was decided early in the research program to maintain the same BWB geometry throughout the numerous wind tunnel tests. This provided greater opportunity for test to test and ground to flight correlation. Table 1 provides the reference dimensions for the various models discussed in this paper.

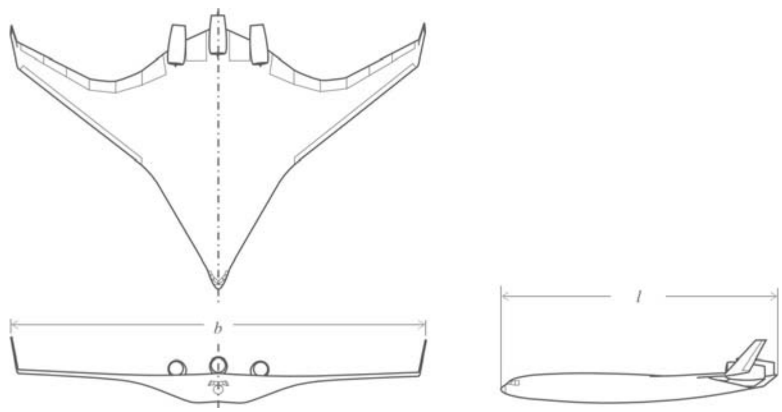

Fig. 1 Boeing BWB configuration.

This BWB configuration has three pylon-mounted nacelles located on the upper surface of the aft center body. The control surfaces consist of 18 elevons distributed along the trailing edge, rudders on each winglet and leading edge slats, as shown in figure 2. The two outboard elevons (labeled as "8 Upper / 6 Lower" and "9 Upper / 7 Lower") split to serve as both elevons and drag rudders.

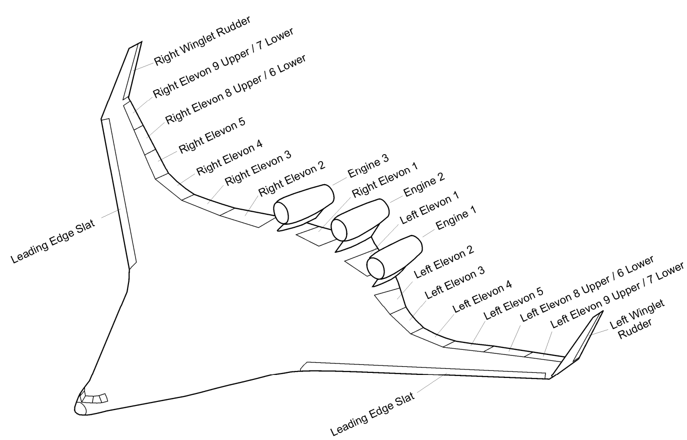

Fig. 2 BWB control surfaces.

Table 1 BWB model dimensions.

Item	Scale	*b*, ft	*l*, ft
Spin/Tumble Model	1.1%	2.76	1.80
Rotary Model	2.0%	4.80	3.13
Multipurpose Low-speed Model	3.0%	7.20	4.70
Free-flight Model	5.0%	12.00	7.83
X-48B	8.5%	20.40	13.30

II. Low-speed Wind Tunnel Tests

A. Spin and Tumble Test

The first of the many wind tunnel tests of this BWB configuration was a free spin and tumble test with a 1.1-percent dynamically scaled model in the Langley 20-Foot Vertical Spin Tunnel (VST) (Figs. 3,4). The three objectives of this test were to quantify the steady state spin and tumble modes, explore recovery control combinations, and develop an emergency single parachute spin and tumble recovery configuration. This emergency recovery system was required for the planned higher risk experimental flight testing outside the normal operating envelope.

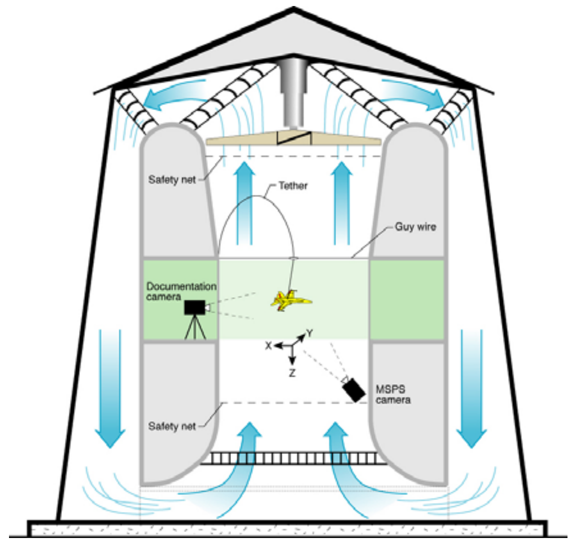

Fig. 3 Cross-section of Langley 20-Foot Vertical Spin Tunnel.

