

Aeroacoustic Computations of a Transonic Truss-Braced Wing Aircraft: Part 1 – Aerodynamic and Airframe Noise Simulations

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Computational results are presented for an 8%-scale, full-span, transonic truss-braced wing (TTBW) model simulated as installed in the NASA Langley Research Center 14- by 22-Foot Subsonic Tunnel and in free-air conditions. The simulations were conducted with the lattice Boltzmann solver PowerFLOW[®] to capture the time-accurate characteristics of the flow. The aerodynamic behavior of the aircraft was investigated in the landing configuration, with high-lift devices and landing gear deployed, as well as in the clean (cruise) configuration, with these components stowed. Analyses were performed on local flow quantities, global forces, and time-averaged surface pressures. Aerodynamic quantities were shown to be sensitive to mesh resolution levels, driven by small geometric features inherent to the TTBW model. Flow features of the TTBW model were examined, with the wing/strut configuration of this model presenting unique behaviors generally not found in conventional transport aircraft. Near-field, time-dependent flow quantities obtained from the scale-resolving simulations were used in conjunction with a Ffowcs-Williams and Hawkins integral approach to predict the far-field airframe noise signature of this advanced concept. The effects of permeable data surface end caps on the far-field noise spectrum in the flyover direction were determined to be negligible.

I. Nomenclature

δ_f	=	flap deflection angle
AoA	=	angle of attack
ARC	=	Ames Research Center
CAD	=	computer aided design
CFD	=	computational fluid dynamics
C_p	=	pressure coefficient
C_L	=	lift coefficient
C_D	=	drag coefficient
C_m	=	moment coefficient
CAE	=	Computer Aided Engineering
FA	=	free air
LaRC	=	Langley Research Center
LBM	=	Lattice Boltzmann method
LG	=	landing gear
M_∞	=	Free-stream Mach number

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Re = Reynolds number
TTBW = Transonic Truss Braced Wing
VCK = variable camber Krueger

II. Introduction

Advanced propulsion and airframe concepts are being matured within the aerospace community that could yield substantial reductions in fuel consumption and emissions to foster the goal of sustainable aviation. In addition to gains in fuel efficiency, an accurate prediction of the ground acoustic signature of these aircraft concepts is necessary to understand their impact on communities near airports during takeoff and landing operations. The transonic truss-braced wing (TTBW) concept is an advanced configuration that has garnered significant attention in the last decade. In this effort, the airframe noise signature of a Boeing-designed TTBW aircraft is examined via high-fidelity aeroacoustics simulations.

Under contract to NASA, Boeing conducted a series of studies to determine the feasibility of a single-aisle, 150-160 passenger TTBW concept to achieve significant fuel burn reduction relative to the best-in-class conventional configurations. The studies documented in Refs. [1], [2], [3], and [4] resulted in the development and assessment of a TTBW aircraft designed for a cruise Mach number $M_\infty = 0.75$. Further refinement of the TTBW concept was undertaken by Boeing to produce a viable design for $M_\infty = 0.8$, a cruise speed comparable to that of conventional civil transports. During this phase, the low-speed aerodynamic characteristics of the $M_\infty = 0.8$ TTBW aircraft in various landing and take-off configurations with different leading-edge and trailing-edge high-lift devices were also examined by Boeing as part of the design process. In addition, 4.5%- and 8%-scale models of the $M_\infty = 0.8$ TTBW aircraft were developed and fabricated. The smaller model was used to evaluate the cruise performance of the aircraft via wind tunnel testing at the NASA Ames Research Center (ARC). The larger, 8%-scale model was fabricated exclusively to: evaluate the low-speed features of the TTBW concept; determine the performance of the high-lift devices at approach, landing, and take-off conditions; and gain insights into the stability and control characteristics of the concept with and without ground effect. To accomplish these goals, the model was tested during 2019 and 2021 in the NASA Langley Research Center (LaRC) 14- by 22-Foot Subsonic Tunnel (14x22), where a significant amount of aerodynamic data comprising model forces, moments, and steady surface pressures were collected. A summary of the Boeing studies, conducted under the Subsonic Ultra-Green Aircraft Research (SUGAR) program, and a description of the resulting sub-scale TTBW models, is provided in Ref. [5].

To date, aeroacoustic measurements of the 8% TTBW aircraft do not exist. Computational studies have focused on the prediction of different aerodynamic effects and characteristics of the $M_\infty = 0.745$ and 0.80 TTBW designs for cruise conditions [6-13]. The only acoustic study for relevant low-speed conditions known to the authors is that of Ref. [14], where a detailed system noise assessment of the concept was performed based on semi-empirical models of airframe and propulsion noise sources. Although substantial improvements have been made to the semi-empirical models currently used to predict system-level aircraft noise, an apparent need exists for an accurate, complementary but separate, physics-based acoustic assessment of novel configurations such as the TTBW concept. The present effort, conducted under the NASA Advanced Air Transport Technology project, is a first attempt to gain a better understanding of the airframe noise signature and major sources of the $M_\infty = 0.8$ TTBW design in landing via high-fidelity, scale-resolving simulations. For this purpose, we follow a carefully planned computational approach similar to that applied to the study of airframe noise generated by a generic low boom concept [15-17], where no previous knowledge of the airframe noise signature existed. The computational approach, aeroacoustic simulations, validation of aerodynamic results, and single microphone far-field acoustic spectra for the overhead position are presented in this paper. A detailed acoustic assessment of the primary and secondary airframe noise sources using synthetic microphone-phased-array data is covered in a companion paper [18].

III. Simulated Configuration and Force Processing

The present computational campaign used the 8%-scale model of the Boeing $M_\infty = 0.8$ TTBW design. Since a CAD geometry definition for the “as-tested” TTBW model in landing configuration was not available, our effort began with simulations of the TTBW in cruise with and without landing gear while an accurate digital model of TTBW in landing was being developed. For aerodynamic validation purposes, a digital replica of the complex model support was generated and integrated into a CAD representation of the NASA 14x22 wind tunnel. In-tunnel simulations were performed to facilitate direct aerodynamic comparisons with measured data. Once these computations were complete, the wind tunnel was removed while maintaining free-stream conditions, and the TTBW model was simulated in free-air (FA) to ensure that wind tunnel and model blockage effects, if any, were quantified. The FA simulation setup accurately predicted the measured aerodynamic data, indicating that model blockage effects were negligible. Two

configurations were simulated to predict the far-field acoustic signature of the TTBW: a clean (cruise) configuration, which consists of the model with landing gear retracted and high-lift devices stowed, represents the quietest possible configuration; and a landing configuration, which corresponds to the TTBW model with landing gear and high-lift devices deployed. In this paper, we will present only aerodynamic and acoustic results obtained from FA computations with emphasis on the landing condition, which is the configuration of highest importance.

A. Aircraft Configuration – Free Air

Geometry definition and generation of the CFD-ready CAD files were accomplished by personnel from the LaRC Geometry Laboratory. The “as-tested” landing configuration was developed meticulously over a period of seven months from extremely accurate laser scans of the various high-lift components re-installed on the TTBW model. To determine precisely the geometry and settings of the leading-edge variable camber Kreuger (VCK) flaps, multiple laser scans of the various VCK segments, including their brackets, were conducted. After each uninstalled element was scanned separately, the flap system was incorporated into the model’s wing and scanned again.

Both clean (Fig. 1) and landing (Fig. 2) configurations share identical main geometric components that include the fuselage, t-tail, wing-to-body fairings, main wings, jury strut, nacelles, chines, and flap track fairings. The landing-configured TTBW model is distinguished by the presence of landing gear, trailing-, and leading-edge high-lift devices. Landing gear contain major flow-facing components such as bay doors, wheels, axles, braces, and other large structural members. But, as tested, the finer details of the gear were not included in the 8%-scale TTBW model. The tested and simulated model also lacks typical landing gear bay cavities, mating the deployed landing gear main post directly to the fuselage surface. The trailing edge high-lift device used in the landing configuration is of the Fowler type, deflected to approximately $\delta_f = 30^\circ$, and is comprised of three spanwise elements. Between the inboard and middle flap elements, a small gap allows air to flow between the bottom (pressure) and top (suction) surfaces. The leading-edge high-lift device used on this model is a VCK flap, as mentioned earlier. Along the span, the flap is comprised of nine independent elements (segments) with distinguishable gaps between element one and two in the vicinity of the engine pylon, and between elements four and five where the wing leading edge sweep angle changes. Pains-taking effort was put into accurately capturing the gaps and overlaps implemented between the remaining VCK elements of the wind-tunnel model. Differential deflections of the VCK elements were required to maintain reasonable stall characteristics [5]. For example, segment 1, residing between the nacelle and the fuselage, was deflected at a nominal angle of 63° , and segment 9, near the wing tip, was deflected at 36° . The differential deflections of the various VCK segments created spanwise discontinuities in the leading-edge flap surfaces that are sufficiently large to act, potentially, as secondary noise sources. Care was exercised to ensure that these surface discontinuities were adequately resolved.

As observed in Fig. 2, the VCK brackets are bulky and not representative of the actual brackets that would be used in a full-scale aircraft. Due to the relatively small size of the VCK flap, the size of model-scale brackets had to be increased to carry the anticipated aerodynamic loads. Since these brackets are bluff bodies, most likely they will be identified as prominent noise sources during the simulations. However, given the exploratory nature of our initial airframe noise simulations, we decided to maintain the entire “as-tested” TTBW geometry for this phase. More importantly, if the 8%-scale model is used to acquire acoustic measurements for validation purposes, the same VCK brackets will be maintained. For the next phase, when we consider a full-scale TTBW model, configurations without the VCK brackets and with more realistically shaped brackets will be examined to assess the full contribution of these components to the far-field airframe noise signature of the TTBW concept.

Care was also taken to ensure that all other relevant geometric features of the tested TTBW model were maintained in the simulations – the engine features a flow-through nacelle and core section, as well as chines inboard of the nacelle pylons. Additionally, the engines were simulated with a slight toe-in angle, consistent with the experimental geometry. For reasons of structural integrity and ease of fabrication, the “as-tested” 8%-scale model has very thick trailing edges (TE) for the wing, strut, flap, and nacelle. During initial airframe noise simulations for the cruise configuration (see Ref. [18]), we observed that the broadband noise spectrum was dominated by numerous broad tonal sources produced by vortex shedding from the variable, thicker-than-normal TEs. The CAD geometry was carefully modified to eliminate these tonal sources, resulting in a TTBW model with much thinner and uniform TEs that are more representative of an actual full-scale aircraft. For the lift-producing components, such as the wing, flap, and strut, only the pressure surfaces were altered to arrive at the thin TEs. The VCK elements were not modified. Although the camber lines for the wing, strut, and flap were altered slightly, the end effect on the model aerodynamic characteristics is negligible, as will be demonstrated in the following sections.

