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TRANSONIC TRUSS-BRACED WING VISION VEHICLE TECHNOLOGY MATURATION

Neal A. Harrison[1], Gregory M. Gatlin[2], Eric D. Dickey[3], Adam M. Malone[4]

[1]Boeing Research & Technology, Everett, WA
[2]NASA Langley Research Center, Hampton, VA
[3] Boeing Commercial Airplanes, Long Beach, CA
[4] Boeing Commercial Airplanes, Everett, WA

Abstract

The maturation of technologies that can potentially enable a Transonic Truss-Braced Wing (TTBW) vision vehicle have continued under the latest phase of the Subsonic Ultra Green Aircraft Research (SUGAR) program. Ground testing in this phase has further reduced configuration unknowns and provided valuable data for future potential design activities. Additional test campaigns have been conducted at both low and high speeds. Low-speed, high-lift performance has been investigated in ground effect as well as under simulated icing conditions. High-speed analysis and testing examined the TTBW's performance at high-speed buffet onset to determine if the vehicle's non-linear aerodynamics have an appreciable effect on the vehicle's high-speed design criterion.

Keywords: Truss-braced, sustainability, transonic, buffet, high-lift, ground effects, icing

1. Introduction

In 2020 Boeing was awarded the latest phase of technology development under NASA's Advanced Air Vehicles Program (AAVP). The objective of this program is to advance technologies that show significant potential for revolutionary improvements in aircraft efficiency, emissions, noise, and safety as compared to conventional aircraft currently in service. Through this program over the past 14 years, Boeing has continually increased its focus on the development of the Transonic Truss-Braced Wing (TTBW) configuration (**Error! Reference source not found.**), a technology of significant promise first identified as part of the Subsonic Ultra-Green Aircraft Research (SUGAR) technology investigations.

Figure 1 - The Transonic Truss-Braced Wing (TTBW) Concept

As a part of the AAVP, the Advanced Air Transport Technology (AATT) project matures fixed-wing commercial transport technologies that offer the greatest potential to meet these greater objectives. The AATT project's target metrics for dramatic reductions in noise, emissions, and fuel consumption as a function of near, mid, and far-term objectives are shown in Figure 2.

TECHNOLOGY BENEFITS	**TECHNOLOGY GENERATIONS** Technology Readiness Level = 5/6		
	Near-Term 2015-2025	**Mid-Term** 2025-2035	**Far-Term** 2035+
Noise (cum below Stage 4)	**22 – 32 dB**	**32 – 42 dB**	**42 – 52 dB**
LTO NOx Emissions (cum below CAEP 6)	**70 – 75%**	**80%**	**>80%**
Cruise NOx Emissions (rel. to 2005 best in class)	**65 – 70%**	**80%**	**>80%**
Aircraft Fuel/Energy Consumption (rel. to 2005 best in class)	**40 – 50%**	**50 – 60%**	**60 – 80%**

Figure 2. NASA Subsonic Transport System-Level Metrics/Goals [1]

Under AATT, the SUGAR Phase V investigation continues the aircraft development where it left off in Phase IV [2], by continuing its focus on both the low- and high-speed performance potential of the vehicle. Specifically, the study of transonic performance was extended to the investigation of high-speed buffet onset after initial computational investigations identified the vehicle's potential to experience buffet onset at both high and low lift coefficients – a result of the aerodynamic interaction between the wing and strut. To accomplish this goal, a transonic semi-span wind tunnel test was conducted at the NASA Ames Unitary Plan Wind Tunnel (UPWT) complex, beginning in January 2022. In addition, this phase of study also focused on aspects of low-speed performance not previously studied on the TTBW by extending investigations into the area of ground effects and ice accretion. These low-speed investigations were carried out in the NASA Langley Research Center's 14- by 22-Foot Subsonic Tunnel beginning in July 2021.

As the TTBW configuration has matured and some of the vehicle's highest risks have been retired, interest in the configuration has grown. NASA AATT has increased its focus on the concept by making the TTBW configuration one of the 'fab four' technologies on which it is focusing its resources. A series of risk-reduction contracts funded by NASA has also brought the potential for a subsonic flight demonstrator to the forefront of government interest, for which the TTBW configuration is considered a contender [3].

In addition to the potential for a TTBW-based flight test demonstrator, plans for development of TTBW-specific vision vehicle technologies continues. Discussions with NASA are underway for the next phase of TTBW technology development, with a potential 'SUGAR Phase VI' project proposed to extend work into additional areas of configuration development, with increased focus on structural design, icing effects, acoustic performance, and high-lift performance. Boeing has also engaged in internal studies of the configuration, including an investigation of the TTBW configuration using multidisciplinary design optimization. [4]

2. TTBW Vision Vehicle Development under the SUGAR Program

Over 14 years, the TTBW configuration has been systematically studied and matured to both reduce the configuration's highest risks and identify additional areas worthy of future study. Figure 3 illustrates a series of configuration challenges that were identified in the earliest days of the SUGAR Program. The resulting investigations have led to significant design efforts in the areas of aerodynamics, structures, aeroelastics, and performance. Seven high-fidelity wind tunnel tests have examined high- and low-speed performance, as well as aeroelastic stability of the configuration. Structures investigations have matured our understanding of the non-linear aspects of TTBW design. However, while the technologies on this initial list of configuration design challenges have been studied, significant design and integration challenges remain before the configuration could be considered for a potential product. Increasing levels of detail and the challenges of creating a fully-integrated design - complete with systems and manufacturable structures – still pose a significant barrier to realizing this concept.

