NASA TRANSONIC TRUSS-BRACED WING STUDIES

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Abstract

NASA aeronautics research on the transonic truss-braced wing (TTBW) concept started in the 1970s. A substantial amount of research has occurred over the last 10–15 years through the Subsonic Ultra-Green Aircraft Research (SUGAR) and related NASA studies. The SUGAR studies included the conceptual design and development of the TTBW configuration as well as wind tunnel testing to reduce the development and performance risk for a future production aircraft. NASA internal studies and technology development have also contributed to maturation and risk reduction of this concept. This paper presents NASA-sponsored TTBW research that is leading to revolutionary improvements in subsonic transport aircraft, which contribute toward achieving the US Aviation Climate Action Plan goal of net-zero greenhouse gas emissions while remaining commercially viable. The focus of this paper is to provide an overview of the NASA-funded and NASA-led TTBW research within the context of the integrated TTBW vehicle design and analysis.

Keywords: NASA, TTBW, Truss-Braced, Systems Analysis, Conceptual Design

1. Introduction

The National Aeronautics and Space Administration's (NASA) Aeronautics Research Mission Directorate (ARMD) focuses on increasing aircraft efficiency, safety, mobility, speed, and more. NASA has advanced aviation and aeronautics research since the establishment of its predecessor, the National Advisory Committee for Aeronautics, in 1915. NASA research now includes sustainable aviation and enabling the United States (US) Aviation Climate Action Plan's goal of net-zero greenhouse gas (GHG) emissions by 2050 [1, 2]. One promising aircraft concept that NASA has been researching for years is the transonic truss-braced wing (TTBW) [3]. The TTBW has efficiency benefits and incorporates numerous technologies that could be a step toward sustainable aviation and achieving the US Aviation Climate Action Plan's goal. Figure 1 is an artist's rendering of a TTBW vision concept aircraft.

This paper highlights recent NASA TTBW studies to mature the concept. In addition to internal studies, NASA funds research with external partners, including the Boeing Company (Boeing)*. Boeing's involvement started in 2008 through a NASA Research Announcement (NRA) focused on advanced concepts [4]. This research included TTBW conceptual design and development as well as wind tunnel investigations to mature the concept [5]. The original truss-braced wing concept resulting from that NRA was called the Subsonic Ultra-Green Aircraft Research (SUGAR) High. NASA is now funding a near full-scale TTBW demonstrator through a Funded Space Act Agreement (FSAA) with Boeing [1]. This demonstrator will enable research in building, testing, and flying the TTBW concept at near full-scale. It will be the first time data will be generated at a large scale for a TTBW configuration, enabling validation of analysis software and methods. NASA is also funding several internal technology and systems analysis studies to research and mature the TTBW concept. The TTBW is often referred to as the TTBW vision concept, configuration, or design. "Vision" refers to an aircraft concept with rigorous analysis that may be more idealized than the eventual production version realized in a future year. This paper presents the NASA and NASA-funded TTBW research within the context of the integrated TTBW vehicle design and analysis.

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Figure 1 – Artist's rendering of a transonic truss-braced wing concept aircraft.

2. Subsonic Ultra-Green Aircraft Research

In 2008, NASA's Subsonic Fixed Wing Project released an NRA as part of its research efforts to explore and develop technologies and concepts to reduce fuel consumption, noise, and emissions resulting in increased performance characteristics and environmental compatibility for fixed-wing subsonic/transonic transports [6]. Boeing's first SUGAR contract was awarded from this NRA [4]. The SUGAR award has continued with five follow-on phases to mature the TTBW concept through testing and risk reduction activities. Boeing designed five aircraft during the first phase of the NRA: a 2008 tube-and-wing baseline called the SUGAR Free, a 2030 tube-and-wing advanced conventional design called the Refined SUGAR, a 2030 TTBW called the SUGAR High, a hybrid fuel / electric powered version of the SUGAR High called the SUGAR Volt, and a 2030 Hybrid Wing Body called the SUGAR Ray. The Phase I results showed that a 154-passenger TTBW configuration could produce 38.9% lower fuel burn, 22 dB lower airport day-night average sound level (DNL) contour noise, and 28% lower NOx emissions than a 2008 baseline tube-and-wing configuration without future technology, when flying the same mission. The Phase II results showed 53.6% lower fuel burn, 23.9% lower landing and takeoff (LTO) NOx emissions, and 64.8% lower mid-cruise NOx emissions. To date, six contract phases have been awarded to Boeing in an effort to identify areas of risk in the development of the TTBW along with reducing these risks through research activities. A timeline showing the research and development efforts conducted in Phase I through Phase VI is presented in Figure 2.