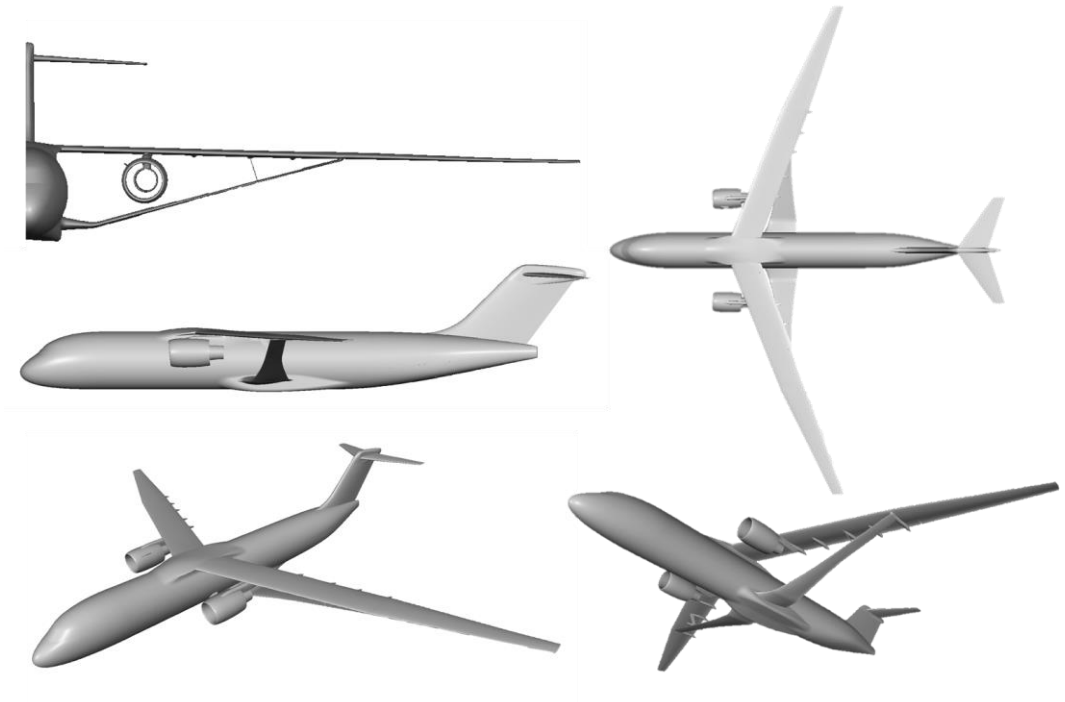


Fig. 1 Images of TTBW aircraft in clean configuration as simulated in free-air conditions

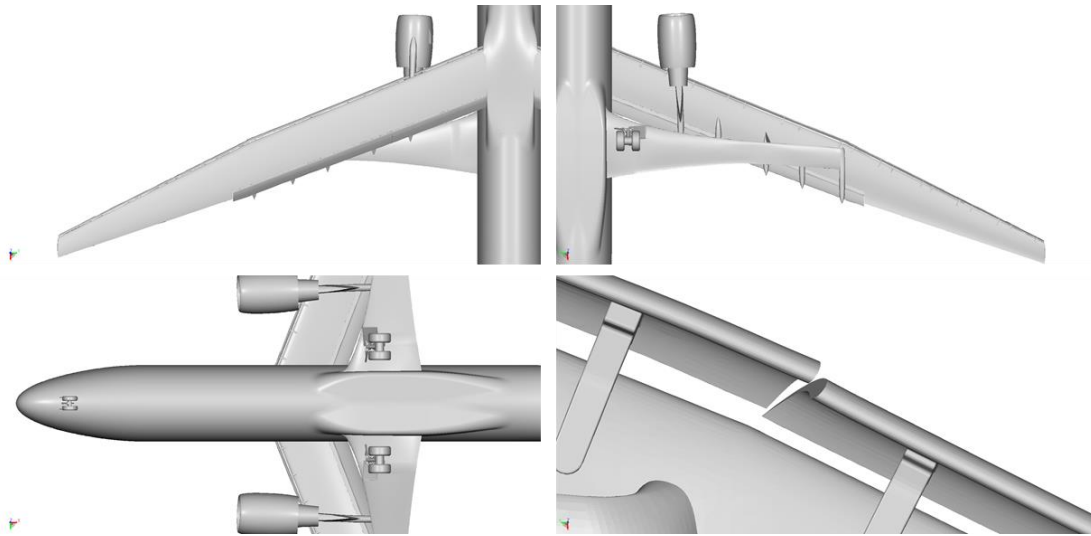


Fig. 2 Images of TTBW features unique to the landing configuration.

B. Flight Conditions

The simulations were executed at a fixed angle of attack $AoA = 6.0^\circ$ and at $AoA = 6.1^\circ$ for the clean and landing configurations, respectively. Different $AoAs$ were used to improve alignment with wind tunnel test set up – clean configuration simulations were performed at $AoA = 6.0^\circ$ before discovering that the tests were, in fact, performed at $AoA = 6.1^\circ$. Despite this difference, little change in aerodynamic properties was expected.

The Reynolds number for both configurations was approximately $Re = 975,000$ (based on mean aerodynamic chord) with a free-stream Mach number of $M_\infty = 0.2035$ to match wind tunnel test conditions. Due to the enhanced lift-to-drag ratio, L/D , of the TTBW concept, the landing speed for the full-scale aircraft is also projected to be close to $M_\infty = 0.2$.

IV. Computational Approach

The numerical simulations were performed using Dassault Systèmes’ PowerFLOW® solver, which is based on the three-dimensional 19 state (D3Q19) lattice Boltzmann method (LBM) [19-22]. LBM has been validated extensively for a wide variety of applications ranging from academic direct numerical simulation (DNS) cases to industrial flow problems in the fields of aerodynamics [23] and aeroacoustics [24-26]. At a macroscopic level, LBM uses a simpler and more general physics formulation than methods based on the Navier-Stokes equations [19]. The LBM equations recover the macroscopic hydrodynamics of the Navier-Stokes equations through the Chapman-Enskog expansion [27, 28].

The local formulation of the LBM equations allows a highly efficient implementation for distributed computations on thousands of processors. The low dissipation and dispersion properties of the numerical scheme typically produce aerodynamic and aeroacoustic results that are comparable to those obtained with classical CFD solvers that use higher-order large eddy simulation (LES).

A. Turbulence Modeling

A lattice Boltzmann flow simulation is equivalent to a DNS of the flow. For high Re flows, such as those addressed in this work, the lattice Boltzmann Very Large Eddy Simulation (LB-VLES) approach is used to reduce computational resource requirements [19, 29]. This means that turbulence is modelled in areas of attached flow, such as boundary layers, but resolved in wakes or regions of detached flows.

B. Wall Treatment

The standard lattice Boltzmann bounce-back boundary condition for no-slip or the specular reflection for free-slip condition are generalized through a volumetric formulation [19, 20] near the wall for arbitrarily oriented surface elements (surfels) within the Cartesian volume elements (voxels). This formulation of the boundary condition on a curved surface cutting the Cartesian grid is automatically mass, momentum, and energy conservative while maintaining the general spatial second-order accuracy of the underlying LBM numerical scheme. To reduce the resolution requirements near the wall for high Re flows, a hybrid wall function is used to model the region of the boundary layer closest to the solid surfaces [21, 30].

C. Extensions to High-Subsonic Flows

To enhance the numerical stability of high-speed flow simulations, the current 19-state LBM employs an extended collision operator [31] when $M > 0.5$, as it may occur in areas of flow acceleration near wing leading edges. For energy conservation, the lattice-Boltzmann equation is coupled with an entropy solver similar to that found in Ref. [32]. An improved pressure coupling algorithm [33] has been used to couple the entropy solver and the LBM flow solver. This extends the Mach number limit of the standard LBM to near sonic conditions. The LBM used in this study has been shown to be second-order accurate in both time and space [34, 35]. An extended volumetric boundary scheme for implementing the LBM particle bounce-back algorithm on arbitrary geometries has been applied to achieve no-slip wall boundary conditions. For high Re flows, turbulent wall boundary conditions are realized through a generalized LBM slip algorithm and a modified wall-shear stress model, which reduce the high near-wall resolution requirement for turbulent flow simulations.

D. Meshing

PowerFLOW® implements the lattice Boltzmann method on automatically generated Cartesian meshes. These meshes benefit from Variable Refinement (VR) regions that allow local mesh refinement by successive factors of two. The present study employs a three-level mesh refinement strategy labeled coarse, medium, and fine. The mesh sizes for the resolutions sampled thus far are presented in Table 1. Two mesh strategies were implemented in the course of this study, one to capture aerodynamic characteristic of the TTBW aircraft, and the other to ensure adequate resolution of the desired acoustic frequencies. The ability to quantify accurately far-field acoustics from simulations requires a far more stringent maintenance of finer spatial resolution over a larger domain than a representative aerodynamics-focused simulation. Since the focus of this work is airframe noise prediction, the relatively large mesh sizes used for the acoustic simulations are listed in Table 1. Of note is the larger surfel count for the aircraft in cruise configuration. Due to the manner in which resolution was applied, some surfels were created on areas of the aircraft that were not flow-critical. This issue was rectified during the setup steps of the aircraft in landing configuration.

Table 1 Grid sizes for acoustic TTBW aircraft simulations.

	Smallest Voxel Size [mm]	Landing Config. Voxels [M] Surfels [M]		Clean Config. Voxels [M] Surfels [M]	
Coarse	0.1760	1,648	36	1,356	41
Medium	0.1173	5,230	64	4,029	74
Fine	0.0782	TBD	TBD	TBD	TBD

V. Numerical Results

The lack of measured acoustic data for the TTBW concept dictated that the initial focus of our effort be aerodynamic computations and validation of the predicted results against 14x22 wind tunnel measurements. At a minimum, both cruise and landing configurations were simulated at two spatial resolutions to assess the accuracy of the computed aerodynamic trends. Once the predicted data were assessed and validated, our effort shifted to the much more challenging simulation of the TTBW model airframe noise signature.