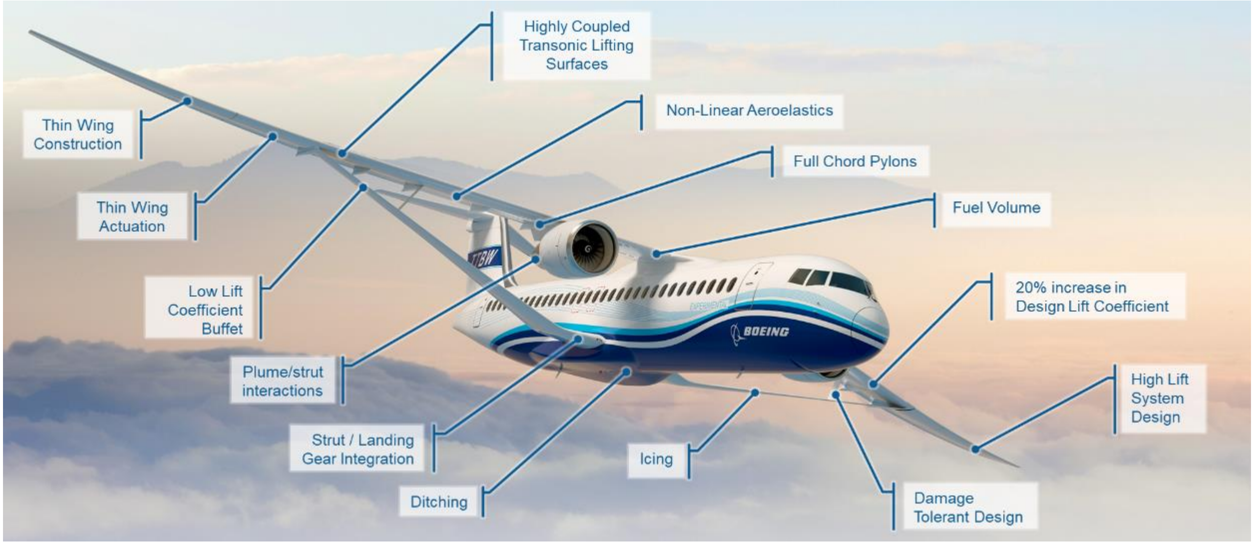

Figure 3. TTBW Design Challenges

Since a potential flight demonstrator will mature only a subset of the technologies needed for a TTBW vision vehicle, it is therefore highly desirable to continue the development of TTBW vision-vehicle-enabling technology under the SUGAR program.

3. SUGAR Phase V Development

Boeing was awarded Phase V of the SUGAR program in September of 2020, with the contract currently scheduled to draw to a close in August of 2022.

3.1 Program description

The Phase V program continues aerodynamic investigations of the TTBW configuration by examining vehicle performance at high and low-speed beyond those previously examined under the SUGAR program. Transonic investigations of the vehicle performance were extended to examine high-speed buffet onset to better characterize whether the TTBW's non-linear aerodynamic interactions between the wing and strut give the vehicle unique behaviors. Low-speed investigations were extended to two separate areas that are heavily influenced by the vehicle's high aspect ratio. The first objective was to quantify the vehicle's performance In-Ground-Effect (IGE). The second objective was to perform preliminary investigations of low-speed performance under icing conditions.

3.2 Low-Speed Investigations

In the latest phase of SUGAR, low-speed wind tunnel testing built on the high-lift investigations begun in SUGAR Phase IV. In that phase, Boeing designed a high-lift system for the vehicle and tested its performance in a first test at the NASA Langley 14- by 22-Foot Subsonic Tunnel located in Hampton, VA. That first entry focused on high-lift system performance optimization, as well as acquiring stability and control data for the configuration. However, due to limited time in the tunnel, some of the objectives intended for testing in Phase IV were deferred to a second test entry. These deferred test objectives formed the foundation for low-speed testing under Phase V, in which a second low-speed test was conducted. This second entry ran from mid-July 2021 to early September 2021 and totaled ~350 occupancy hours.

The primary objectives of the second low-speed wind tunnel test at the NASA 14x22 Tunnel were:

1. Develop a high-lift performance database for the vehicle in-ground-effect
2. Develop a performance database for the effect of ice accretion on the wing and strut
3. Continue development of a stability and control database, including vehicle lateral-directional properties, control surface effectiveness, and trim effects

The high-lift configuration used in the second low-speed entry is the same configuration as was tested in the first low-speed entry under Phase IV. This system consisted of full-span leading edge variable camber Krueger flaps (VCKs) and single-segment Fowler-motion slotted flaps (which were divided into three spanwise segments).

Information and insight gained in the second wind tunnel test focusing on IGE performance and icing accretion effects will be presented in the sections below.