2.1 Phase I

In the initial Phase I contract task, the SUGAR team completed the development of a comprehensive future scenario for worldwide commercial aviation and then selected baseline and advanced configurations for detailed study [4]. Boeing identified technology suites and associated risks for each configuration as part of this conceptual design study. Detailed performance analyses and technology roadmaps were also developed. The study identified significant improvement in air traffic management, aerodynamics, materials and structures, aircraft systems, propulsion, and acoustics as future

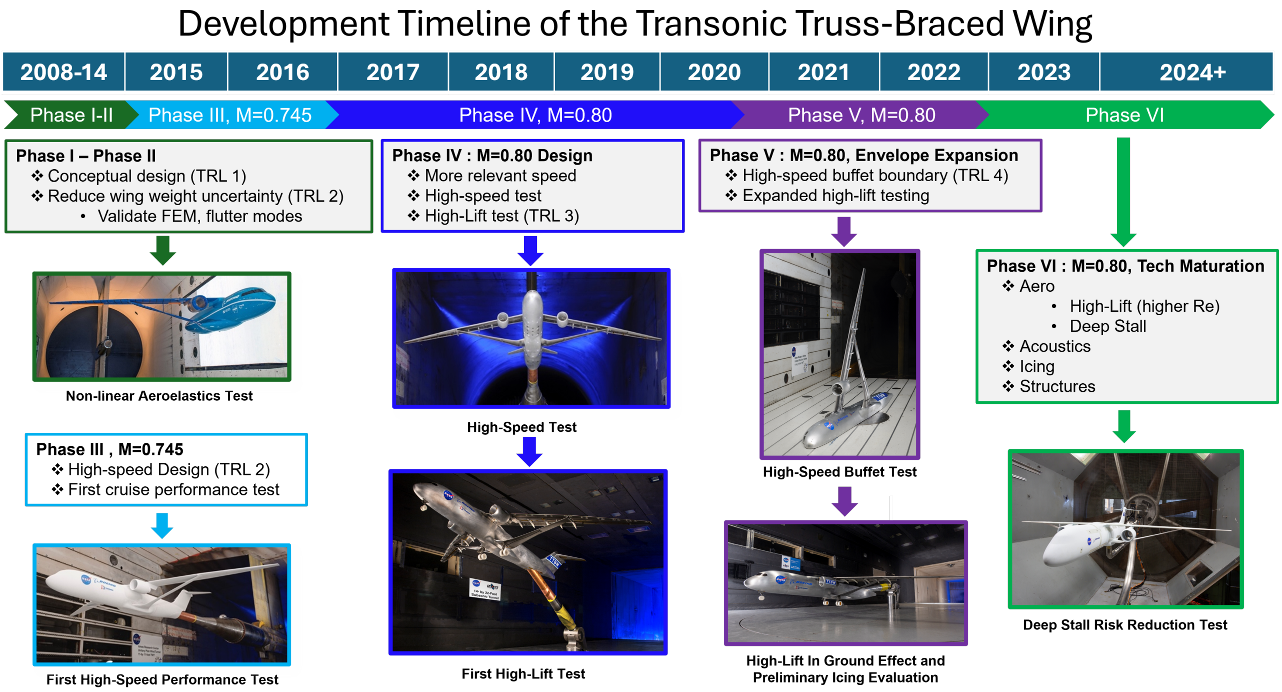

Figure 2 – Development timeline of the SUGAR TTBW.

needs.

One of the advanced configurations studied in the Phase I task was the TTBW concept. This concept enables increased wing aspect ratio at a lower weight than would be typical for a cantilever wing aircraft of the same span. The Phase I task aircraft concepts were designed with a cruise Mach number of 0.70, which is lower than current aircraft of the same size to reduce the fuel burned during flight. One of the Phase I recommendations was for a comprehensive study of high aspect ratio strut/truss braced wings, accounting for coupled aerodynamics, structures, materials, propulsion, and control. A detailed finite element model would be needed and an aeroelastic test would be necessary to validate the structural analysis and to determine the weight of the wing. The high cruise lift coefficient for the high aspect ratio wing would require additional analysis, optimization, and experimental validation.