A. Aerodynamic Analysis

In this section, we assess the convergence trends of time-averaged surface pressures and integrated forces, and compare aerodynamic results with measured data. Evaluation of integrated forces and moments, such as C_L , C_D , and C_m , and their comparison with measured values is complicated and requires careful consideration.

1. Grid Resolution Study: Free Air

Representative plots illustrating the sensitivity of the predicted surface pressure coefficients, C_p , to increasing spatial resolution are shown in Fig. 3 for the clean configuration. These results were obtained from free-air (FA) simulations. The plots present chordwise pressure distributions at a spanwise location on the wing and strut. The data clearly illustrate very good convergence of the time-averaged pressures even at the coarser mesh level. Although not shown, the C_p values show similar convergence behavior at all other spanwise stations examined. The distributions presented in Fig. 4 compare predicted pressures with measured data. Also included in Fig. 4 are simulated pressure values from a steady Reynolds-averaged Navier-Stokes (RANS) computation performed with the LaRC FUN3D [36] unstructured mesh solver³. The predicted surface pressures on the model wing and strut (Fig. 4) show a near perfect match between PowerFLOW[®] and FUN3D solutions. Moreover, both sets of computed pressures are in excellent agreement with measured data. This level of agreement between predicted and measured C_p s provides clear evidence that model blockage effects at low to moderate AoA are negligible, reinforcing the fact that the FA setup used in our simulations is quite appropriate for validating low-speed aerodynamic results.

The corresponding lift and drag coefficients also closely track the measured values. Although not shown, a variation of 0.6% is observed in C_L and 3.3% in C_D for the clean configuration when considering coarse-to-fine values.

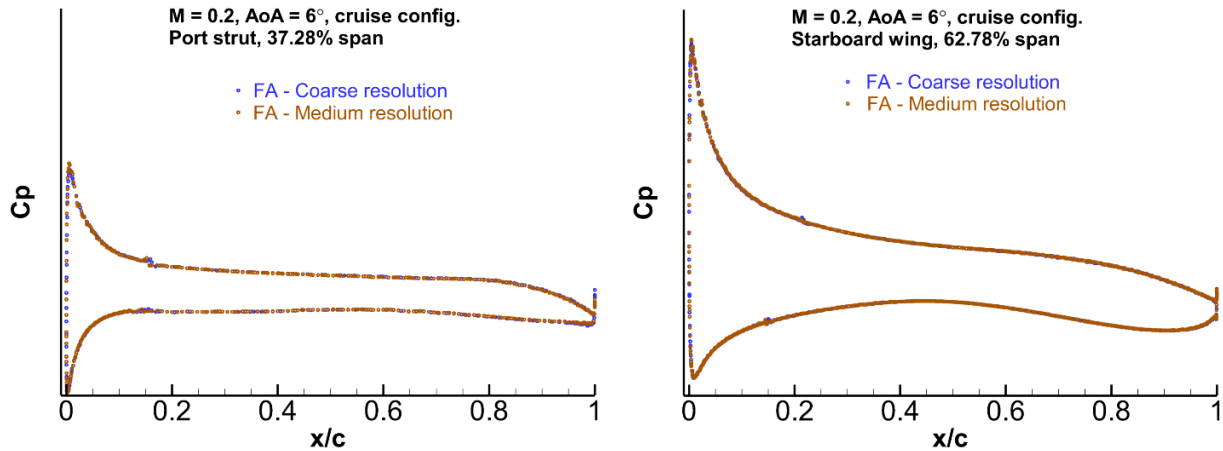


Fig. 3 Spatial resolution effects on chordwise pressures for clean (cruise) configuration. Starboard wing (right) and port strut (left).

³ The FUN3D computation (unpublished) was performed by Veer Vatsa of NASA LaRC.

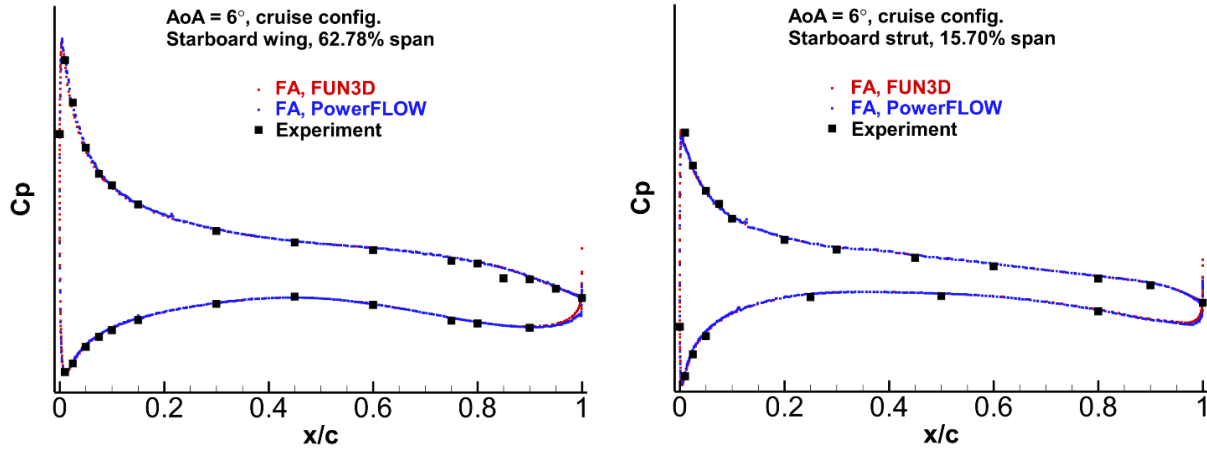


Fig. 4 Comparison of chordwise pressures with results obtained from FUN3D and measured data for clean (cruise) configuration. Starboard wing (left) and strut (right). Coarse resolution PowerFLOW® values.

The computed lift (C_L) and drag (C_D) coefficients for the landing configuration are presented in Fig. 5. The data contain results from the simulated model with the original trailing edge thicknesses (thickTE) and with the modified, thinner trailing edges (thinTE). Very good agreement with measured values is observed for both coefficients even at the coarser resolution level. As anticipated, reducing the trailing edge thicknesses had a negligible effect on the TTBW model integrated forces. A more direct comparison between predicted and measured aerodynamic quantities is given in Table 2. With the original trailing edges (thickTE), the computed forces are within $\pm 3.25\%$ of the measured values, with the C_D showing closer agreement. During the wind tunnel tests, several static probes were used to measure the pressures inside the large fuselage cavity where the model support arm mated with the force balance. These interior pressures were used by Boeing test engineers to correct force balance output. In our simulations, we avoided this step by eliminating the model support system and resorting to a FA setup. Despite this major difference in model setup, we were encouraged by the close agreement between predicted results and measurements.

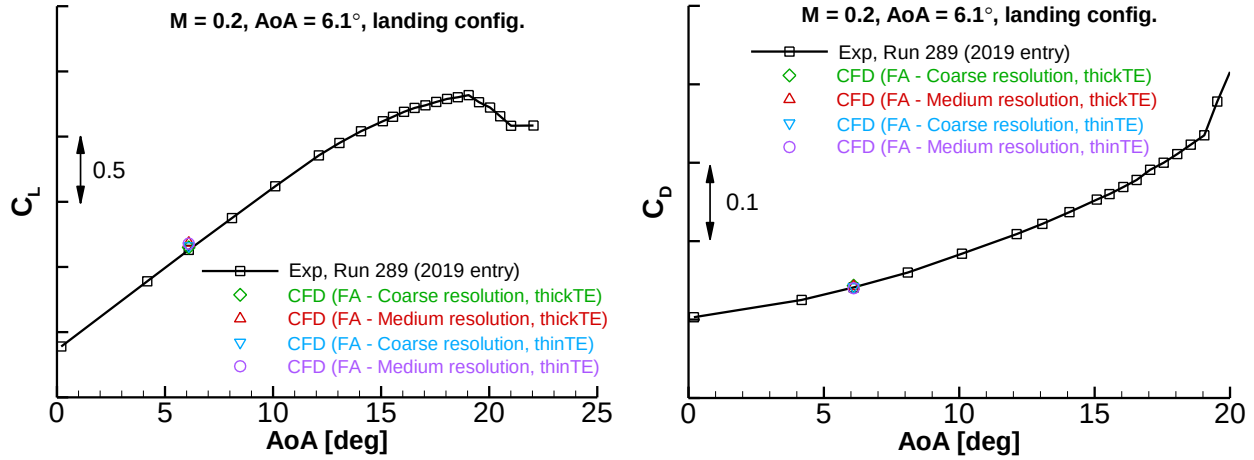


Fig. 5 Comparison of force coefficients obtained at two mesh resolutions with measured data for landing configuration. Lift coefficient (left) and drag coefficient (right).

Table 2. Quantitative comparison of predicted aerodynamic coefficients with measurement.

	% difference = ((simulated – measured)/measured) x 100					
	“As-tested” original geometry (thick TEs)			“As-tested” geometry (thin TEs)		
	C _L	C _D	L/D	C _L	C _D	L/D
Coarse resolution	1.2%	1.6%	-0.4%	1.84%	2.84%	-0.97%
Medium resolution	3.25%	1.0%	2.2%	2.84%	-0.71%	3.68%

Representative chordwise pressure distributions for the TTBW model in landing configuration are shown in Fig. 6 and Fig. 7. The figures display comparisons of computed wing and flap pressures at two different spatial resolutions with measured values at two spanwise locations between the fuselage and jury strut. Results from starboard (right) and port (left) sides of the aircraft model are presented. The predicted pressures display good convergence behavior with increasing resolution. Results from the medium-resolution solution are in close agreement with measured C_p distributions. The C_p distributions at two spanwise locations situated closer to the wing tips are shown in Fig. 8. Very good agreement was obtained even at the lower resolution level. Observe, however, the presence of small discrepancies between predicted and measured pressures at the wing and flap leading edges. The suction peaks in this region are extremely sensitive to any deviations in gap and overlap settings of the VCK and flap components. We provide two possible reasons for these discrepancies. First, during CAD geometry development, we may have erred in duplicating precisely the high-lift settings used on the “as-tested” model. Second, we doubt that the 8%-scale TTBW model acted as a rigid structure during wind tunnel testing. For a model with such a large wing aspect ratio, even small wing deflections under loading are sufficient to alter slightly the model settings. These small deviations are hard to measure and even harder to simulate.