3.2.1 Model Installation

The second low-speed test utilized the existing 8% scale full-span model developed in SUGAR Phase IV. This model had two available support configurations. When conducting free air and icing testing, the model utilized a ventral mount – this was the support configuration used in previous testing. However, an upper (dorsal) model mount was used for IGE testing to enable the model to be tested at lower height/span (h/b) ratios. These model installations are shown in the photographs presented in Figure 4. Note the vertical and horizontal tails were necessarily removed for IGE testing when using the upper (dorsal) model mount.

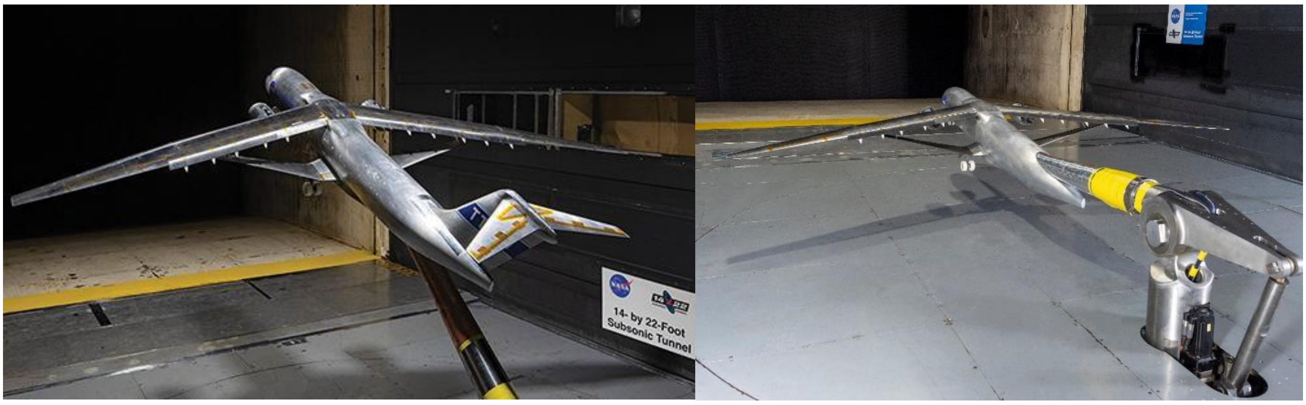

Figure 4. Low-speed model using ventral mount (left image) and dorsal mount (right image). Configurations are both shown in the NASA Langley 14x22 subsonic wind tunnel

3.2.2 Ground Effects

The TTBW's high aspect ratio wing is designed to reduce the effects of lift-induced drag at cruise. The tip vortices created by the wing are therefore weaker than for conventional lower-aspect-ratio wing designs. As a result, the vehicle's free-air high-lift performance should theoretically be less affected by proximity with the ground. That is to say, vehicle performance IGE should be less sensitive to variation of vehicle height/span ratios (h/b) than for a conventional commercial transport aircraft.

Note: with a model wingspan of 13.6ft the TTBW low-speed model is never completely outside of the conventional limit of ground effect (assumed to occur at an h/b of ~1.0) even when operating in the center of the wind tunnel. The low-speed model used for this test campaign therefore has a maximum h/b=0.53 (the vertical height of the test section is actually 14.5ft).

In addition to span-driven limitations to achievable h/b values, the model position was also limited in part by the model support system. The support system was designed to adjust the model to a range of angles and heights while maintaining the height of a selected reference point at a constant distance from the floor throughout the pitch sweep. For this test, the model reference center location was maintained at a fixed height above the tunnel floor. As the model approached the floor the support system had a mechanically-limited decreasing pitch angle range, such that the ability to capture stall was progressively reduced as h/b decreased. This limitation was also influenced by a minimum safety clearance of three inches between the model and floor. The net result was that stall could only be captured above h/b values of 0.24 in the takeoff configuration, and 0.31 in the landing configuration.

Despite the limitations of the support hardware, general trends in vehicle performance as a function of h/b were ascertained. The following observations held true for the cruise, takeoff, and landing configurations:

1. As h/b was decreased there was a small increase in the lift curve slope and an increase in the slope of the drag polars. This corresponds to an expected increase in vehicle L/D ratio.
2. As h/b was decreased the vehicle stall angle of attack and C_{Lmax} are reduced.
3. Vehicle pitching moments show an increase in nose-up moment at the lower model heights as the aft fuselage interacts with the ground.

IGE lift trends from the test are shown in Figure 5 for the takeoff configuration. This figure demonstrates the gradual reduction in stall alpha and C_{Lmax} as the model approached the floor. As mentioned, the full vehicle stall could not be measured under h/b=0.24.