The tests successfully identified both spin and tumble modes but only when pro-spin or tumble control deflections were used in conjunction with certain mass conditions. Recovery control deflections were effective in arresting the tumble modes but were ineffective for satisfactory spin recovery. The full range of desired mass and inertia cases could not be tested due to practical limitations of ballasting the 1.1-percent scale model to the projected flight conditions. The pro-spin and tumble combinations of mass properties and control deflections were used to determine requirements for the emergency spin and tumble recovery parachute system. Numerous combinations of canopy size, towline (i.e., riser plus suspension line) length, number of parachutes used, and attachment point location (trailing edge, one or both wing tips, etc.) were tested before arriving at a final configuration. For example, it was determined that both single and dual wing tip mounted chutes provided very good spin recovery, but were unsatisfactory for tumble recovery due to their tendency to foul on the wings and winglets. The best arrangement tested was a small parachute with a very short towline attached to a rigid boom extending off the rear of the model along the centerline. This arrangement allowed the parachute to perform satisfactorily for arresting both spins and tumbles. The short towline permitted the canopy to clear the aft end of the model, including the center engine nacelle, as the model pitched through a 90 degree nose-high attitude during a tumble while still providing good spin recoveries. The boom increased the moment arm (in yaw and pitch) available for the drag forces produced by the parachute, allowing a significantly smaller parachute to be used relative to more standard spin chute installations. Based on the results of this test, a scaled-up version of the boom-mounted recovery system was incorporated into the X-48B flight-test vehicles (Fig. 5).

Fig. 4 Free-spin test of 1.1% dynamically-scaled BWB model in the VST.

Fig. 5 X-48B spin/tumble recovery system boom.

B. Rotary Test

Following the spin and tumble test a rotary balance test was conducted on a 2-percent scale BWB model in the VST. The objective of this test was to measure forces and moments under steady rotation for a large range of angle of attack, sideslip, and rotation rate. Data from rotary balance tests are used for analyzing subsonic rate damping characteristics, predicting spins, and for implementation of spin modeling in high-fidelity 6-DOF simulations. The BWB model with an internal force and moment balance was sting-mounted on a rotating rig capable of rotation rates up to 68 RPM in either a clockwise or counter-clockwise direction (Fig. 6). Data were collected over an angle-of-attack range of ±90° and sideslip range of ±30° at non-dimensional spin rates ($\Omega b/2V$) up to 0.67 in both directions. Data were collected with a series of combined control deflections in both the slats extended and retracted configurations. Full analysis of this rotary test data set has not yet been completed.

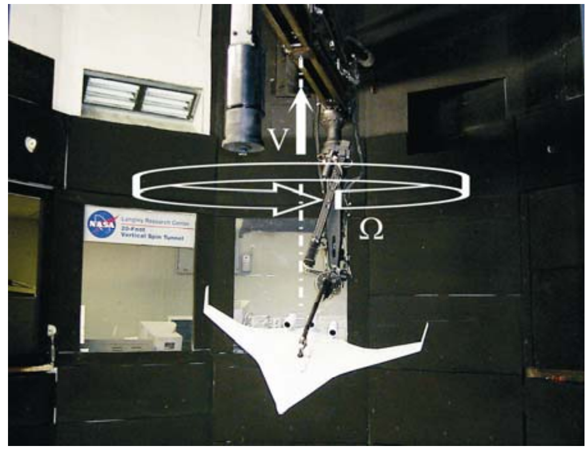

Fig. 6 BWB rotary balance test.