The computed pressure field at two spanwise locations on the starboard strut are presented in Fig. 9. Excellent agreement between computed and measured values is observed for this lifting component as well. As noted previously, this level of agreement in C_p s on different components lends support to the observation that, at low to moderate AoA, tunnel blockage effects due to model installation were negligible during the 14x22 tests, even for the landing configuration when higher lift is produced. As was the case for the integrated forces, the steady surface pressures presented in Figs. 7-10 reinforce the fact that thinning the model trailing edges has a minimal effect on the C_p values.

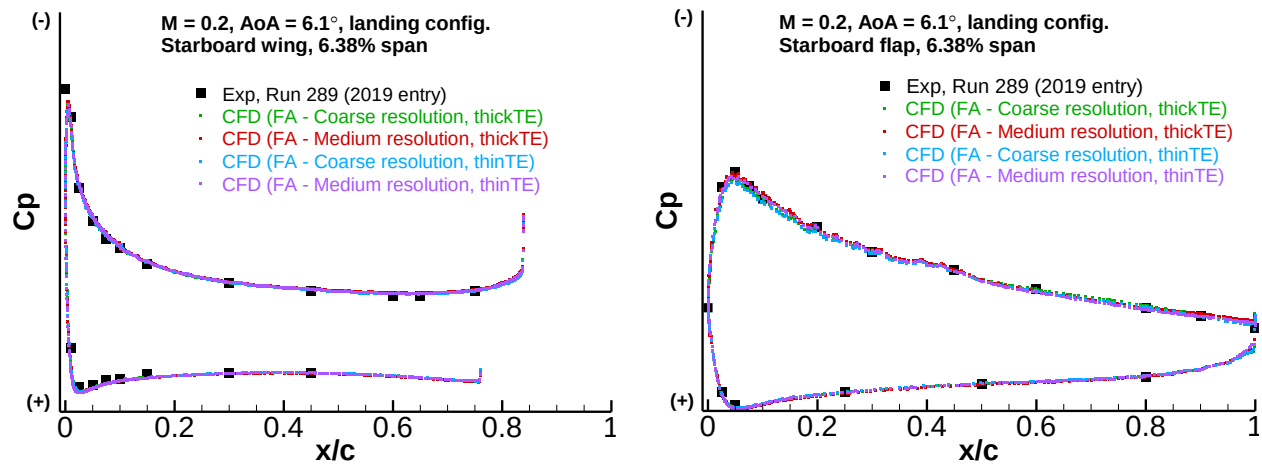


Fig. 6 Comparison of chordwise pressures at two mesh resolutions with measured data for landing configuration. Starboard wing (left) and flap (right).

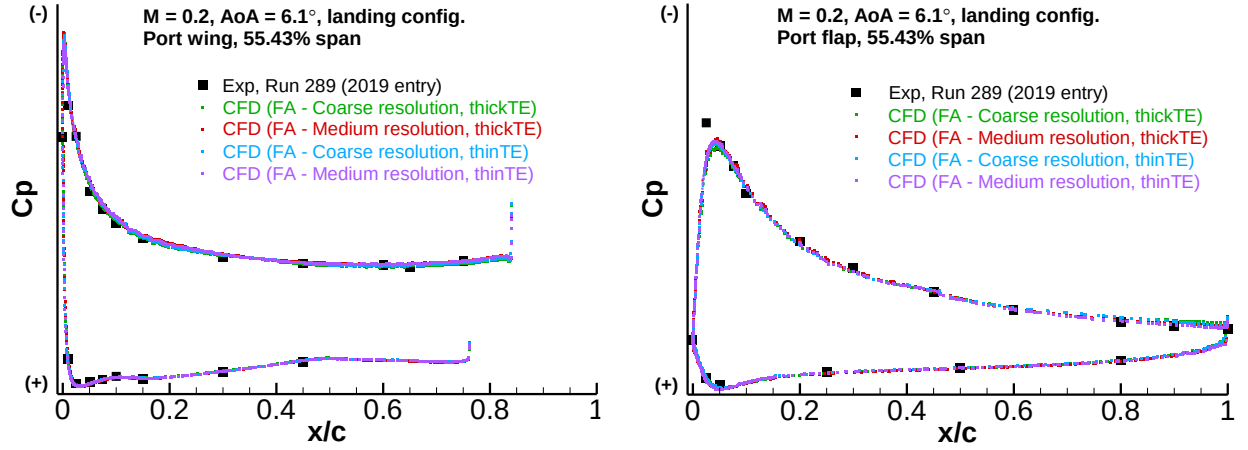


Fig. 7 Comparison of chordwise pressures at two mesh resolutions with measured data for landing configuration. Port wing (left) and flap (right).

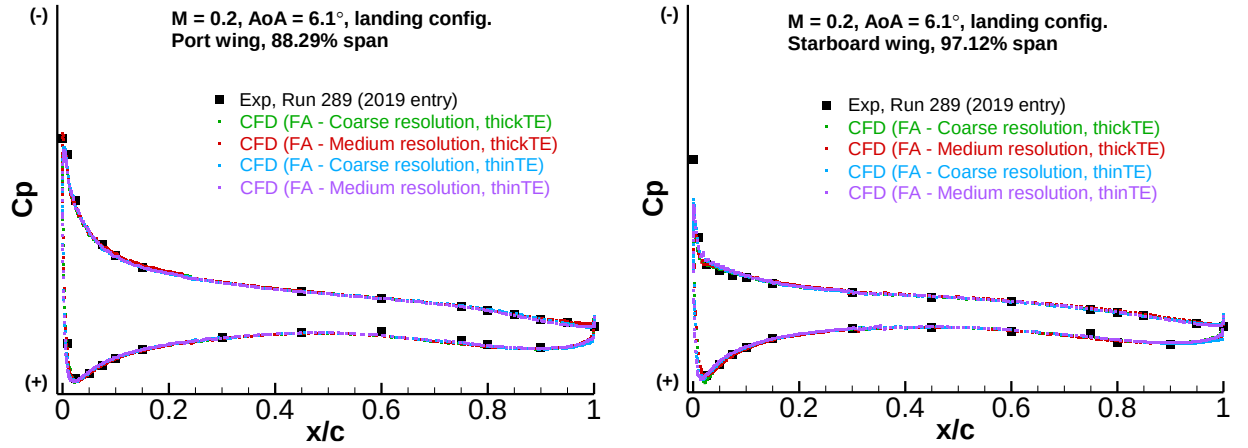


Fig. 8 Comparison of chordwise pressures near the wing tips at two mesh resolutions with measured data for landing configuration. Port wing (left) and starboard wing (right).

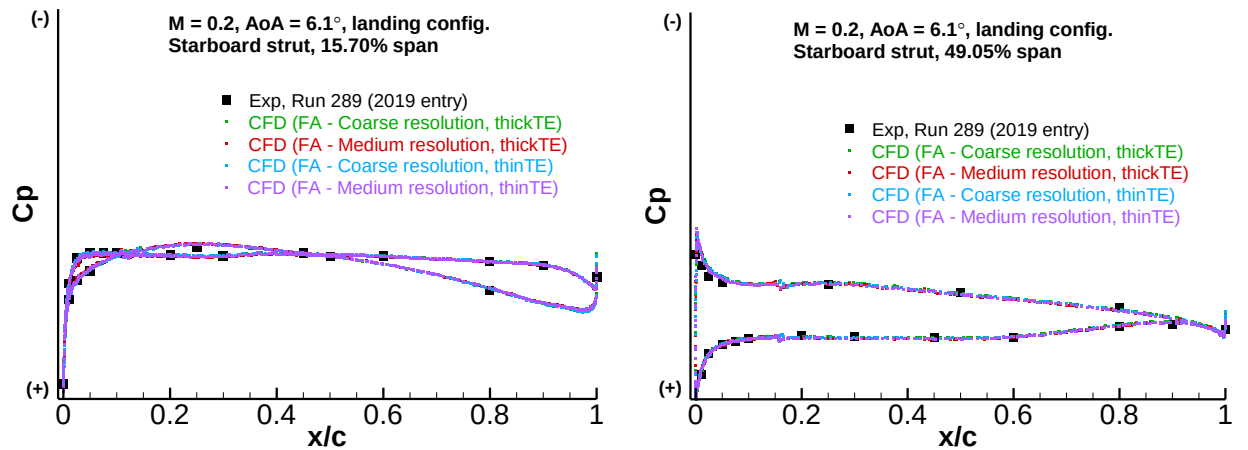


Fig. 9 Comparison of chordwise pressures on starboard strut at two mesh resolutions with measured data for landing configuration. 15.70% span (left) and 49.05% span (right).

The only alteration to the surface C_p s caused by TE thinning occurred on the VCK flaps. Representative C_p distributions at two spanwise locations are shown in Fig. 10. The small change in wing and flap camber lines associated

with thinner trailing edges caused minor alterations in local flow circulation and affected the suction peak at the nose and the pressure levels within the cove separated zone. The high deflection angles of the VCK flaps caused the flow in the LE region of these elements to attach on the upper surface and the suction peak to occur on the bottom surface, right before the flow enters the cove region and separates. At the spanwise location of 73.08% (right image in Fig. 10), note that the magnitude of the LE suction peak decreases with increased spatial resolution for the thicker TEs, while the pressure peak increases with better resolution for the case with thinner TEs. This trend was observed at several other spanwise stations (not shown). Unfortunately, the small size of the VCK elements precluded installation of surface pressure ports on these components; thus, full validation of predicted C_p s for this important high-lift device cannot be attempted. However, because of the accuracy of our computed integrated forces, we are very confident that the predicted VCK C_p s are not too far from the experimental values. Moreover, thinning the TEs caused only a slight alteration to the established flow features associated with the original TEs. Therefore, for our airframe noise simulations, we have resorted mostly to the configurations with thinner TEs to eliminate the strong tonal noise that emanated from the original edges.