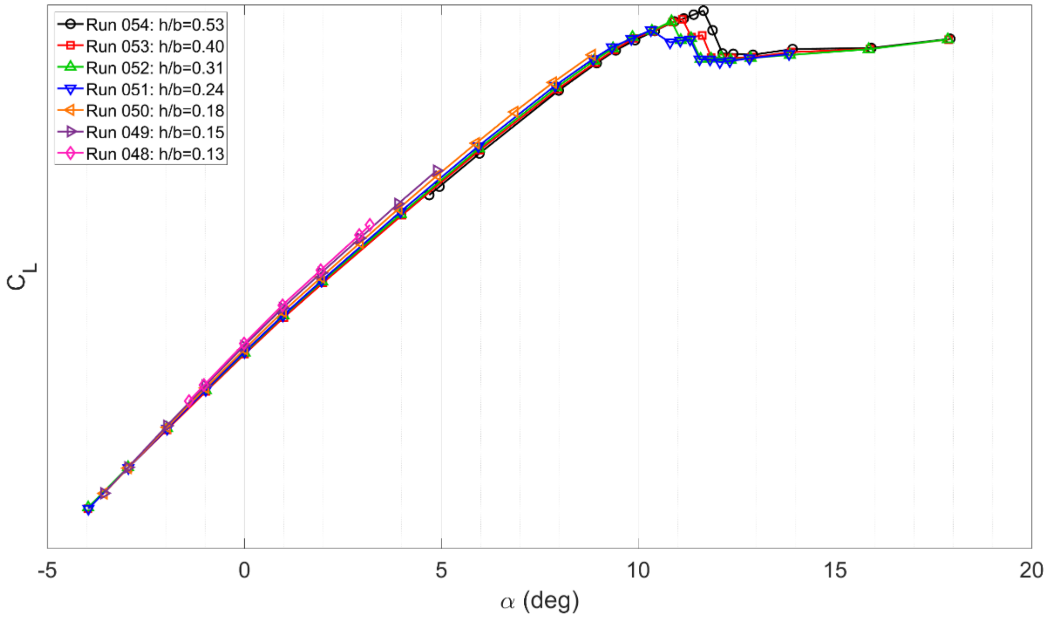

Figure 5. IGE Performance over a range of h/b ratios [Takeoff Configuration, M=0.2, Re_{MAC}=0.98M]

These behaviors are consistent with expectations from in-ground-effect data from other commercial transport aircraft. However, the magnitude of these changes are smaller as a function of h/b than for cantilever-wing designs.

While this test was successful in collecting valuable data IGE using the existing support hardware, a new model-to-support system interface for the installation in the LaRC 14x22 facility will be necessary if future testing is to more completely quantify these effects at very low h/b values.

3.2.3 Ice Accretion

Because the TTBW is a significant departure from a conventional cantilever-wing aircraft configuration, it was necessary to evaluate the performance and handling qualities effects due to ice early in the conceptual development phase. The increased concern in the system development is primarily because the long, high-aspect ratio wing (with a relatively small chord) is potentially more susceptible to ice accretion due to the following effects:

1. A small physical leading edge radius collects ice more efficiently as a result of droplet inertia effects
2. The long span results in more area, requiring energy for ice protection (on the wing, strut, and jury strut leading edges) that pose potentially significant challenges for ice protection system design and energy requirements

Understanding these effects and how they fit into the current aircraft certification icing regulatory environment will help inform risk mitigation plans and affect configuration development and testing in future phases of study.

Wing and Strut Icing Regions and Analysis

For initial testing, the ice shape types deemed most critical for impacts to vehicle lift and drag were down-selected from a larger possible set commonly used for aircraft certification studies. Ice shapes from holding in icing conditions for 45 minutes – per FAA Advisory Circular (AC) 25-25A[5] – were calculated for both a cruise configuration with trailing-edge flaps and leading edge device retracted (0/RET), and for a leading-edge-extended configuration with trailing-edge flaps retracted (0/EXT). The NASA Glenn Research Center Icing code, LEWICE3D, was used to determine the ice shapes. The resulting ice shapes were tested in a cruise configuration as well as a number of flaps-extended configurations during this test campaign. Representative ice shapes were 3D printed, had grit applied to simulate surface roughness, and were then attached to the model's wing, strut, and jury strut for testing. In addition, rubble ice (representing roughness left over when a high-lift leading edge device deploys and knocks the large ice horns off of the wing fixed leading edge) was simulated through the use of grit-covered tape. Figure 6 shows some of the simulated ice parts applied to the model wing, strut, and jury strut during testing.