C. Low-speed Baseline Aerodynamics Test

The bulk of the BWB low-speed aerodynamic database was developed from a series of tests with a 3-percent scale multi-purpose model in the Langley 14- by 22-Foot Subsonic Tunnel. The basic static aerodynamic data were collected with the model on a post mount system (Fig. 7). Force and moment data were collected over an angle-of-attack range of -12° to 36° and ±30° sideslip range at dynamic pressures from 4 to 95 psf. The majority of the data were collected at a dynamic pressure of 60 psf. The test included individual and combined control effectiveness, slat geometry effects and ground effects (Fig. 8). The complete dataset is presented in graphical form in reference 7 with limited analysis.

The extent of the data collected during this test is too large to cover in this brief paper. However there were a couple of notable results that have been selected to highlight. The first result is that with the slats retracted, the configuration exhibits an unstable pitch break over the angle of attack range where the outboard wing section begins to stall prior to the inboard and center body sections (Fig. 9). The stall of the outboard wing sections which are aft of the moment reference center results in a nose up pitching moment change. Deflecting the slat delays the stall of the outboard section and eliminates the unstable pitch break. The deflected slat also increases the maximum lift coefficient as expected. (note that Fig. 9, and all subsequent data plots in this paper have the vertical scales removed due to the proprietary nature of the data).

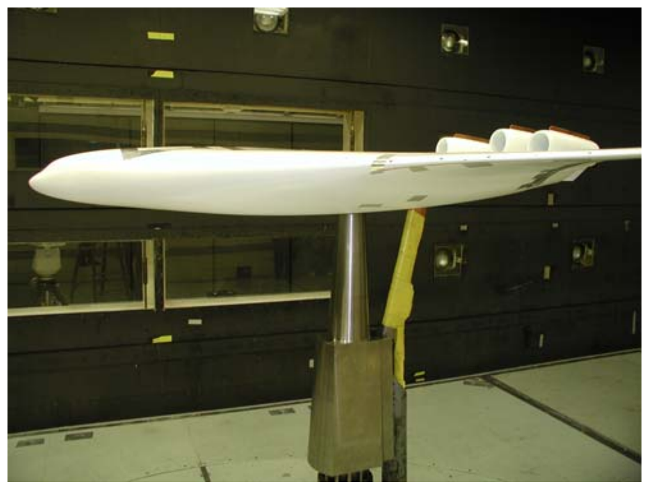

Fig. 7 BWB 3% scale model on post mount.

The interaction effect of combined control deflections is illustrated in figure 10. The figure shows the change in lift coefficient due to the combined deflections of elevons 1 thru 5 at deflection angles of -40°, -10°, and +30°. Also shown in the figure are the sums of the individual effects of elevons 1 thru 5 at the same deflection angles. The summed values are designated with a "Σ" symbol in the figure key and a "+" in the plot symbol. The summed values generally over-predict the magnitude of the combined elevon increment indicating the presents of control surface interaction effects, particularly at the larger control deflections.

Fig. 8 Ground effects test on post mount.

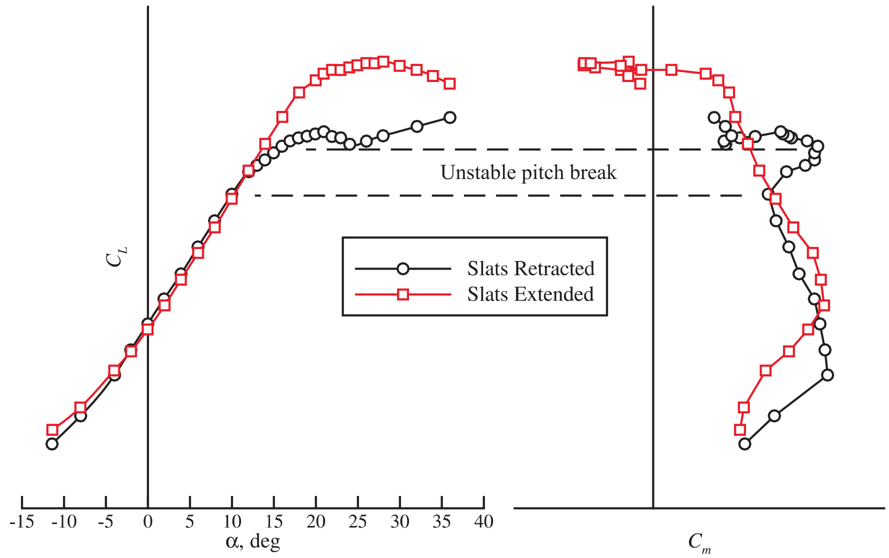

Fig. 9 Lift and pitching moment of slat extended and retracted configurations.