2.2 Phase II

The Phase II task was directed at the reduction of structural wing weight uncertainty through verification of aeroelastic modes and nonlinear behavior and validation of the high-fidelity finite element model [7]. This included an aeroelastic wind tunnel test in the NASA Langley Research Center's (LaRC) Transonic Dynamics Tunnel, which successfully demonstrated flutter margin and active aeroelastic suppression [8, 9]. Results indicated flutter and aeroelastic issues should not be a concern. The Phase II task also included exploration of alternative energy sources including hybrid electric [10] and other advanced technologies [11]. An initial system noise assessment showed that the SUGAR High concept had certification noise below current regulatory limits but fell short of the NASA goal. A preliminary technology roadmap was proposed to increase noise reduction, which NASA leveraged for internal assessments.

2.3 Phase III

The Phase III task was initiated with the objectives to use high-fidelity aerodynamic analyses to refine the design of a TTBW aircraft at a design Mach number of 0.70 and to verify the performance by building a wind tunnel model and conducting a high-speed wind tunnel test [12]. The design refinement led to a new TTBW concept with an increased design Mach number of 0.745 to be closer to current aircraft of the same size. A scale model of the new design was built and tested in the NASA Ames Research Center (ARC) 11- by 11-Foot Transonic Wind Tunnel (11-ft TWT). The initial conceptual design of a TTBW aircraft with a design Mach number of 0.80 was also included in Phase III. The uncertainty in performance estimates were reduced via the Phase III design refinement and complementary wind tunnel test results.

2.4 Phase IV

The Phase IV task was focused on further development of a TTBW concept with a design Mach number of 0.80 [13]. The higher design cruise Mach number increases the number of flights an aircraft could make in a day, which would result in more tickets sold and more value to an airline operator. The four main objectives of the Phase IV effort were: 1) Refine the conceptual design of the TTBW concept with a design Mach number of 0.80 and incorporate any lessons learned from the previous high-speed wind tunnel investigation, 2) Verify the performance of the TTBW at a cruise Mach number of 0.80 by building a wind tunnel model and conducting a high-speed wind tunnel test, 3) Conduct a high-lift system study and use high-fidelity aerodynamic analyses to refine the design of the most promising TTBW high-lift system for sufficient high-lift performance, and 4) Verify the performance of the TTBW high-lift system by building a high-lift wind tunnel model and conducting a low-speed wind tunnel test. Figure 3 is an artist's rendering of the TTBW vision aircraft from Phase IV.

Figure 3 – Artist's rendering of the SUGAR TTBW vision aircraft (courtesy of Boeing).

The higher design Mach number required a redesign of the TTBW concept outer mold line, including an increase in wing sweep. Each of the Phase IV objectives noted above were successfully addressed, with the high-speed wind tunnel test validating performance predictions and the low-speed test providing a start at building a database to support the continued development of the high-lift configuration. The high-speed test, conducted in the NASA ARC 11-ft TWT, produced important data to be used for the future development of the TTBW aircraft and established the potential for aerodynamic performance benefits at a design cruise Mach number of 0.80. An additional outcome of the high-speed test was that the dataset from the 4.5% scale Mach 0.80 TTBW was used for computational validation by NASA researchers at LaRC and ARC using USM3D and LAVA flow solvers [14].

The low-speed test, conducted in the NASA LaRC 14- by 22-Foot Subsonic Tunnel (14x22-ft ST), primarily focused on optimization of the leading edge variable camber Krueger and trailing edge flaps, assessment of longitudinal and lateral/directional stability and control, and acquisition of control surface effectiveness. One issue that became more evident as the wind tunnel testing progressed was that the high aspect ratio wing configuration drives the chord Reynolds numbers down in the wind tunnel facilities. Also, the high aspect ratio configurations result in smaller model scales than traditional transport configurations, which in turn drives down wing and strut chords and thicknesses. This limits model strength and the number of pressure orifices that can be placed in the wing and strut, particularly the wing/strut junction area. Consequently, future wind tunnel test might require semispan models.