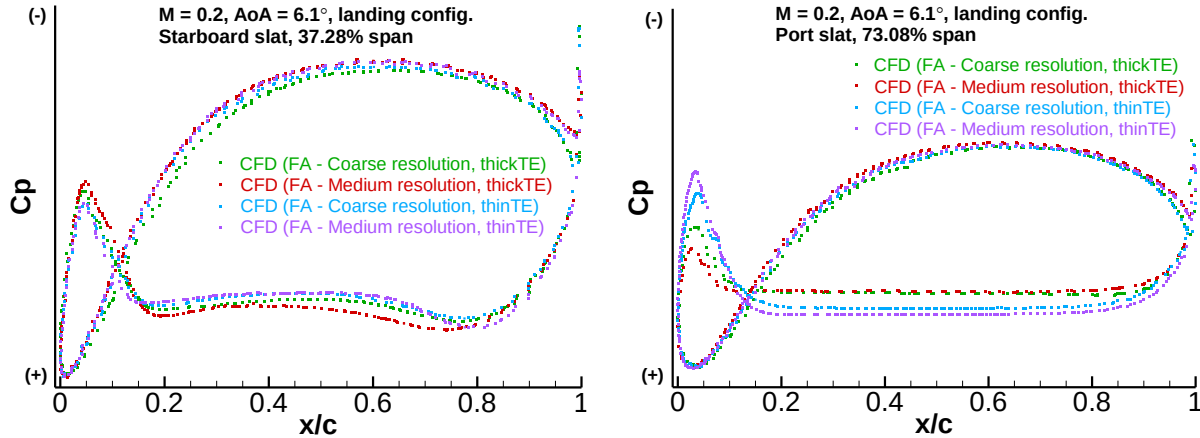


Fig. 10 Comparison of chordwise pressures on LE VCK flaps at two mesh resolutions with measured data for landing configuration. Starboard flap, 37.28% span (left) and port flap, 73.08% span (right).

2. Flow Features

Fig. 11 shows the standard deviation of pressure as measured on the surface of the TTBW model in clean and landing configurations. By examining this parameter, we can identify areas of strong fluctuating surface pressures. These regions are of interest to aerodynamicists aiming to improve the efficiency of the design, and to acousticians as potential noise sources. Two areas of note appear on the clean configuration results: a region of elevated rms pressure that begins at the wing LE where the engine pylon attaches, and an elongated area emanating from the upper wing-to-body fairing. The latter region is likely of more interest, as the wing-to-body fairings utilized are unique to this design. The resulting surface pressure fluctuations suggest the presence of a vortex generated by the upper wing-to-body fairing that subsequently propagated downstream. In contrast, the image for the landing configuration shows numerous regions of elevated fluctuating pressure on the wing upper surface. Most of these zones can be attributed to the wakes and pockets of flow separation caused by the VCK flap brackets. The largest of these fluctuating pressure zones are associated with the engine pylons and the side-edges of the VCK segments inboard and outboard of the nacelle pylons.

Fig. 12 presents surface streamlines, based on the Line Integral Convolution (LIC) methodology, isolated to the surface of the three flap segments. The streamlines near the outboard flap tip (left image) show the typical pattern indicative of formation and presence of a flap-side edge vortex. Moving inboard of the side-edge, regions of separated flow are visible on the suction side of the flap aft of the flap-track fairings. Flow separation occurs for each flap-track fairing, except the one located inboard of the nacelle (closest to fuselage). The influence of the small gap between the inboard and middle flap elements is clearly visible, as it pushes the region of separated flow outboard of this innermost flap-track fairing. On the section of the flap closest to the fuselage, the flow appears to be well attached without evidence of a clearly formed vortex at the flap side-edge adjacent to the fuselage. This is likely due to partial closing of the flap-fuselage gap that spanned the forward 50% of the flap chord to duplicate taping of the gap during the 14x22 test.

Fig. 13 presents surface streamlines, also based on the LIC methodology, isolated to the surface of the VCK segment inboard of the nacelle pylon. The streamlines on the suction side of the VCK (left image) show the stagnation line extending spanwise at a consistent chord location until it nears the engine pylon. In the presence of the pylon, the

stagnation line moved rearward slightly towards the VCK trailing edge. There is also a distinct change in the path of the surface streamlines over the suction side of the VCK at the spanwise location where the stagnation line begins to shift. The streamlines observed on the pressure side of the VCK (right image) show the presence of a separation line that has formed near the leading edge upstream of the cove region. The complexity of the surface streamlines in this region is evident, with the exposed VCK tip, bracket and engine pylon all contributing to a highly three-dimensional local flow.

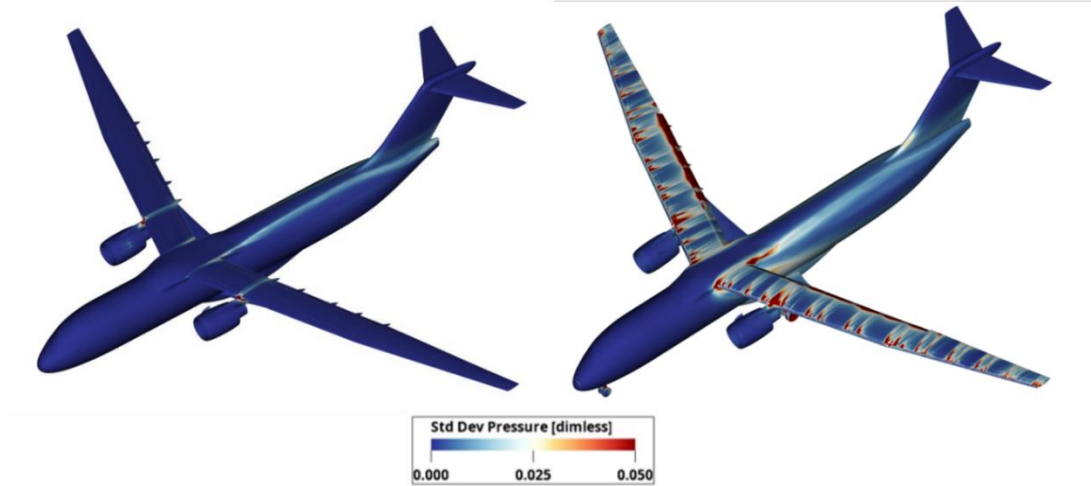


Fig. 11 Standard deviation of pressure on the surface of the TTBW in clean configuration (left) and landing configuration (right).

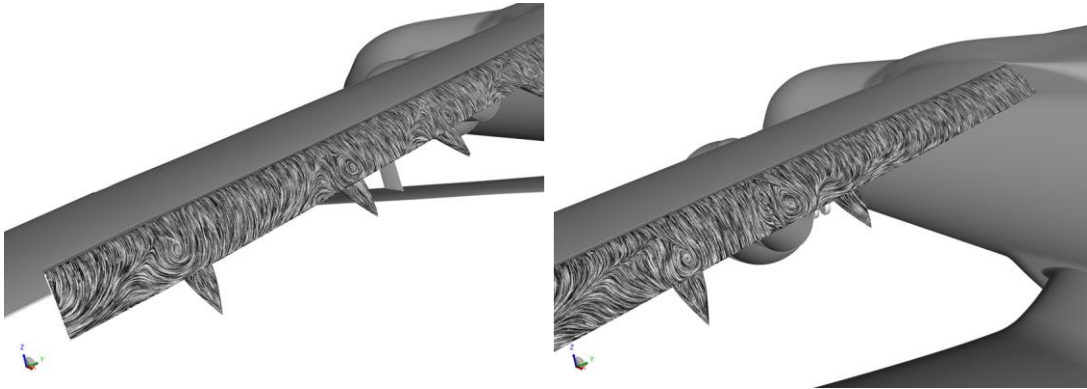


Fig. 12 Surface streamlines on the flap segments for the TTBW in landing configuration. The left image focuses on the outboard flap region while the right image focuses on the inboard flap region.

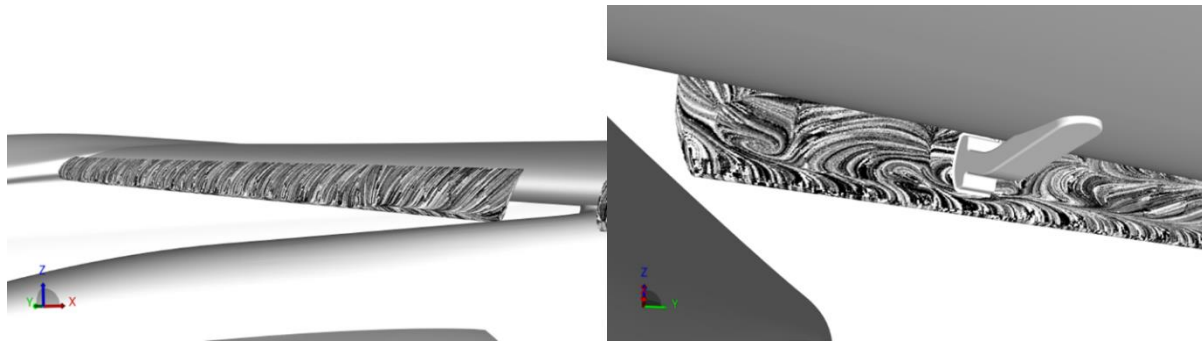


Fig. 13 Surface streamlines on the VCK for the TTBW in landing configuration. The left image focuses on the suction side while the right image focuses on the pressure side regions in the vicinity of the engine pylon.

Fig. 14 presents LIC surface streamlines isolated to the inboard surface of the main wing body in the vicinity of the nacelle pylon. Distinct differences in the streamline behavior are observed at several spanwise locations along the wing. These regions indicate the wakes generated downstream of the VCK brackets and the vortex residing over the main wing created by the nacelle pylon. Among these geometry features, the surface streamlines show attached flow with no evidence of separation.

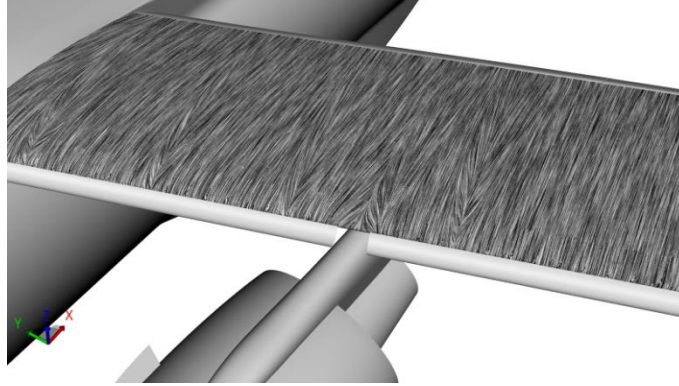


Fig. 14 Surface streamlines on the suction side of the main wing body near the nacelle pylon for the TTBW in landing configuration.

Fig. 15 compares LIC surface streamlines between landing and clean configurations. Due to the proprietary nature of cross-sectional shapes of the wing and strut, these areas have been intentionally covered by the red rectangles shown. The impact of the wing and strut combination, for the clean configuration, is visible in the streamline pattern. The main strut seems to influence local flow significantly – at the junction with the fuselage, the lift-producing effect of this component is clearly seen in the streamline pattern. Deployment of the high-lift devices and landing gear, as illustrated in the landing configuration (bottom image), causes a clear change in surface streamlines. The VCK and Fowler flap create a downward trend in the streamlines that moves toward, and hints of possible flow interaction with, the trailing edge of the main strut. Evidence of vertical structures along the fuselage, emanating from the VCK, add to the complexity of the flow in this region.