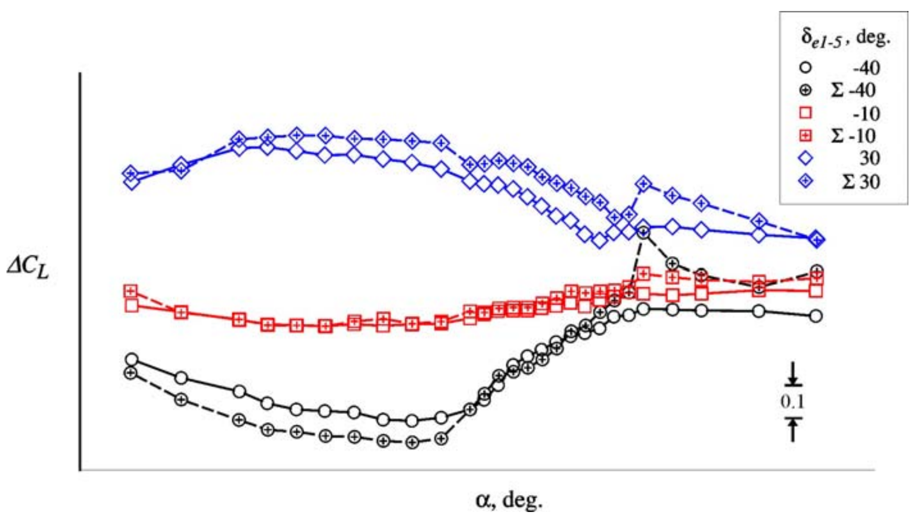

Fig. 10 Change in lift due to combined deflection of elevons 1 thru 5.

D. Large Angle Test

A large angle static test was also conducted in the NASA Langley 14- by 22-Foot Low-Speed Wind Tunnel with the same 3-percent scale model used in the previous test discussed in section D. This large angle test was conducted to evaluate the low-speed static stability and control characteristics of the configuration over the full envelope of angle of attack (±180°) and sideslip (±90°).[8] These data were collected for use in simulation studies of the edge-of-the-envelope and potential out-of-control flight characteristics. The model was mounted on a bent sting (Fig. 11) in four different positions (upright and inverted facing both forward and aft) to provide the full angle-of-attack range. The range of dynamic pressures varied from 1 to 27 psf with the majority of the data collected at 8 psf. The test included

Fig. 11 BWB 3% scale model on bent sting mount.

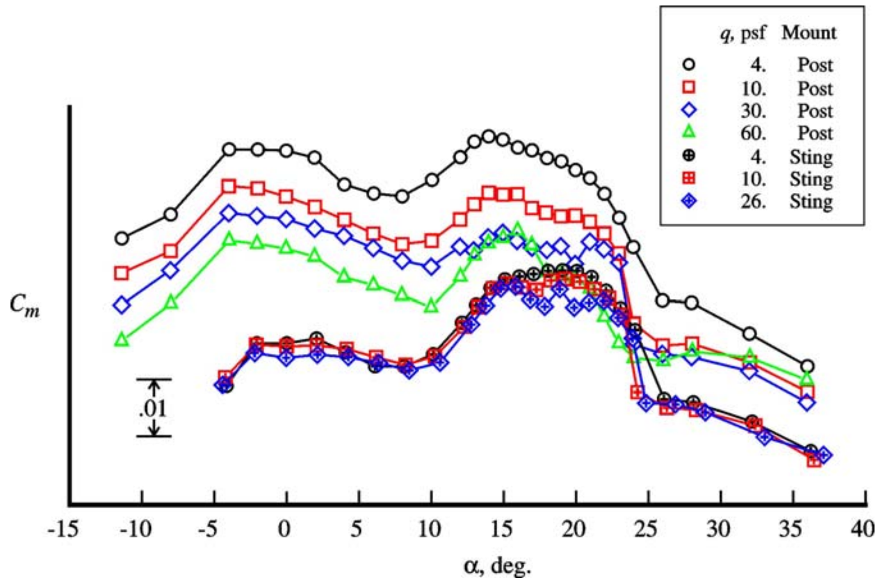

Fig. 12 Support interference effect on pitching moment.

a limited set of combined control deflections in both the slat extended and retracted configurations.

