

Aeroacoustic Computations of a Transonic Truss-Braced Wing Aircraft: Part 2 – Acoustic Signature and Noise Source Identification

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High-fidelity, time-dependent simulations of a Boeing-designed, transonic, truss-braced-wing aircraft in cruise (clean) and landing configurations are leveraged to generate synthetic microphone-phased-array data for airframe noise prediction and assessment. These data sets are used to compute source localization (beamform) maps to determine the location and strength of primary and secondary airframe noise sources associated with this unique configuration. The synthetic phased-array implementation mimics the setup of a flight test. As this study is ongoing, preliminary integrated far-field spectra for the cruise configuration obtained at multiple spatial resolutions revealed significant tonal content that lacked convergence with increased resolution. The origin of several of these tones and their unusual convergence behavior was traced to the larger-than-normal trailing-edge thickness of the “as-tested” cruise model being simulated. Reducing the trailing-edge thickness to more realistic values eliminated most of the tones at low to moderate frequencies and improved spectrum convergence significantly. Applying lessons learned from the cruise simulations, several modifications to the geometry of the landing configuration were made and are described in this work. Results from permeable and solid Ffowcs-Williams and Hawkings surfaces at two different spatial resolutions (coarse and medium) are used to illustrate the major noise sources and determine convergence of the CLEAN integrated noise levels for the entire aircraft as well as major subcomponents. We demonstrate that the low-frequency content of the far-field spectrum is dominated by noise generated from the main landing gear, while the medium- and high-frequency content is dominated by the wing-leading-edge Krueger flaps. Since analysis of the acoustic maps for the landing configuration revealed several clusters of multiple sources along the wing leading edge, “high resolution” processing of the array data was used to distinguish more accurately the locations of sources.

I. Nomenclature

<i>FTA</i>	=	flight test array
<i>FWH</i>	=	Ffowcs-Williams and Hawkings
<i>LE</i>	=	leading edge
<i>LG</i>	=	landing gear
<i>MLG</i>	=	main landing gear
<i>SNR</i>	=	signal-to-noise ratio

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TE = trailing edge
 $TTBW$ = Transonic Truss-Braced Wing
 VCK = variable camber Krueger
 VR = variable resolution

II. Introduction

The transonic truss-braced wing (TTBW) aircraft is an advanced transport concept designed to foster sustainable aviation by providing substantial reductions in fuel consumption and emissions. As an important part of the development process, an accurate prediction of the ground acoustic signature of the vehicle is necessary to determine its impact on communities near airports during takeoff and landing operations. Currently, a clear understanding of the TTBW noise footprint does not exist. To remedy this shortcoming, we have tried to assess the airframe noise signature of a Boeing-designed TTBW aircraft using synthetic microphone-array data generated via high-fidelity aeroacoustic 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 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 $M_\infty = 0.745$. 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, a 4.5%- and an 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, including a description of the resulting sub-scale TTBW models, is provided in Ref. [5].

To date, aeroacoustic measurements of the 8%-scale TTBW aircraft model 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 (see Refs. [6] through [13]). The only acoustic study for relevant low-speed conditions known to us is that of Ref. [14], where a detailed system noise assessment of the concept was performed via 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, the need for an accurate, complementary but separate, physics-based acoustic assessment of novel configurations – such as the TTBW concept – is apparent. The present effort, conducted under the NASA Advanced Air Transport Technology (AATT) 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 followed a carefully planned computational approach similar to that applied to the study of airframe noise generated by a generic low boom concept (GLBC) [15], [16], [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 described and presented in a companion paper [18]. The scale-resolving simulations of Ref. [18], in conjunction with a Ffowcs-Williams and Hawkings (FWH) integral approach were leveraged to generate synthetic pressure records for the microphone locations of a phased array on the ground that mimics a flight test setup. The present paper uses those synthetic data sets to conduct an initial acoustic assessment of the TTBW model and identify the primary and secondary airframe noise sources associated with this unique aircraft configuration. We emphasize that the airframe noise simulations of Ref. [18] and the acoustic analysis presented here are exploratory in nature. Due to the unique airframe geometry of the TTBW, certain aspects of the noise prediction process need to be examined further and evaluated carefully. Among them is the shape and extent of the permeable data surface used to propagate near-field sound to the far field, and the number of end caps used for averaging purposes. Any insights and lessons gained from the present study will be used in the next phase of our effort when we attempt to predict the airframe noise signature of a full-scale TTBW aircraft.