2.5 Phase V

The Phase V task was initiated with the primary objectives focused on assessing buffet conditions and building upon the initial high-lift wind tunnel investigation. The buffet assessment included conducting a transonic buffet wind tunnel investigation focused on determining buffet boundaries and understanding buffet characteristics. In order to enable a higher chord Reynolds number, greater model strength, and a larger scale model to incorporate more instrumentation, a semispan model was built for the buffet investigation. This 9% scale model was twice the scale of the previously tested full-span, high-speed models. The buffet test was conducted in the NASA ARC 11-ft TWT, and results consisting of multiple static and dynamic measurements indicated similar buffet trends. The strut and the wing-strut channel were shown to not be buffet critical, and the wing buffet-critical station was found to be mid-span as opposed to a more typical 70-percent span location.

The high-lift system assessment was continued by conducting a second, low-speed investigation in the NASA LaRC 14x22-ft ST. The objectives for this investigation were to continue with the objectives of the first low-speed test, while also assessing the ground effects and impacts of having simulated ice on the wing leading edge. At the conclusion of the test, the low-speed database had been expanded in regard to high-lift system design. Additional data had also been gathered to assess lateral-directional effects as well as the effects of landing gear, ground spoilers, inboard strut flaps, and individual ailerons. The in-ground-effect test data obtained indicated there is not a strong influence of ground height on longitudinal aerodynamic characteristics other than at the very lowest ground heights. The wing leading edge ice accumulation test data indicated that an ice protection system was needed to mitigate the effects ice accumulation would have on the maximum lift coefficient for both cruise and high-lift leading edge configurations.

2.6 Phase VI

The Phase VI task was divided into two parts, A and B. Part A was recently completed and part B is currently progressing in its early stages.

Part A was directed toward providing specific geometry and information relevant to systems analysis studies and development of future research plans, including the creation of a technology development roadmap for TTBW-enabling technologies. Additional geometry, sizing, weights, and performance information was provided to support NASA's systems analysis studies. The vision aircraft was refined to reflect updated engine performance projections and high-lift model geometries suitable for CFD analysis were provided.

Part B is focused on the next most significant risk reduction areas and includes three wind tunnel investigations to address those areas. The first planned wind tunnel investigation is a low-speed, high-Reynolds number test of a modular 13% scale semispan model. This new model needs to be designed and fabricated. The investigation is to be conducted in the QinetiQ 5-Meter wind tunnel located in Farnborough, UK[†]. The model will be mounted with a peniche on the tunnel floor and will have an unpowered, flow-through nacelle. Cruise, takeoff, and approach configurations will be investigated.

[†] This is not an endorsement by the National Aeronautics and Space Administration (NASA).

The second planned wind tunnel investigation is a deep stall test of the existing 8% scale full-span, low-speed, wind tunnel model that was previously tested in the NASA LaRC 14x22-ft ST. A new model attachment system appropriate for deep stall investigations needs to be designed and built.

The third planned wind tunnel investigation is focused on the effects of icing on the variable camber Krueger high-lift system in the wing-strut junction region of the wing. An icing test article needs to be designed and built that will be a partial spanwise wing/strut section that includes the wing-strut junction. This test is planned for the NASA Glenn Research Center (GRC) Icing Research Tunnel.

3. Boeing X-66

NASA established the Sustainable Flight National Partnership (SFNP) to work with industry, academia, and other agencies toward the US Aviation Climate Action Plan's goal of net-zero GHG emissions from the US aviation sector by 2050. One of SFNP's key components is NASA's Sustainable Flight Demonstrator (SFD) project. The purpose of SFD is to identify, select, and mature airframe technologies and use a full-scale technology demonstrator aircraft to prove their predicted benefits in flight to inform industry decisions associated with the next-generation single-aisle product.

In 2023 NASA awarded Boeing a FSAA to develop, build, test, and fly a near full-scale TTBW demonstrator aircraft, designated X-66 [15]. The SFD project's FSAA includes a $425 million investment over seven years with access to NASA facilities and technical expertise while Boeing and its industry partners will invest approximately $725 million [16]. Boeing and its partners will plan, build, and test the aircraft, and NASA will receive ground and flight data for validation. The X-66 is expected to validate the efficiencies identified in TTBW research, which will contribute to improvements in economics and environmental performance and the US Aviation Climate Action Plan goal of net-zero GHG emissions while remaining commercially viable. Experience from the design and testing of the X-66 will be used to refine the TTBW vision aircraft conceptual designs. Figure 4 is an artist's rendering of the X-66 demonstrator aircraft.