It had been noted in the previous static test with the post mount[7] (Fig. 7) that there was a larger than anticipated installation effect that was particularly evident in the pitching moment (Fig. 12). The 3-inch diameter post and aft pitch link mounting resulted in large sensitivity in pitching moment with dynamic pressure. There was also a considerable shift in pitching moment between the post mount and the smaller 1.2-inch diameter bent sting mount (Fig. 11), which was much less sensitive to dynamic pressure. In hindsight, the large pitch sensitivity induced by the post mount, which had been used with minimal installation effects on traditional tube and wing configurations, seems obvious on a flying wing configuration with a large lifting center body.

E. Forced Oscillation Test

The third in the series of tests with the 3-percent model in the Langley 14- by 22-Foot Low-Speed Wind Tunnel was a forced oscillation test (Fig. 13). The model was mounted to a forced oscillation rig through a six-component strain gauge balance. The rig produces constant frequency and amplitude sinusoidal motion about the pitch, roll or yaw axes. The desired amplitude and frequency are set prior to each run. A limited set of combined control deflections were tested in both the slat extended and slat retracted configurations. The pitch oscillation runs were conducted over a ±160° angle-of-attack range at amplitudes of ±5°, ±10° and ±15°. The pitch oscillation reduced frequencies ($\omega \bar{c}/2V$) varied from 0.070 to 0.301 to cover the envelope of predicted low-speed maneuvering range of pitch rates. The roll and yaw oscillations were conducted over an angle-of-attack range from -8° to 90° at

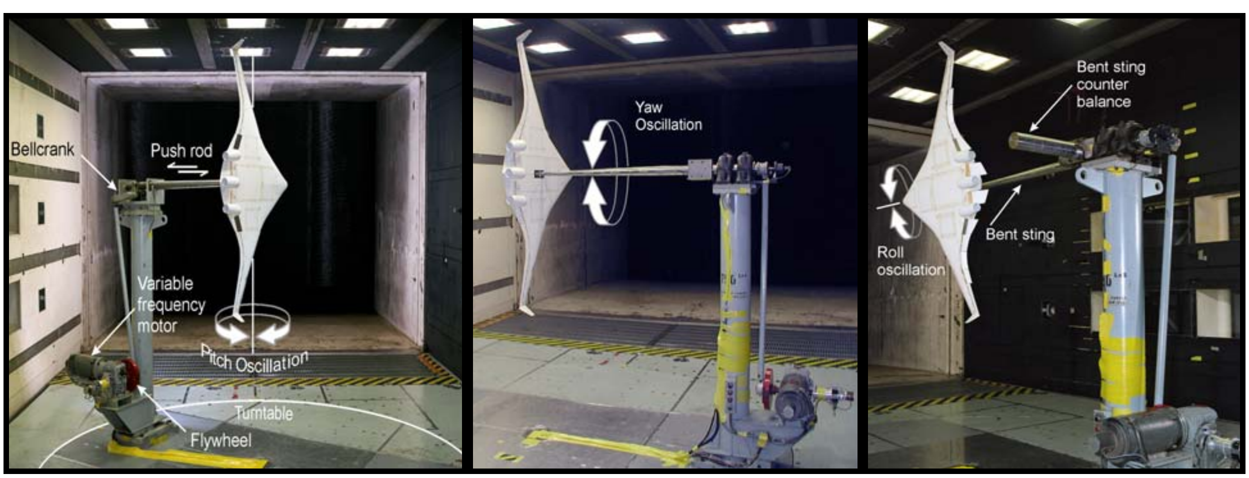

Fig. 13 Forced-Oscillation setup of 3% scale BWB model.

amplitudes of ±5°, ±10° and ±20°. The reduced frequencies ($\omega b/2V$) for the roll and yaw oscillations varied from 0.2 to 0.8. The contribution of landing gear and gear doors as well as engine nacelles and winglets on the yaw damping characteristics were also tested. The documentation of this forced-oscillation test dataset is under development and has not yet been published.