III. Computational Data Sets

A brief description of the simulated model configurations and computational data sets is provided in this section. Details on digital geometry development and aeroacoustic simulations of the 8%-scale, $M_\infty = 0.80$ TTBW aircraft model used to generate the data are included in a companion paper [18]. For aerodynamic analysis, both in-tunnel and free-air setups were employed. For acoustic assessment, the simulations were performed exclusively in free-air conditions. The Reynolds number (based on mean aerodynamic chord) and Mach number were 0.975×10^6 and 0.2035 (matching wind tunnel test conditions), respectively. The angle of attack (AoA) was set at 6° for cruise and 6.1° for landing configurations. Both Mach and AoA values are representative of landing conditions for this aircraft.

A. Simulated Model Geometries

To accomplish the aeroacoustic simulations, high-definition, digital representations of the TTBW geometry in both cruise (clean) and landing configurations were developed. The simpler geometry, the “as-tested” CAD model for cruise, was completed first. Initial aeroacoustic simulations of this configuration were used to gain insights on how to tailor the computational approach to the unique TTBW airframe [18]. Fig. 1 shows the simulated cruise geometry without and with landing gear deployed.

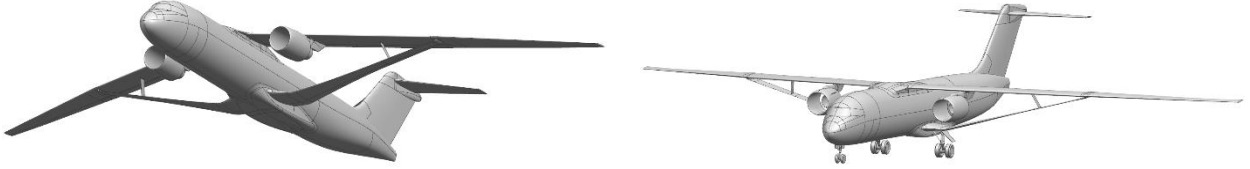


Fig. 1 Images of TTBW CAD model in cruise configuration without and with landing gear as simulated in free-air conditions.

Development of a digital replica of the “as-tested” TTBW model in landing configuration was labor-intensive and required 7-8 months to accomplish. A description of TTBW model development for high-lift applications is provided in Ref. [18]. CAD images of the simulated TTBW model in landing configuration are shown in Fig. 2. Note that the model includes landing gear and trailing/leading-edge high-lift devices. The leading-edge high-lift device used in this model is a variable camber Krueger (VCK) flap. Along the span, the flap is comprised of nine independent elements (segments) with distinguishable gaps between elements one and two in the vicinity of the engine pylon (Fig. 3), and between elements four and five where the wing leading-edge sweep angle changes (Fig. 4). Much care was taken to capture accurately the gaps and overlaps that were set between the remaining VCK elements of the wind-tunnel model. Differential deflections of these elements were required to maintain reasonable wing 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 (Fig. 4) that are sufficiently large to act, potentially, as secondary noise sources. Care was exercised to ensure that these surface discontinuities were adequately resolved.

As illustrated in Fig. 4, 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 scale of the model-scale brackets had to be increased to carry the anticipated aerodynamic loads. Since these brackets are bluff bodies, we expected that they would be identified as prominent noise sources during the simulations. 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 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.