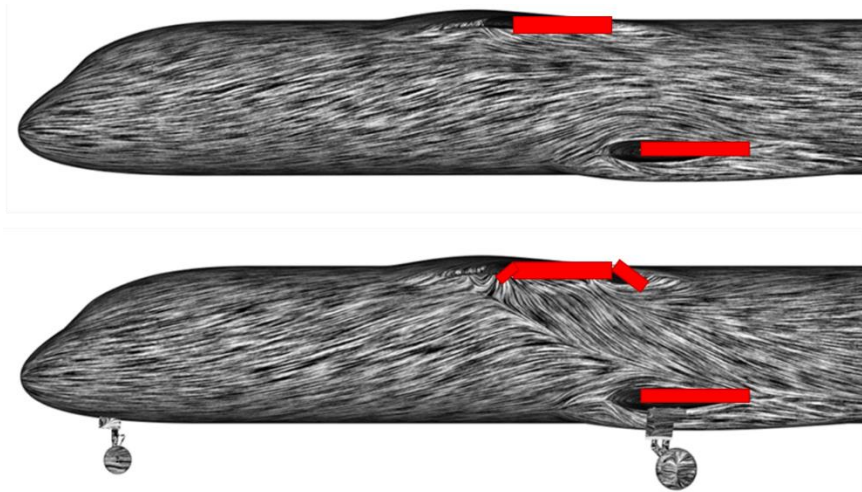


Fig. 15 Surface streamlines on the TTBW fuselage. Clean configuration (top image) and landing configuration (bottom image). Red boxes cover proprietary airfoils.

Fig. 16 presents coarse-grid-resolution contours of time-averaged flow velocity magnitude on a plane parallel to the main wing TE. The upper image, centered on the outboard flap tip, clearly shows the presence of a flap-side edge vortex. The influence of the flap-track fairings is present in relatively large regions of low velocity flow positioned over the suction side of the flap. The compact regions of low-velocity flow inboard of each flap-track fairing result

from vortices generated by the upstream VCK brackets. The lower image illustrates a unique aerodynamic feature of the TTBW in landing configuration as simulated – contrary to the outboard flap-side edge, no inboard flap-side edge vortex is visible. The close proximity of the flap edge to the fuselage, and partial closing of the flap-fuselage gap that spanned the forward 50% of the flap chord (necessary to duplicate taping of the gap during the 14x22 test), may prevent formation of this vortex, generally a prominent airframe noise source. Visible in the lower image also is the wake of the flow-through nacelle and pylon.

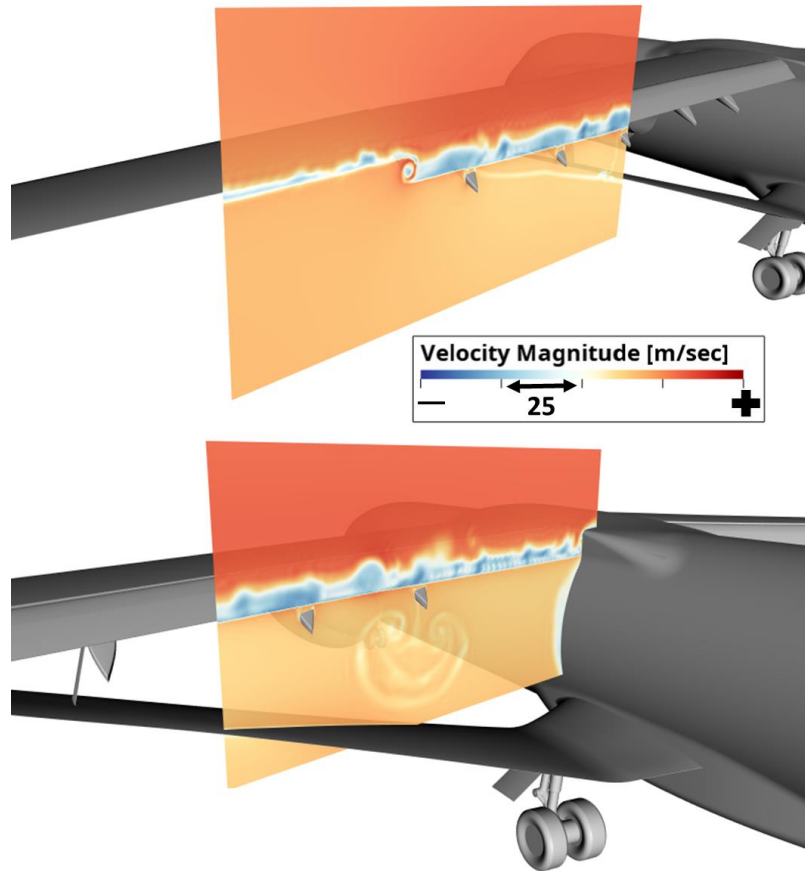


Fig. 16 Mean planar velocity magnitude parallel to the trailing edge of the port-side flap, Outboard flap region (top image), inboard flap region (bottom image).

B. Acoustic Analysis

In this section we provide a description of the permeable surfaces used for propagating the near-field signal followed by presentation of single-microphone far-field noise spectra. Differences in the computed spectra obtained from permeable surface data and model solid surface data are highlighted. The effects of end cap averaging on the spectra obtained from a permeable surface are discussed.

1. Description of Data Surfaces

Following our previous studies, for acoustic analysis we use the highly resolved near-field simulated solutions in conjunction with a permeable Ffowcs-Williams and Hawkins (FWH) surface to predict the far-field noise signature. The FWH permeable surface developed for the clean configuration is shown in Fig. 17. The corresponding surface for the landing configuration is presented in Fig. 18. Both surfaces contain numerous endcaps for averaging purposes. These end caps are spread over a large section downstream of the aircraft wake that contains a successively coarser mesh (VR regions). The placement and number of end caps used for averaging is aircraft-dependent and assessment of their impact on the far-field noise signature is an active area of research [37]. The present airframe noise prediction effort is exploratory in nature, as the unique airframe geometry of the TTBW poses several challenges that require careful consideration. For example, the presence of a main strut and whether it partially shields or scatters the propagating sound field complicates the development of an appropriate FWH permeable surface. As can be seen in Fig. 18,

we may be overly conservative in the extent of the permeable surface used to generate the far-field noise spectrum. Obviously, having a larger volume enclosed within the permeable surface will substantially increase the cost of the airframe noise simulations. Iterations on the extent of the permeable data surface to arrive at an optimal location are left for the next phase of our study. Currently, our effort is focused on determining the location and number of endcaps that would yield the most accurate acoustic results in the flyover direction.

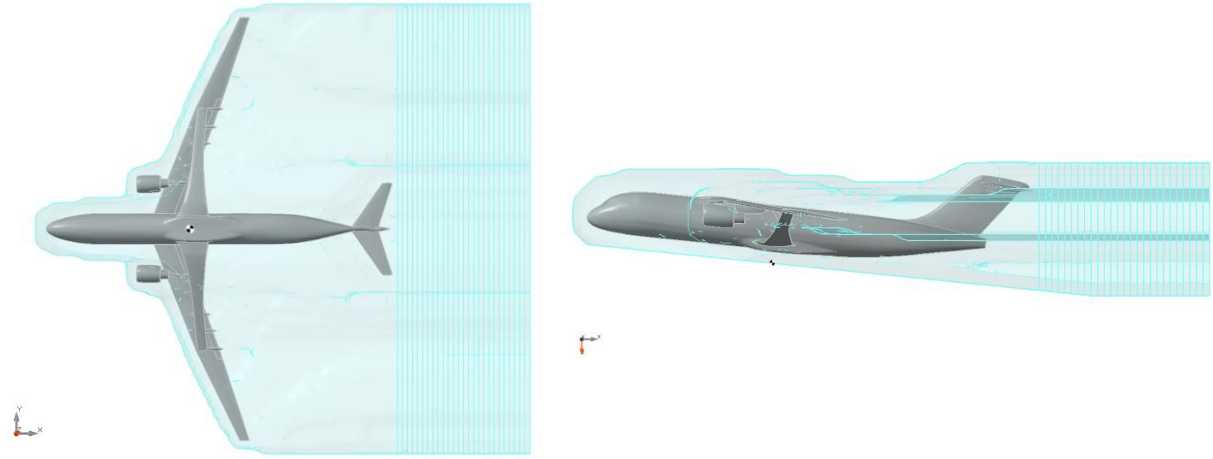


Fig. 17 Schematic of permeable FWH data surface with multiple endcaps for clean (cruise) configuration. Bottom view (left) and side view (right).

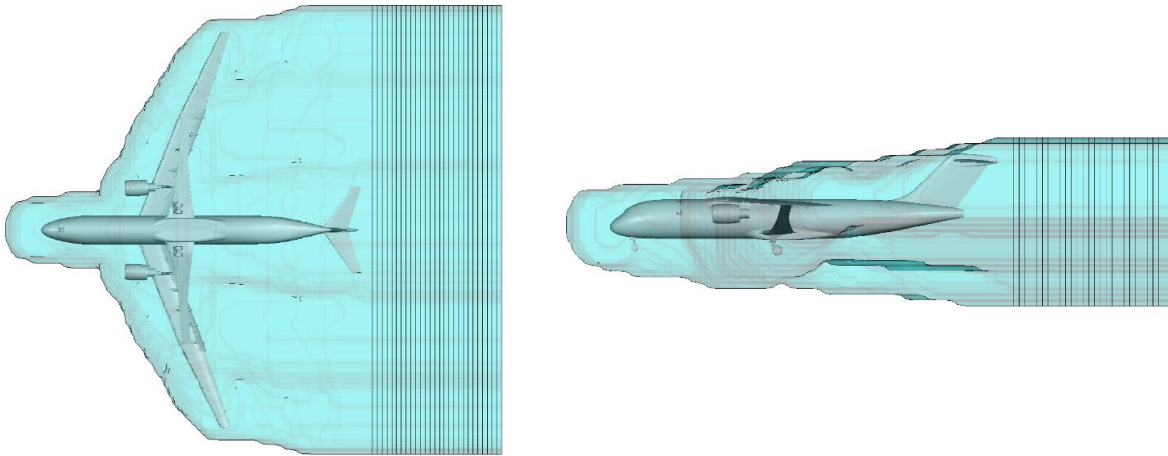


Fig. 18 Schematic of permeable FWH data surface with multiple endcaps for landing configuration. Bottom view (left) and side view (right).