Figure 4 – Artist's rendering of NASA and Boeing X-66 demonstrator aircraft (courtesy of Boeing).

4. NASA TTBW Airframe Icing Research

NASA's ARMD commissioned a study into airframe icing in 2020 that included TTBW as one of the focus areas [17]. The purpose of the study was to assess the priority needs for NASA and enduring needs for the aviation community. The study was performed by icing experts from NASA's GRC and

LaRC with input from icing stakeholders in industry, government, and academia. Icing impacts on the TTBW were evaluated, including identification of needs, gaps, and recommendations. Four key challenges were identified: 1) certification requirements may compromise efficiency goals, 2) comparative analysis cannot be relied upon for icing certification, 3) current icing simulation tools are not fully validated for relevant icing certification, and 4) thin-wing, high-aspect-ratio designs pose challenges for ice protection integration.

The results of this study, along with the icing research performed under SUGAR, will be used to inform the integrated TTBW system studies. If the ice formations or required ice protection systems affect the aircraft performance, restricted flight envelopes may need to be implemented or alternative systems tested. Additionally, the ice protection systems must integrate into the aircraft and work with the other systems.

5. NASA Transonic Truss-Braced Wing Systems Studies

NASA has funded several systems studies that explore the TTBW concept. These studies focused on the overall aircraft performance and the critical subsystems that are key to making the TTBW concept viable. The impact of different technologies, propulsion systems, energy sources, and mission requirements were explored. The following subsections present that research.

5.1 NASA-Sponsored Studies with Virginia Polytechnic Institute and State University

NASA has sponsored TTBW research with the Virginia Polytechnic Institute and State University's (Virginia Tech) Multidisciplinary Analysis and Design (MAD) Center[‡] for configuration exploration and feasibility. Starting in 1996, Virginia Tech used Multidiscipline Design Optimization (MDO) methodology to design TTBW aircraft with a goal of drastically improving aircraft performance [18]. The MDO methodology consisted of a suite of analysis software capable of conceptual-level aircraft design, including analysis modules for TTBW aerodynamics and wing weight that enabled coupling between the aerodynamic and structural analyses necessary for TTBW configurations. This MDO methodology is now used by NASA for independent assessments and internal systems analysis studies. The results of the study [19] show 15% reduction in takeoff weight and 29% lower fuel burn for a TTBW compared to a Boeing 777-200 aircraft with 305 passengers, a design cruise Mach number of 0.85, and a range of 7,380 nmi.

NASA funded additional efforts to improve the TTBW structural analysis [20] and explore the TTBW configuration [21]. The 2012 study [21] explored a TTBW configuration at the Boeing 737-800 size with 162 passengers, a design Mach number of 0.78, and a range of 3,115 nmi. The results show 4% reduction in takeoff weight and a 8% lower fuel burn for the TTBW compared to the tube-and-wing configuration with a design objective function of minimum takeoff weight. The study explored two technology levels, a 1990s aerodynamic technology level and an advanced aerodynamic technology level that included aggressive laminar flow and riblets to reduce the skin friction drag. The tube-and-wing configuration was compared to a strut-braced wing (SBW) and a TTBW. The SBW and TTBW had two different engine installations: fuselage mounted and wing mounted. These studies showed a small, but promising fuel burn reduction for the TTBW configuration.

5.2 Performance Assessment of the SUGAR Phase IV TTBW Configuration

NASA conducted an independent assessment of the SUGAR Phase IV TTBW configuration presented by Harrison et al. [13]. The purpose of the study was to use NASA's internal aircraft modeling and analysis tools to independently verify the fuel burn benefit of the TTBW configuration compared to a conventional tube-and-wing baseline aircraft with similar technology factors. The conventional aircraft was designed with the same mission as the TTBW and used the same engine model. The conventional aircraft was allowed to employ folding wingtips similar to the TTBW configuration, removing the wingspan constraint associated with FAA Airplane Design Group III [22].

[‡] This is not an endorsement by the National Aeronautics and Space Administration (NASA).