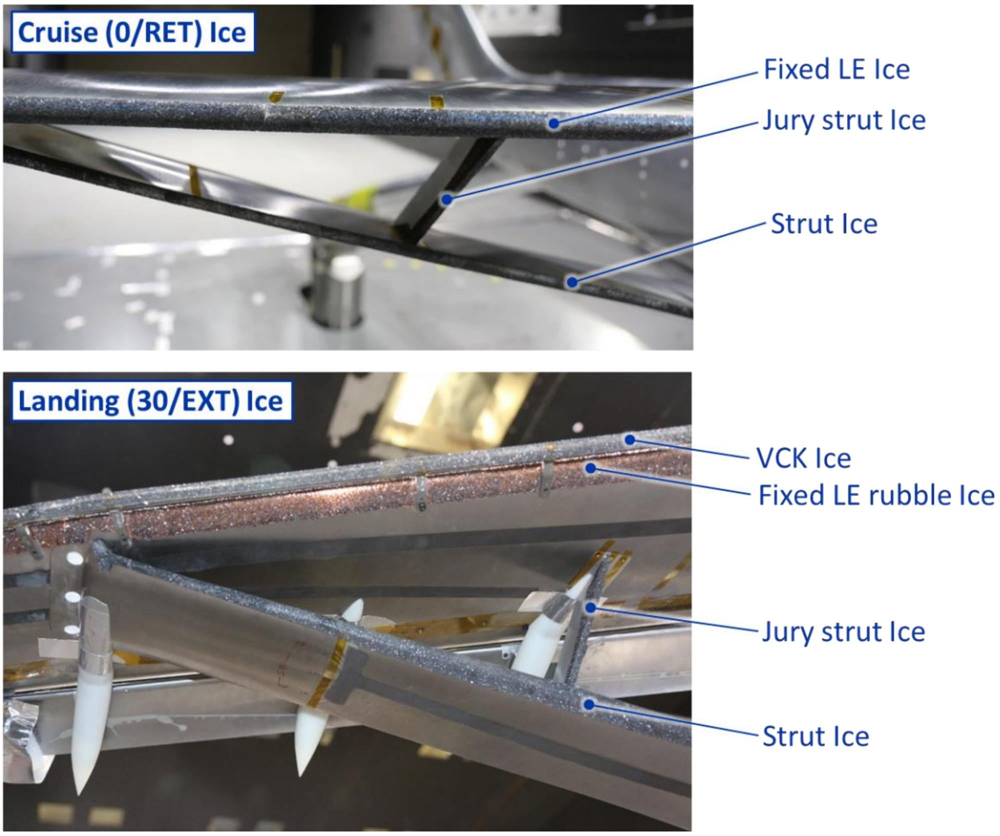

Figure 6. Ice parts were added to the wing, strut, jury strut, and VCK

Key Icing Results Findings

The impacts of simulated ice on vehicle performance varied depending on the component which was iced. The most unique aspects of the TTBW configuration, namely the strut and jury strut, both showed high collection efficiencies in computation. When these shapes are applied however, the vehicle performance was not as adversely impacted as was expected. While ice on the strut and jury strut had an obvious impact on vehicle drag, the lift curve slope, stall angle, and C_{Lmax} of the configuration were largely unaffected by the presence of ice horns for cruise, takeoff, and landing configurations. The result (illustrated in Figure 7) appears to favorably suggest that a large anti-ice system will not be required for the strut and jury strut, and that anti-ice system requirements would be most beneficially focused mainly on the wing fixed leading edge and leading edge high-lift device.

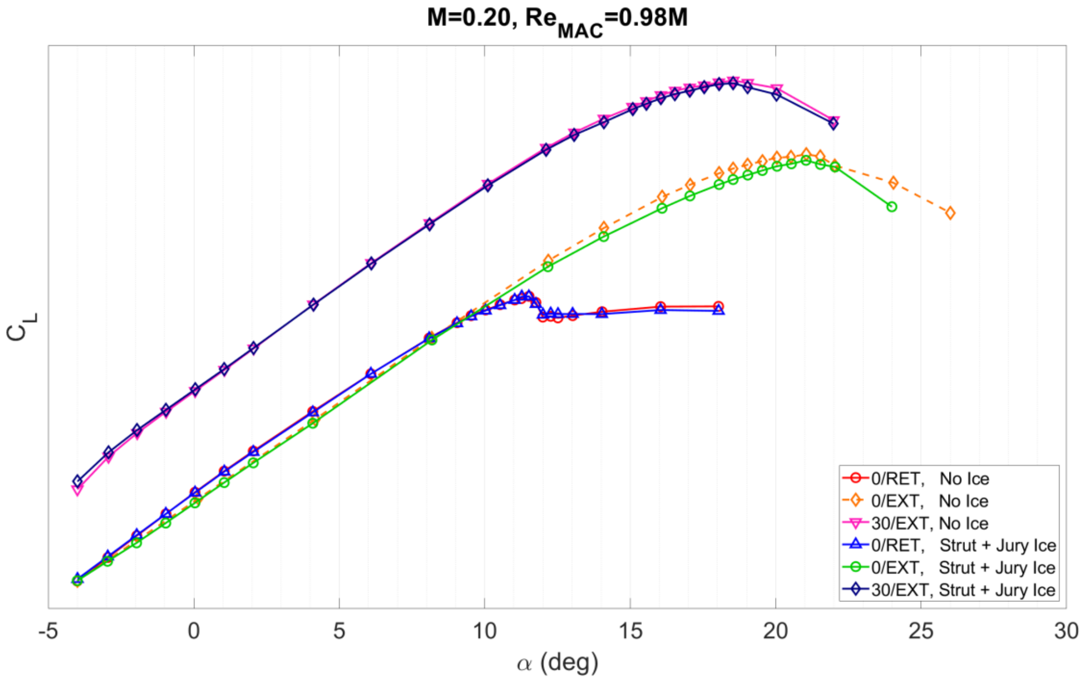

Figure 7. Effect of Ice on Vehicle Lift [M=0.20, Re$_{MAC}$=0.98M]

The results for ice accretion on the wing had a greater impact on vehicle performance. Investigations in the tunnel examined various spanwise extents of ice for the cruise, takeoff, and landing configurations.