The large-angle static data along with the forced oscillation and rotary data are all part of the information set required to simulate spins, tumbles and recoveries from these and other extreme attitudes. The sufficiency of this data set to accurately model and simulate such dynamic maneuvers is an area of ongoing research.

F. Ground Effects Test

The large installation effects from the post mount in the Langley 14- by 22-Foot Low-Speed Wind Tunnel brought into question the ground effects data collected during that test. A follow-on ground effects test was conducted in the Swift Engineering 8- by 9-Foot Wind Tunnel (Fig. 14**)**. This tunnel had a rolling road ground belt with a top mount telescoping blade strut that allowed the angle of attack and height above the ground belt to vary.

A related BWB ground effects test was also conducted in this tunnel that investigated the use of a "belly flap" for improved lift and pitching moment during take-off and landing.[9] Relative to the baseline configuration, this concept showed a 35% increase in takeoff lift coefficient with a 10% increase in pitching moment at a 90° belly-flap deflection.

Fig. 14 Ground effects test of 3% scale model in Swift Engineering tunnel.

G. Free-flight Test in LFST

A free-flight test was conducted in the Langley Full-Scale Tunnel with a 5-percent scale model.[10] The free-flight test technique uses a remotely controlled model flown unconstrained (except for the slack umbilical cable which houses the safety and electrical cables and the pneumatic hose for the jet ejectors) in the tunnel test section (Fig. 15). This technique, with a dynamically scaled model, provides a six-degree-of-freedom, 1g flight environment for early evaluation of an aircraft configuration's stability, controllability and flying qualities. It is particularly useful in flight regimes that are highly dynamic or difficult to model such as 1g departures, asymmetric thrust conditions or configuration transitions. The technique has also been used to evaluate flying qualities in dynamic environments such as formation flight or wake encounters.

Although free-flight testing has been conducted in this tunnel since the early 1950's this model with its 12-foot wing span was the largest model ever free-flight tested (Fig. 16). The size of the model was driven by the dynamic scaling requirements which can be very challenging for large, low density aircraft configurations such as the BWB. The required model mass scales with the cube of the model scale and the inertias scale to the fifth power.[11] The roll inertia requirement was particularly challenging for this configuration. Every ounce of additional material added to the wing tip resulted in approximately 2 pounds of additional model weight required to balance the inertias and maintain the CG location. Because of this mass scaling sensitivity the wings of the model were left unpainted and the scale of the model was chosen to be as large as practical for free-flight testing in LFST, which limited the maneuvering

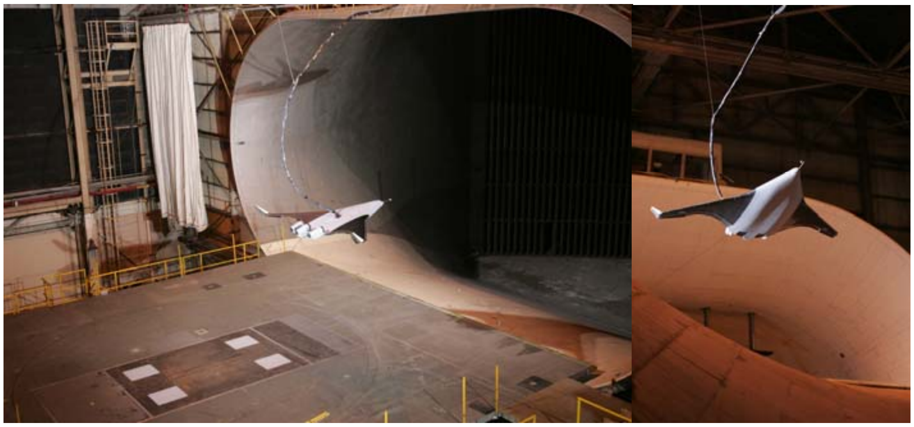

Fig. 15 BWB free-flight test in Langley Full-Scale Tunnel.

Fig. 16 BWB free-flight model.

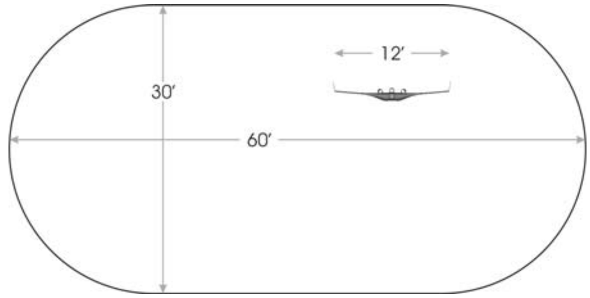

Fig. 17 Model size relative to LFST test section.

space during the test (Fig. 17).