The Boeing TTBW design presented in Ref. [13] is called the “As Drawn” configuration. This “As Drawn” design was used as a relatively static reference for the analysis and design of the vehicle subsystems. It was purposely not put through an aircraft sizing analysis to optimize the vehicle performance for the design mission range and other constraints. At the end of the SUGAR Phase IV work, Boeing performed a sizing analysis on the “As Drawn” configuration, producing a “Sized” configuration for TTBW. The sizing procedure produced changes in the wing area, engine size, tail size, and the system weights. The NASA analysis consisted of independent assessments of the aerodynamics, system weights, vehicle static margin, and mission performance for the “As Drawn” aircraft. The focus of this performance assessment was on the airframe technologies, so the engine model technology factors were calibrated to match the engine thrust and fuel burn performance data presented in the Boeing report.

The NASA assessments of the “As Drawn” vehicle were consistent with the Boeing data. NASA followed a similar sizing procedure on the NASA TTBW vehicle model to evaluate the reported fuel burn for the Boeing “Sized” configuration. NASA calculated the fuel burn benefit metric for the TTBW by comparing the calculated block fuel of the sized NASA TTBW model to the calculated block fuel of the conventional aircraft for the design mission range (3500 nmi) and an economic mission range (900 nmi). Aircraft-level performance predictions show that the TTBW offers a 7.2% improvement in fuel burn (per seat) for an economic mission of 900 nmi, and a 9.0% improvement in fuel burn (per seat) for a 3500 nmi mission with full passenger payload, relative to an aspect ratio 13 conventional tube and wing configuration of equivalent technology.

The independent assessment showed that the NASA sized TTBW offers a 5.0% improvement in fuel burn (per seat) for an economic mission of 900 nmi, and a 11.4% improvement in fuel burn (per seat) for a 3500 nmi mission with full passenger payload, relative to a NASA sized aspect ratio 13 conventional tube and wing configuration of equivalent technology. The aircraft models developed in this assessment were used to generate trajectory and engine noise parameter information used for the TTBW system noise assessment described in Section 5.4

5.3 Structural Analysis of the TTBW Wing

To support the NASA independent performance assessment of the SUGAR Phase IV configuration described in Section 5.2 the NASA-developed Higher-fidelity Conceptual Design and Structural Optimization (HCDstruct) software was modified to enable analysis of TTBW configurations [23]. The modifications to HCDStruct included the capability for a user to attach the wing either to the top or belly of the fuselage. A transonic truss-braced wing can now be created by defining and generating a strut and jury as supports to a high aspect ratio wing. Additionally, cross-sectional areas and contact points on the wing and fuselage can now be defined by the user.

For the NASA TTBW independent assessment, these modifications were employed to define the fuselage, wing, strut and jury in HCDStruct. The resulting finite element model was optimized for minimum weight for the wing and fuselage and for minimal cross-sectional area for the strut and jury. Reference [23] describes the weight prediction comparisons made between the HCDStruct results and the SUGAR Phase IV report data. The HCDstruct wing truss weight, which includes the wing, strut, and jury, for the Boeing “As Drawn” vehicle agrees reasonably well with the corresponding Boeing weight from Ref. [13], differing by about 8.3%.

5.4 System Noise Assessments

NASA created an in-house model of the SUGAR Phase IV TTBW to perform an independent noise assessment using NASA’s Aircraft NOise Prediction Program 2 (ANOPP2) framework [24]. The purpose of this study was to estimate the certification noise levels of a TTBW relative to NASA’s noise goals and compare noise levels with a conventional tube-and-wing configuration. This study also developed a noise reduction technology roadmap that showed the potential for further noise reduction.

The noise assessment showed that TTBW had a greater cumulative margin (lower community noise) compared with the conventional configuration. Two of the configuration features that contribute to that advantage are increased shielding of engine noise by the fuselage and better low-speed performance. The noise reducing technologies investigated enabled the TTBW to be better than the historical noise reduction over time trend, but the TTBW still does not meet the NASA mid-term noise reduction goal of 32–42 dB cumulative margin below ICAO Annex 16, Chapter 4 for vehicles with entry-into-service dates prior to 2035 [25]. The fan element was the dominant noise source for the approach, flyover, and lateral certification points. Figure 5 is an artist's rendering of a TTBW vision concept and notional turbofan engine that shows the noise reduction technologies with their corresponding location on the aircraft.