Cruise wing icing showed significant decrements in performance when the entire leading edge was iced. While the mid wing ice protection appeared most effective in reducing the decrement to C_{Lmax}, outboard wing ice protection had the largest effect on pitching moment (pitch-up) at stall. Therefore, initial investigations suggest that mid and outboard wing ice protection will be the most effective in returning the wing to acceptable stall characteristics. However, in practice the icing system configuration needs to be studied at an aircraft level in order to determine effects on (leading-edge retracted) landing speeds and vehicle go-around climb gradients needed for aborted landings.

Ice effects in the takeoff and landing configurations (leading edge Kruegers and trailing-edge flaps deployed) were more significant than cruise configuration icing. The effects of icing on the high-lift configurations would primarily manifest in increased approach speeds and reduced maneuver bank angle capability. Similar to the cruise wing icing, the mid-wing region was most sensitive to ice accretion, showing very significant C_{Lmax} decrements when iced. Outboard leading edge device icing resulted in severe pitch-up. In most cases anti-icing of the fixed leading edge reduced the severity of the stall and pitch-up decrements, but overall system performance suggests that most (or all) of the mid and outboard wing leading edge devices and fixed leading edge will require serious consideration for anti-ice systems.

A more rigorous investigation of varied ice effects, including the use of flow visualization techniques, would provide additional insight into the varied effects on vehicle performance. In addition, the low Re of the 14x22 test facility contributed additional uncertainty to the results – future testing would therefore also benefit from increased flow Re such that the inertial/viscous effects could be more completely understood and quantified.

3.3 High-Speed Buffet

Starting in Phase III [6], a series of wind tunnel tests were conducted to investigate and validate the high-speed (cruise) transonic performance of the TTBW concept. The first transonic wind tunnel test campaign for the M_{CRUISE}=0.745 vehicle helped to highlight the various challenges involved in testing very high aspect ratio wing designs at high tunnel dynamic pressures. Lessons from these tests, and the subsequent M=0.80 TTBW design transonic tests, demonstrated restrictions in the achievable Reynolds number (via limitations to model strength) along with instrumentation limitations associated with the wing and strut's small volume. As a result, only limited model surface pressure data could be measured in the tunnel, and significant restrictions were put on the model's operating envelope. Operations near buffet were avoided due to the potential dynamic loads that may be created by the oscillatory shock movement associated with buffet onset.

The interest for testing the TTBW at buffet onset began in the first NASA-funded demonstrator risk-reduction contract. This study identified an uncommon behavior – that the TTBW exhibited the potential for transonic buffet to occur at very low lift coefficients (on the underside of the strut near the wing-strut juncture) and/or in the channel in between the wing and strut. Since many of the heritage tools used for buffet prediction had a strong (or direct) basis in empirical data from conventional cantilever-wing aircraft, it was unclear whether these tools could accurately predict buffet onset within the context of the TTBW's non-linear aerodynamics. A preliminary computational investigation of buffet onset using heritage tools showed a significant variance between the buffet boundaries predicted by these different tools. It was therefore determined to be necessary to investigate this phenomena in the wind tunnel and compare the accuracy of these methods so that safe and accurate predictions of buffet onset could be made for future designs.

3.3.1 Test objectives

To investigate high-speed buffet onset for the TTBW, a new model had to be designed, built, and tested that could withstand the high loads associated with buffet testing while providing a comprehensive instrumentation suite that could measure and monitor flow and physical phenomena associated with buffet onset. To meet this goal, under Phase V a new semi-span model was designed, built, and tested in the NASA Ames 11-ft Transonic Wind Tunnel located at Moffett Field, CA. The test campaign began in late January and ran until late February 2022, for a total of ~320 occupancy hours. The primary objectives of this test campaign were to:

1. Investigate high-speed buffet boundary, including the TTBW's potential for wing upper surface, wing-strut channel, and low-C_L buffet onset
2. Validate buffet boundary prediction tools
3. Acquire loads data across a range of operating conditions and configurations
4. Expand control surface effectiveness database collection previously limited by high model loads

3.3.2 Model Design and Instrumentation

The buffet model (shown in Figure 8) is a 9.0% scale representation of the M=0.80 TTBW vision vehicle. The geometry of this model is the same baseline geometry as was used for the high-speed testing conducted in Phase IV, with minor modifications to the geometry to account for a different objective dynamic pressure (i.e. different model jig twist) and to address wing upper surface-to-floor shock-boundary layer interactions. The model also employed a series of keel dams on the underside of the model to inhibit flow between the semi-fuselage and floor.

Figure 8. 9.0% Scale High-Speed Buffet Semi-Span Model in the NASA Ames 11ft Transonic Wind Tunnel

The buffet model was considerably more heavily instrumented than previous full-span TTBW wind tunnel models. The model was mounted to a semi-span balance and contained 420 static pressure taps, 24 dynamic pressure sensors (Kulites), three accelerometers, and three strain gauges. With this instrumentation the test campaign was able to evaluate a variety of different experimental buffet-prediction techniques based on both steady and unsteady model data. The model also included a full array of deflectable control surfaces, including inboard and outboard ailerons, spoilers, and an outboard strut flap used to alter the flow into the tightest confines of the wing-strut juncture.