2. FWH Data Surface Effects – Solid vs. Permeable

As an initial attempt to determine the most suitable data source for input into the FWH analogy, a comparison was made of acoustic spectra on a simulated sample probe in the TTBW's near field. To illustrate differences between the various data sources, a high-sampling-frequency time history of pressure was recorded during simulation at a location below the main landing gear, along the center plane of the aircraft (direct probe). The noise spectra at the direct probe were predicted using both the solid and permeable FWH data surfaces. Comparing the resulting spectra provides insight into the appropriateness of using solid or permeable datasets for subsequent far-field spectra. The approach taken herein is discussed in greater detail in Ref. [16].

Fig. 19 shows, for both coarse and medium resolutions, predicted spectra based on permeable and solid surfaces and the direct CFD probe data recorded during simulation. All frequencies in the spectral distributions presented in this paper are model scale. For the permeable surface result set in this section, end cap averaging was performed before processing the high-frequency pressure records. Observe that the permeable surface spectrum agrees well with the

spectrum from the direct probe for both coarse and medium resolutions. Both spectra show a rapid roll off that starts around 13-14 kHz for the medium resolution. This behavior is caused by insufficient spatial resolution (i.e., excessive diffusion) of mid- and high-frequency waves as they propagate through the enclosed volume before reaching the permeable surface where the data were collected. Moreover, there is a noticeable change in the direct probe spectral trend at approximately 27 kHz (medium resolution), likely attributable to a noise floor in the simulation itself. For the coarse resolution the spectral results from the solid measurement surface are in line with spectra from the direct probe and permeable surface up to approximately 7 kHz, with a clear over-prediction into the higher frequencies. The point at which the over-prediction begins is delayed slightly with increased resolution, occurring at approximately 9 kHz for medium resolution results. Since the current effort is exploratory in nature, we intend to investigate further the possible causes of over-prediction as it relates to the solid surface dataset, though the absence of shielding effects could be the main cause. This requires executing the simulations at finer spatial resolutions, which is currently ongoing.

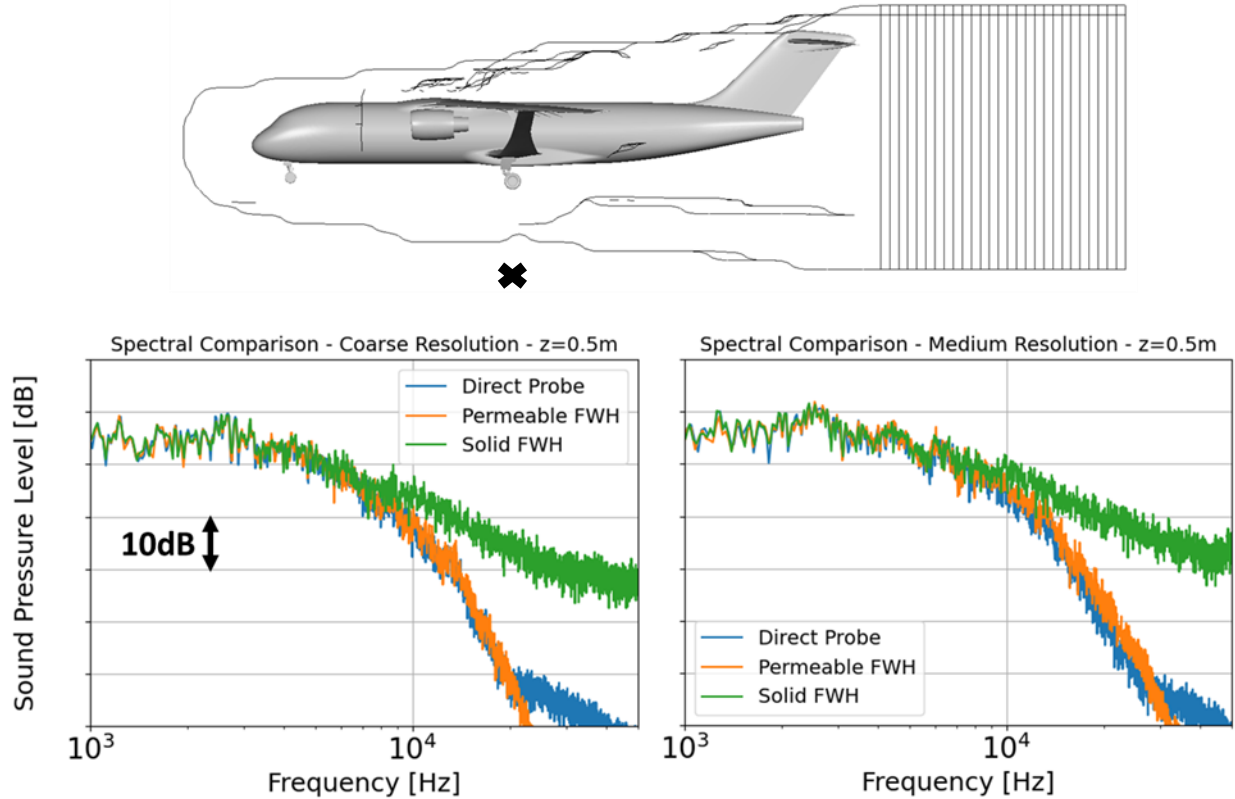


Fig. 19 Acoustic comparisons in the near field of the TTBW in landing. Position of direct probe (cross) relative to the permeable surface outline (top). Coarse (bottom left) and medium (bottom right) resolution results.

3. Single-Microphone Far-Field Noise Spectra

Fig. 20 presents the far-field noise spectra of both the landing and cruise-configured TTBW aircraft. The spectra were generated using the permeable surface datasets obtained from the medium resolution simulations. Prior to processing the high-frequency pressure records, end-cap averaging was performed across all end caps present during simulation. The four microphone locations sampled were part of the far-field synthetic phased array discussed in Ref. [18]. Three of the microphones (forward, overhead, and aft positions) are aligned in the flyover direction and cover a directivity range of approximately 45°. The position of the port side microphone corresponds to a directivity angle of 22° in the sideline direction. Given the overprediction of spectral levels by the solid surface discussed in the previous section, here we will only present results from the permeable dataset. As expected, the landing configuration produced substantially higher sound pressure levels than the cruise-configured TTBW aircraft at each respective microphone location. The differences in levels are on the order of 15-20 dB over a broad range of frequencies. This indicates a good signal-to-noise ratio and will help determine the contributions from various airframe components to the far-field noise signature [18]. The spectral plots in Fig. 20 clearly demonstrate the widespread influence of the deployed landing

gear and high-lift devices on noise levels across a broad directivity angle range. The plots also show a tonal behavior for the TTBW aircraft in cruise configuration beyond 10 kHz that is sensitive to directivity. The tone observed at 10 kHz is generated by vortex shedding from the thicker than normal nacelle chine. The thickness of this chine was also reduced to a more realistic value during simulations of the aircraft in landing configuration. Moreover, the magnitude of the tonal levels in the cruise spectra may be somewhat influenced by the decreasing spatial resolution at these higher frequencies.

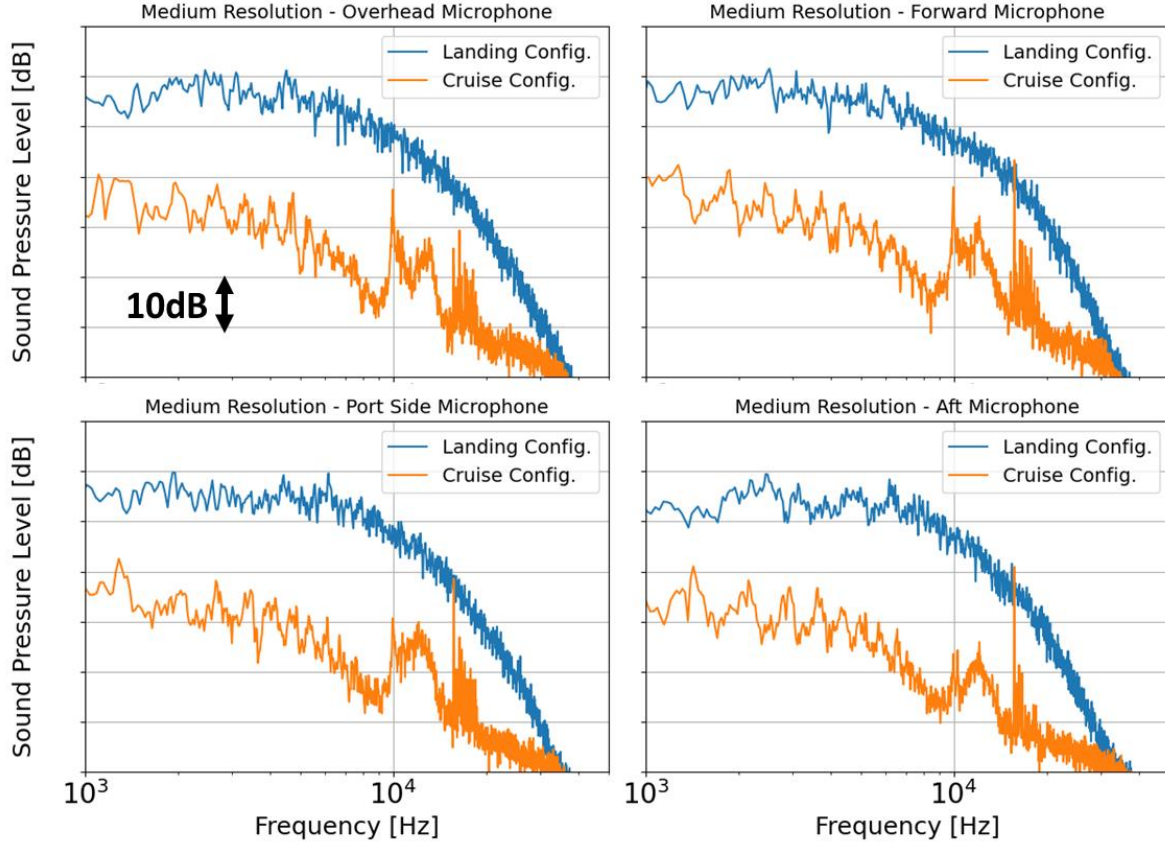


Fig. 20 Sound pressure levels from the permeable surface at specified microphones in the far field for both landing and cruise configurations. TTBW simulations in medium resolution.