A static force and moment test of the 5-percent free-flight model was conducted in the LFST prior to the free-flight test (Fig. 18). This test was conducted to calibrate the high pressure pneumatic ejectors used for model thrust and for comparison of the model aerodynamics with the previously discussed wind tunnel datasets. The model control surfaces were remotely actuated during the static test. This capability provided an opportunity to conduct a design of experiments exploratory study on the efficiency of response surface methodology to characterize the model aerodynamics and control surface effectiveness.[12]

The free-flight model control laws were developed from the aerodynamic data provided from this and the previous 3-percent model tests.[13] The control laws were designed to allow the model to be manually flown within the operating wind tunnel test section in all six degrees-of-freedom at a variety of speeds and angles of attack. The control laws also had to provide control of the model during tunnel start-up which began with the model hanging from the umbilical in the test section. In still air the model, supported near its center-of-gravity, hung mostly level but the nose was relatively free to wander from side-to-side. To provide directional control during tunnel startup, the center engine nacelle could be commanded to swivel horizontally providing some directional thrust vectoring control. In addition to stability augmentation the control laws provided a means to allocate pilot commands, in the form of desired pitch, roll and yaw rates, to the various control surfaces.

The objectives of the free-flight test were to characterize the BWB 1g departure characteristics including the asymmetric thrust minimum control speed and evaluate the effectiveness of center engine lateral thrust vectoring. The free-flight test explored the minimum control speed at forward and aft center of gravity locations, with and without slats, and with symmetric and asymmetric thrust.

Historically, free-flight testing has been primarily a qualitative subjective evaluation of flight characteristics, control response and control law gain selection. However, there were some quantitative measures derived from this test. Control deflection histogram data were generated for each center of gravity and slat configuration to assess control allocation and saturation limits. For each run, which generally lasted from 10 to 18 minutes, the data were sorted by free-stream dynamic pressure in 0.1 psf increments. Data taken at times when the model was supported by the free-flight cable were excluded. Summary histogram plots were then generated showing the average data values and percent of time that the control surfaces or commands were at their limits as a function of tunnel velocity. An example result is shown in figure 19 for the slats extended, aft cg configuration. The top plot shows the predicted and measured trim pitch angle as a function of airspeed. The bottom plot shows the corresponding percent of time that the control commands were at the limit values. Also noted on the plots is the minimum control speed obtained during the free-flight test. This result was typical for the BWB configurations tested. As the airspeed decreased the yaw command became increasingly saturated. Roll with pitch was used to compensate. The minimum control speed

Fig. 18 Static force and moment test set-up of 5% scale model in LFST.