3.3.3 Preliminary buffet results

As of July 2022, post-test data analysis of the buffet wind tunnel test results is in progress. Therefore, only initial observations of the acquired data are available at this time.

In general, the buffet test was successful in collecting buffet-onset data at the desired flow conditions in the tunnel. Both steady and unsteady pressure data were collected for several different configurations. Results were also obtained using several different boundary layer trip configurations across a range of forward and aft locations. Additionally, results were collected for free transition on both the wing and strut (independently).

A preliminary prediction of results from pre-test CFD efforts for the forward and aft trip locations is shown in Figure 9. Results in this figure show predicted vehicle lift coefficient at initial buffet onset ($C_{L_{IB}}$) versus freestream Mach number for two different empirically-based methods. The Axial Force Offest (AFO) method is based on a correlation of total aircraft forces to flight test data. Results from the BUFFET code are based on correlations of the computed flow to an empirical database of shock strength vs. shock location. To date, the use of these methods has been limited to predictions and correlations to conventional cantilever-wing aircraft. However, these methods have not been validated for a non-conventional configuration. It is therefore unclear which (if any) of the previous methods are accurate in predicting buffet onset. The difference between the predicted lift conditions where buffet begins clearly illustrates the need for reliable and consistent predictions.

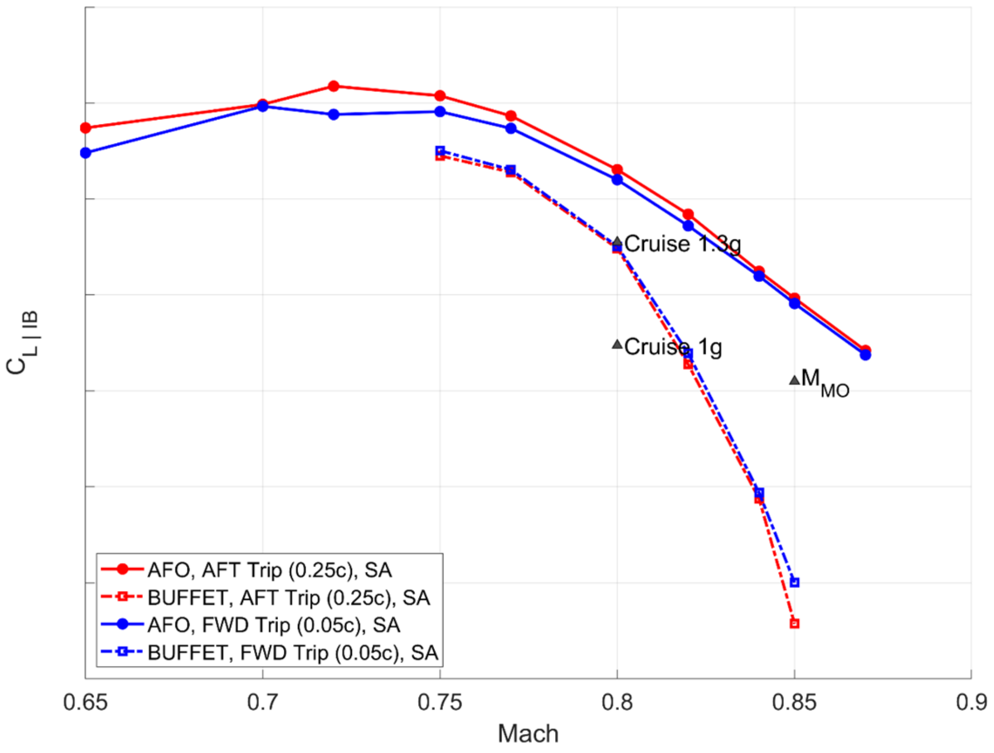

Figure 9. Predicted Buffet Boundary Curve [Re_{MAC}=5.2M]

Results and analysis of the test data will be completed prior to the close of the SUGAR Phase V contract. Comparisons of empirical predictions to test-based methods will be made. Methods to be considered in this analysis include: unsteady-pressure-based methods, trailing edge divergence, pitching moment breaks, AFO, BUFFET, and model response data from the on-board Kulites, accelerometers, and strain gauges.

4. Proposed Objectives for SUGAR Phase VI

As Phase V draws to a close, several areas of technology still require significant maturation in order to make TTBW a viable candidate for future product consideration. While many of the original TTBW design challenges identified in Figure 3 require further maturation, ongoing aircraft integration studies continue to identify additional areas needing development. Some of these technologies are best addressed via flight-scale testing (with a potential X-plane vehicle), while other technologies are more suitably addressed through the use of ground testing and analysis.