4. Effects of End Cap Averaging

As was described in Section B.1, end caps were incorporated into the permeable surfaces used for this study. For the purposes of this section, we will refer to the successively coarser regions of resolution as follows: VR07 for the finest (incorporating the first 12 end caps), VR06 for the intermediate (incorporating the middle 8 end caps), and VR05 for the coarsest (incorporating the last 8 end caps) resolution level applied. The permeable surface image shown in Fig. 21 visualizes the end cap distribution and naming convention used in the present analysis.

Fig. 22 shows the predicted spectral results, in medium resolution from the landing configuration, of various end cap combinations. For these comparisons, we have considered, respectively, the forward, overhead and aft microphone locations to discern any potential directivity biases in the use of end caps. The left column of Fig. 22 compares the resulting spectra when including and subsequently averaging all the end caps versus the result if the contribution of the end caps was not included (i.e., open permeable surface). The right column compares various averaging schemes.

From the results in the left column, we can infer that, for the single microphone results at these isolated locations, end cap averaging does not have a noticeable impact on the spectra. This holds true across frequencies and microphone locations sampled. This means that no unphysical (numerical) sources are generated at the end caps due to the passage of the hydrodynamic wake through the downstream exit plane of the permeable surface. The results in the right column of Fig. 22 show that, except for the lower frequencies, there is little difference found in the spectra by including the additional end caps in the regions of coarser resolution. Given the generous downstream extent of the permeable surface, the wake generated by the TTBW that convects past the end caps is likely not of sufficient strength to register an observable change in the spectra. While these results point to minimal change from the inclusion of any number of

end caps, the single microphone spectra are but a sample of the acoustic field generated by the TTBW aircraft as simulated. As the effort detailed in this paper continues to progress, we will perform a more thorough directivity analysis to better understand this behavior.

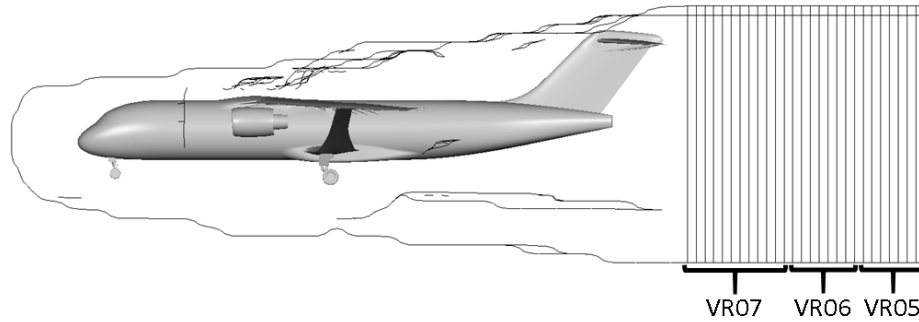


Fig. 21 Permeable surface encompassing the TTBW in landing configuration with endcap regions identified by resolution level.

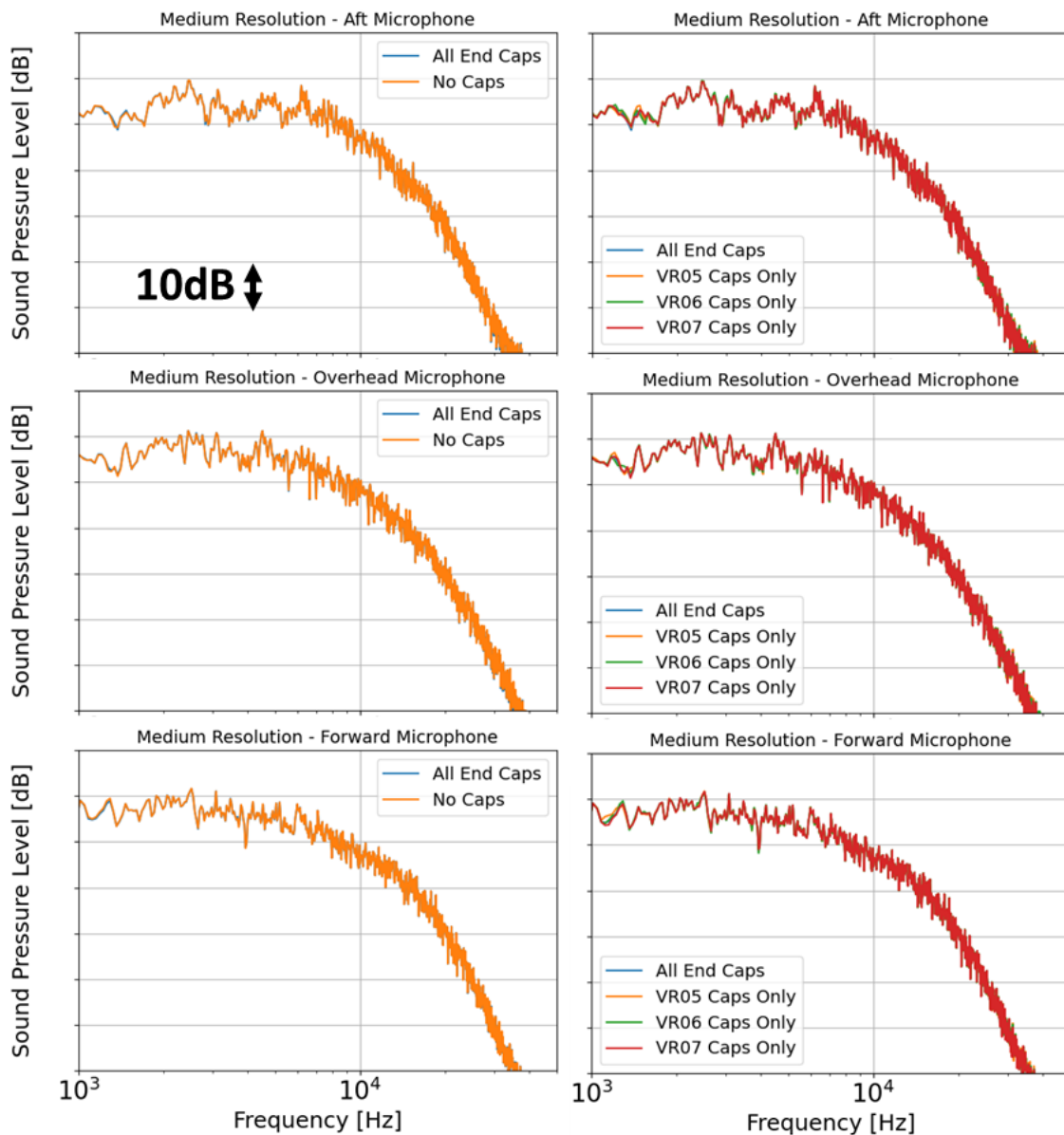


Fig. 22 Single microphone spectra at specified locations comparing indicated end cap combinations.

VI. Concluding Remarks

High-fidelity aerodynamic and airframe noise simulations of a Transonic Truss-Braced Wing (TTBW) aircraft model are being performed using the LBM solver PowerFLOW[®]. The concept is being explored as a potential future transport-category aircraft. Not much information is available on the low-speed aerodynamic characteristics and airframe noise signature of this vehicle. The current study is a first attempt at examining the aeroacoustic behavior of this unique design.

Results from a relatively detailed aerodynamic analysis are presented. Fully converged, time-averaged surface pressures are shown for both cruise (clean) and landing TTBW configurations. Comparisons of the predicted surface pressures and integrated forces, such as lift and drag coefficients, with wind tunnel measurements show very good agreement, validating the simulated results. A qualitative examination of flow behavior in the form of surface streamlines and off-surface velocity contours for specific areas of interest is presented. In landing configuration, the high-wing design, which incorporates both leading-edge and trailing-edge high-lift devices, creates unique aerodynamic characteristics, with the streamlines on the fuselage indicative of wing downwash interaction with the main truss trailing edge. The geometric configuration of the Fowler flap, as tested in the wind tunnel and subsequently modeled for simulation, provides evidence of the importance of accurately capturing the finer details of the TTBW model. For the cruise configuration, contours of fluctuating pressure field on the model surface show evidence of streamwise vortices generated by the wing-to-body fairing and subsequently propagated along the fuselage.

Preliminary acoustic results for the 8%-scale TTBW model are presented and discussed as we continue to strive toward a detailed acoustic analysis of this unique advanced concept. The near-field probe results illustrate the need for a permeable FWH data surface to be considered in subsequent acoustic simulations of this aircraft. The single microphone spectra shown give some initial insight into the difference in noise levels between the cruise and landing configurations, indicating a 15-20 dB increase in broadband noise when high-lift devices and landing gear are deployed. The far-field spectrum for the landing configuration lacked any observable tonal content, while the spectrum for the cruise configuration contains tonal content, most noticeable in the higher frequencies. Finally, the initial results of an ongoing study to determine the optimal implementation of end caps in the permeable data surface for the TTBW aircraft were discussed. For the current end-cap location and distribution, little difference was found in the single-microphone spectral noise levels with and without end-cap averaging at three representative flyover and one sideline microphone locations.

At this point in our overall effort, we have demonstrated the ability of simulations based on the PowerFLOW[®] solver to capture accurately the aerodynamic behavior of this unique aircraft design. Utilizing best practices developed in our previous acoustic analyses, we have initiated a thorough aeroacoustic study of the TTBW vehicle in landing configuration. As this effort is ongoing, future simulations will focus on finer volumetric grids to reduce uncertainty in the higher frequency content of the predicted far-field spectrum caused by insufficient spatial resolution. The influence of the VCK brackets on the resulting noise spectra will be investigated. More importantly, simulations of a full-scale geometry are planned at flight Reynolds numbers to elucidate the effect of Reynolds number on the aeroacoustic behavior of the TTBW concept.

Acknowledgments

This work is supported by the Advanced Air Transport Technology project under the Advanced Air Vehicles Program of the NASA Aeronautics Research Mission Directorate. The authors would like to thank Joshua Brown and Eric Burke of the NASA LaRC Nondestructive Evaluation Sciences Branch for performing the meticulous laser scans of the TTBW model. The authors gratefully acknowledge the invaluable contribution of Scott Brynildsen of Analytical Mechanics Associates for providing geometry work, modifications, and CAD support for all simulations. All simulations were performed on the computer clusters at the NASA Advanced Supercomputing (NAS) facility at the Ames Research Center and K-Cluster computers at NASA Langley Research Center.

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