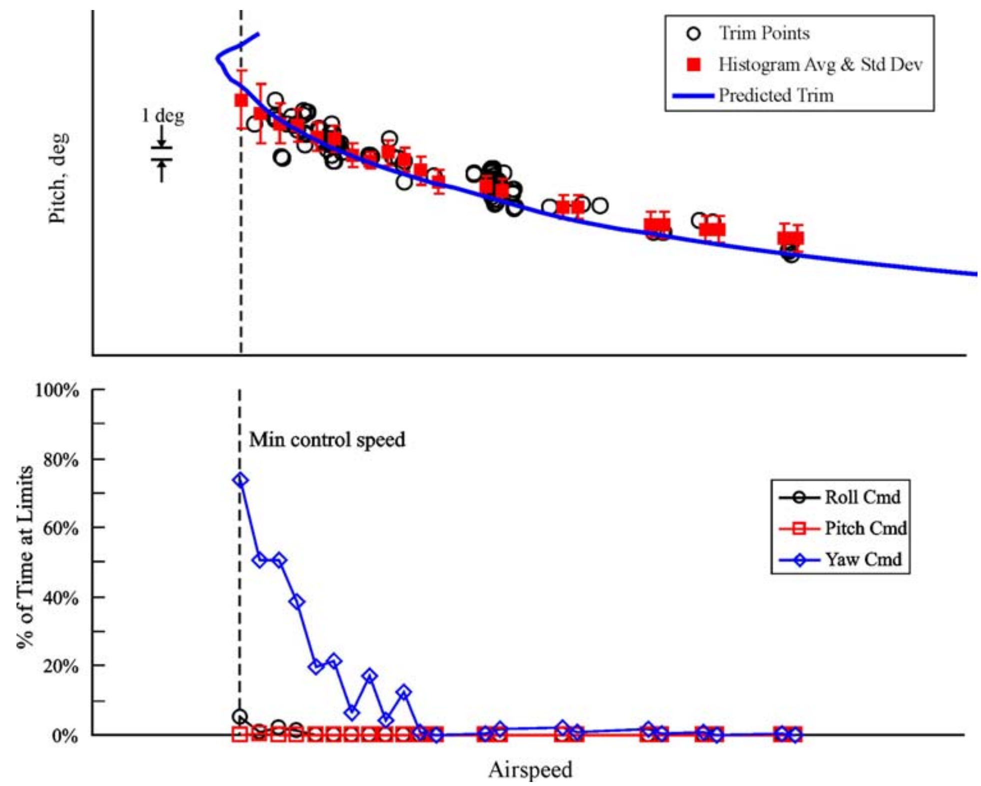

Fig. 19 Example BWB free-flight test results for slats extended, aft cg configuration.

occurred at the airspeed where one of the other axes (pitch or roll) began to saturate.

H. X-48B Test in LFST

The last of the low-speed wind tunnel tests conducted on this BWB configuration was conducted on the X-48B in the Langley Full-Scale Tunnel (Fig. 20). This test provided a rare opportunity to collect wind tunnel data on a flight test vehicle. In addition to the static aerodynamic data the test was used to calibrate the airdata system and measure the control surface hinge moments. The results of this test have not yet been published.

III. Future Test Plans

The BWB research focus is transitioning from BWB enabling technologies, such as structures and flight controls, to BWB benefiting technologies, such as boundary layer ingested inlets, distributed propulsion, adaptive controls and acoustic shielding. The acoustics benefit of the BWB configuration is a rapidly growing research area. Plans are currently under way for another test in the LFST with an acoustically modified X-48B configuration.

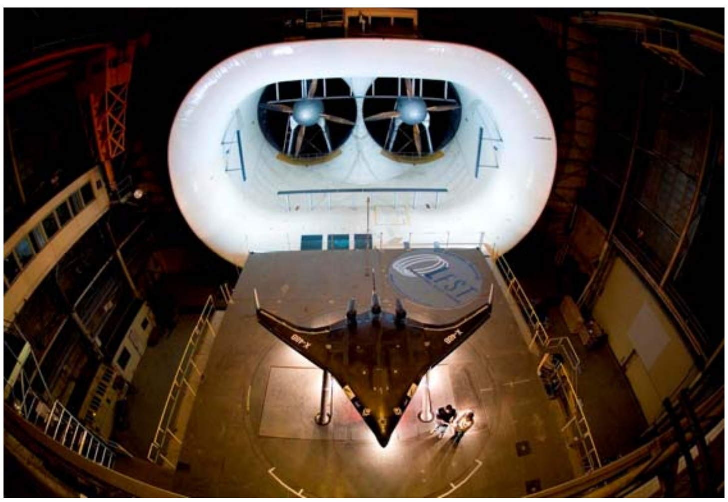

Fig. 20 The 21-foot span X-48B undergoing static balance test in the Langley Full-Scale Tunnel.

IV. Conclusion

Over the past several years a series of low-speed wind tunnel tests of a Boeing proprietary BWB configuration were conducted. These tests generated an extensive full-envelope database for flight simulation and ground to flight correlation. A brief summary of some of the unique BWB lessons learned from these tests are as follows:

- This configuration does have sustained spin and tumble modes of motion but only with pro-spin or tumble controls.
- The configuration has limited directional control authority. Center engine thrust vectoring can help to augment directional control authority in an outboard-engine-out condition.
- Control interference effects can be significant with multiple trailing edge control deflections and should be accounted for in the aerodynamic simulation model.
- Wind tunnel installation effects on pitching moment can be large for BWB configurations with significant center-body lift contribution.

To date no BWB flight dynamics "show stoppers" have been identified from these tests and the associated analyses.

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