Boeing is continuing its focus to identify and retire design challenges of the TTBW. In a proposed next phase of SUGAR, investigations of the TTBW configuration would ideally continue to retire the risks most suitably addressed via analysis and ground test. Potential topics of immediate interest are:

1. Conceptual vision vehicle structural analysis design, including testing of key concepts (wing-strut joint, wing-body joint, strut-body joint, jury-strut joints, and wing-fold)
2. High-Re aerodynamic performance quantification and testing
3. Further studies of alternate high-lift system architectures
4. Icing investigation and test of vision vehicle leading-edge concepts and TTBW-specific junctures
5. Acoustic investigation and test of vision vehicle leading edge concepts and the TTBW configuration

Additional potential future objectives under a potential future phase of study might include:

1. Ditching analysis (loads and certification)
2. Damage tolerance
3. Certification and crashworthiness of non-linear aerostructures

The main objective of these studies would be to mature technologies specific to the TTBW concept that are necessary for the concept to reach a TRL of 5 within the next 5-6 years. It is expected that during this development additional technology challenges may be identified – those technologies would ideally become part of a vision vehicle technology development program as well.

5. Connectivity to a Potential Flight Demonstrator

The development of vision vehicle technologies under SUGAR has initiated significant opportunities for future TTBW development. While SUGAR research is focusing on the maturation of vision vehicle technologies best matured via ground test, a complimentary test and demonstration effort would ideally address those technologies best demonstrated via flight testing. As far back as 2016, Boeing has proposed a subsonic flight-scale demonstrator [7] to mature the TTBW configuration. This demonstrator (shown in Figure 10) would ideally demonstrate transonic and high-lift aerodynamic performance of the TTBW concept, as well as provide critical data regarding vehicle stability and control characteristics and nonlinear aeroelastic stability. In the course of integrating the TTBW into a demonstrator vehicle, technologies addressing thin-wing actuation and thin-wing construction would necessarily be addressed.

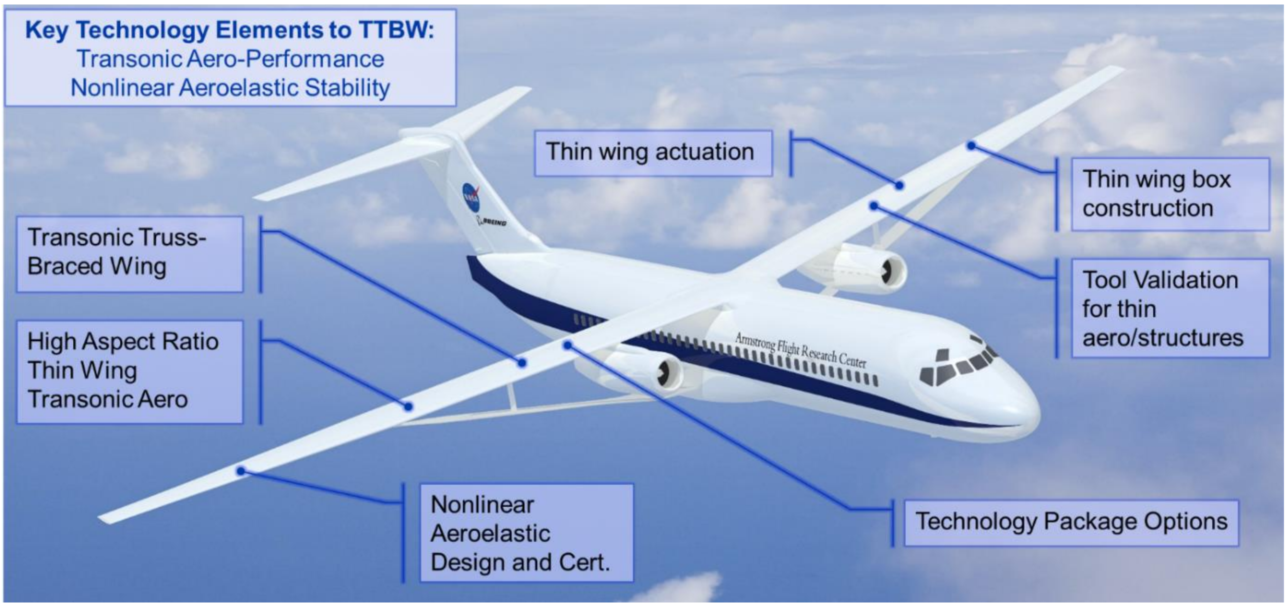

Figure 10. TTBW Demonstrator Concept (c. 2017)

As of July 1, 2022 NASA has released an RFP for a Sustainable Flight Demonstrator, representing aircraft technologies identified for potential insertion into a product in the 2030s timeframe. This program is targeted for award by the end of the 2022 calendar year.

6. Conclusions

Wind tunnel testing in the latest phase of TTBW vision vehicle development has continued to mature the TTBW concept. Investigations of low-speed performance have provided valuable insight into additional aspects of TTBW aerodynamic performance – this data is critical to the sizing and development of a vision vehicle. The preliminary icing testing also provided valuable insight into potential vision vehicle anti-ice systems requirements – a key remaining challenge of the TTBW concept. While post-test analysis of the high-speed buffet data is still being processed, it is believed that the insights gained in this testing will provide valuable guidance for future TTBW designs and predictions of in-flight behavior.

Significant TTBW concept development challenges remain. A comprehensive ground and flight-test campaign will provide the best opportunity to mature the concept to the point where it could be considered for a potential future product.

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8. Contact Author Email Address

For further information, please contact the authors at Neal.A.Harrison@Boeing.com and Gregory.M.Gatlin@NASA.gov.

9. Copyright Statement

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