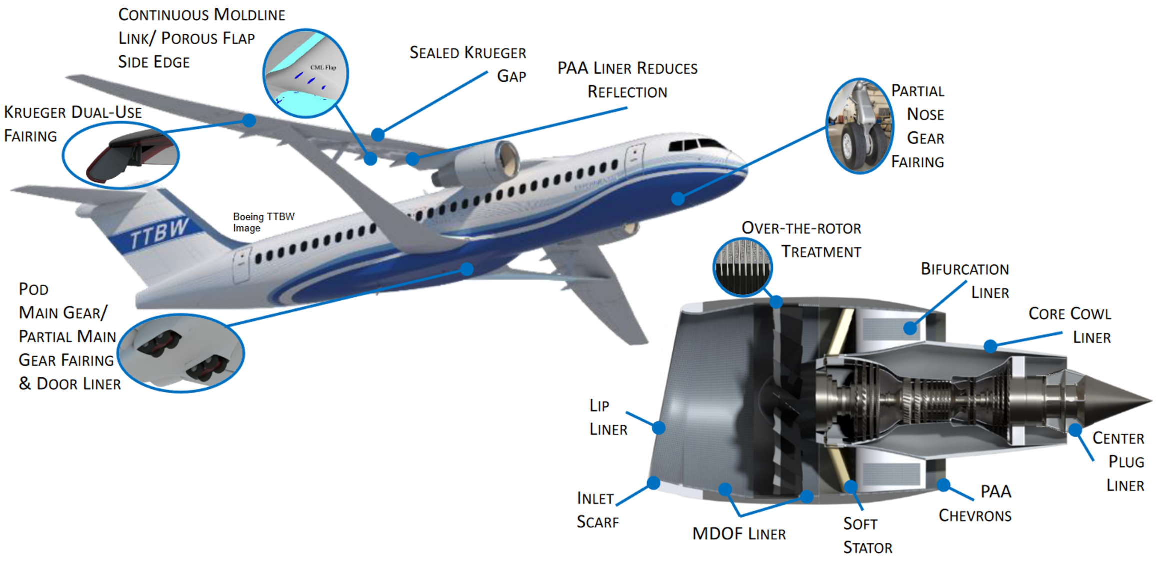

Figure 5 – Artist's rendering of the TTBW and engine featuring TTBW roadmap noise technologies.

NASA plans to continue revising the noise assessment internally. Additionally, NASA has simulated the airframe noise signature of the TTBW [26, 27] using the lattice Boltmann solver PowerFLOW®[§]. This PowerFLOW® analysis complements the system noise assessment, improving the quality of flow-related inputs required by ANOPP2 to predict the airframe noise sources. The airframe simulations also ensure that any TTBW-unique airframe sources are identified. Crucially, the two distinct approaches yield the opportunity to compare trends in predicted relative levels of airframe sources, reducing risk in estimating noise for an aircraft configuration for which no full-scale acoustic data exists. Results from the noise assessments will feed into the integrated TTBW system studies. The TTBW conceptual designs in the systems studies apply the acoustic technologies by accounting for the appropriate weight and/or drag.

5.5 NASA-Sponsored Studies with the Georgia Institute of Technology

NASA has sponsored several studies with the Georgia Institute of Technology (Georgia Tech) Aerospace Systems Design Laboratory (ASDL)[§] to model and evaluate the TTBW configuration. In 2021, NASA funded Georgia Tech to create an aero-structural model of a representative single-aisle class TTBW vehicle. The model had to provide capability for parametric variation of the aircraft design characteristics, including the aircraft size, wing design parameters, and engine weight. The main objective was to improve NASA wing weight prediction methods for the TTBW configuration by including more detailed aero-structural design criteria to assess any potential adverse static or dynamic aeroelastic effects, including maneuvers, gusts, flutter, and divergence. A trade study was performed by developing a design of experiments for the vehicle design variables to generate the data necessary to produce surrogate models for the wing weights. Georgia Tech documented the most relevant aero-

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structural and structural sizing trends and delivered the wing weight surrogate models to NASA for integration into the TTBW conceptual aircraft design synthesis and sizing tools.

In a separate study, Georgia Tech developed their own independent, non-proprietary TTBW aircraft design, which they refer to as their strut-braced wing (SBW) configuration. This work was initiated under a NASA contract to develop an aviation technology dashboard tool to help NASA decision makers evaluate the potential impact of advanced aircraft technologies across a set of different commercial transport aircraft classes and types. The SBW vehicle model was developed as an advanced configuration technology platform for use in the dashboard tool. Work on the SBW configuration continued under a following NASA study with Georgia Tech to look at advanced "zero-emissions" technologies, such as hydrogen-based propulsion systems, propulsion architectures leveraging significant electrification, and other sustainable aviation technologies. The SBW configuration was further matured with the development of a parametric structural sizing model and a parametric aerodynamic drag polar model for integration into vehicle sizing and analysis tools. An initial integration of the SBW model with a single rotor open rotor (SROR) engine model was performed to assess the viability of the open rotor engine concept with the SBW configuration. The engine and airframe were modeled together using computational fluid dynamics (CFD) tools and redesigned to account for aero-propulsive interactions. This work is ongoing and scheduled to finish by the end of 2024.

5.6 Transonic Truss-Braced Wing Design Exploration Study

NASA is currently conducting a design exploration study for the TTBW configuration. The two primary vectors for this study will be aircraft size class and propulsion system type. The size classes will include a 50-passenger regional aircraft, a 154-passenger single-aisle transport aircraft, and a 300-passenger twin-aisle transport aircraft. The propulsion system types will include a turbofan, a mild hybrid electric turbofan, and an open rotor turbine. The TTBW configurations will be compared to conventional tube-and-wing configurations of the same size class, propulsion system type, and technology assumptions. Each study aircraft will be sized to meet mission requirements and constraints for its size class. The design and economic mission block fuel burn differences between the transonic truss-braced wing configurations and conventional configurations will be examined. Trends involving the advantages/disadvantages of the transonic truss-braced wing configuration compared to the conventional configuration for the matrix of aircraft classes and propulsion types will be described.

6. Summary

The TTBW is one advanced aircraft configuration that NASA is researching that shows an advantage over a conventional tube-and-wing configuration in achieving the US Aviation Climate Action Plan's goal of net-zero GHG emissions from the US aviation sector by 2050.

A substantial amount of research was performed during the SUGAR NRA award and the following contract phases. Significant learnings about the TTBW concept were achieved through the risk reduction activities focused on conceptual design, aeroelastic and flutter behavior, high-speed and low-speed/high-lift performance, high-speed buffet, among others. Phase VI-B will continue research with wind tunnel investigations in the low-speed, deep stall, and icing areas. NASA will use this research to refine TTBW modeling methods.

NASA will work with Boeing during the development, building, and testing of the X-66 near full-scale TTBW demonstrator aircraft. This is a valuable opportunity to learn from the development of a near full-scale demonstrator aircraft. NASA will use the ground and flight test data to improve TTBW design and analysis methods.

NASA's research in icing will continue and will leverage results from the SUGAR award tasks. The biggest concern with icing is its impact on takeoff and landing performance. There currently are not any design changes due to icing, but performance must be checked as the TTBW vision aircraft matures. Alternative high-lift and ice protection systems may be needed if an icing condition has a large impact on the takeoff and landing performance.

A recent TTBW system noise assessment performed by NASA showed the fan element was the dominant noise source for the approach, flyover, and lateral certification points. NASA will continue to refine the noise assessment and technology roadmap for the TTBW vision aircraft to reduce the noise certification risks.

NASA performed an independent assessment of the SUGAR Phase IV TTBW configuration to validate the fuel burn performance advantage of the TTBW design over a conventional aircraft. Structural analysis was also performed using NASA's HCDStruct as part of the independent assessment and the results were within an acceptable percent of the SUGAR Phase IV estimates. The independent assessment serves as a validation point for NASA's TTBW design and analysis methods.

The Virginia Tech research developed an MDO methodology that enabled coupled aerodynamic and structural analyses of TTBW configurations. The Georgia Tech studies resulted in wing weight surrogate models and a SBW concept to explore technologies and propulsion systems. The wing weight surrogates were integrated into NASA's TTBW design and analysis methods. NASA is also conducting a design exploration study that will include a 50-passenger regional aircraft, a 154-passenger single-aisle aircraft, and a 300-passenger twin-aisle aircraft. The design exploration also includes turbofan, mild hybrid electric turbofan, and open rotor turbine propulsion systems. The results of these systems studies will guide configuration decisions for future TTBW vision aircraft designs.

7. Acknowledgments

This research was funded by the NASA Aeronautics Research Mission Directorate's Advanced Air Vehicles Program. The authors would like to thank and acknowledge the entire Boeing, Georgia Tech, NASA, and Virginia Tech teams involved in the research, development, testing, and collaboration for the TTBW configuration. The authors would also like to thank the technical reviewers and all who contributed to this paper.

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