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 (Fig. 5). Between the inboard and middle flap elements, a small gap allows air to flow between the bottom (pressure) and top (suction) surfaces.

The landing gear (Fig. 6) contains major flow-facing components such as bay doors, wheels, axles, braces, and other large structural members. However, the finer details of a gear were not included in the 8%-scale TTBW model. As a result, we anticipated an impact on the high-frequency content of noise produced by the gear. Moreover, the tested and simulated model also lacks typical landing gear bays and mates the deployed landing gear main post directly to the fuselage surface (Fig. 6). The missing cavities would affect the low-frequency noise content of the landing gear

associated with wheel wells. In the future, when we consider a full-scale TTBW model, we will develop and integrate appropriate bay cavities and some of the finer details of the gear geometry to assess their impact on the TTBW aircraft far-field noise spectrum.

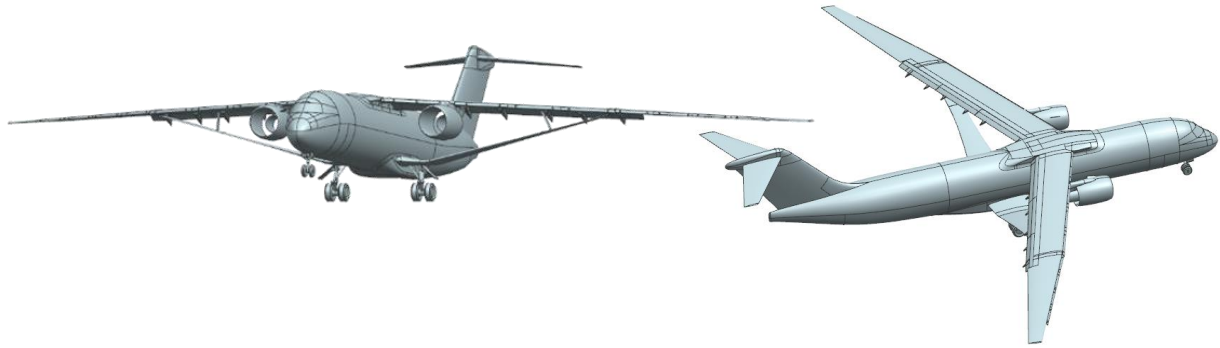


Fig. 2 Images of the TTBW CAD model in landing configuration as simulated in free-air conditions.

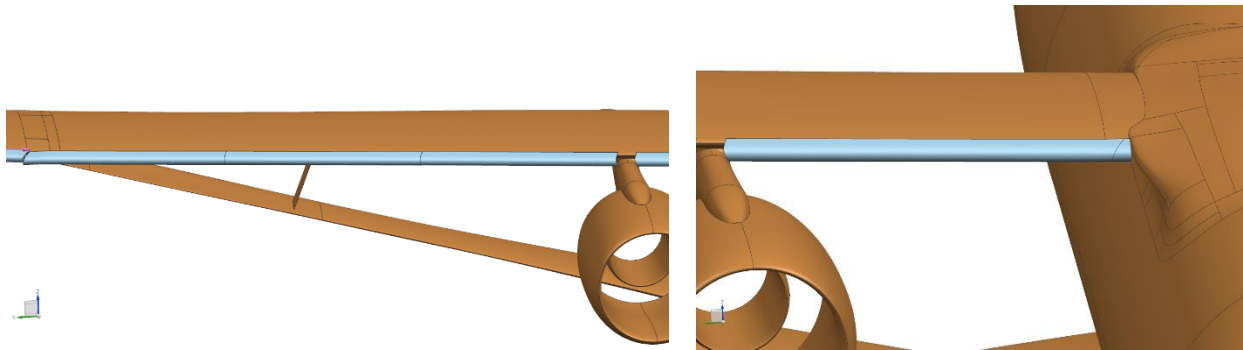


Fig. 3 Close-up view of the TTBW model inboard leading edge VCK flap segments.

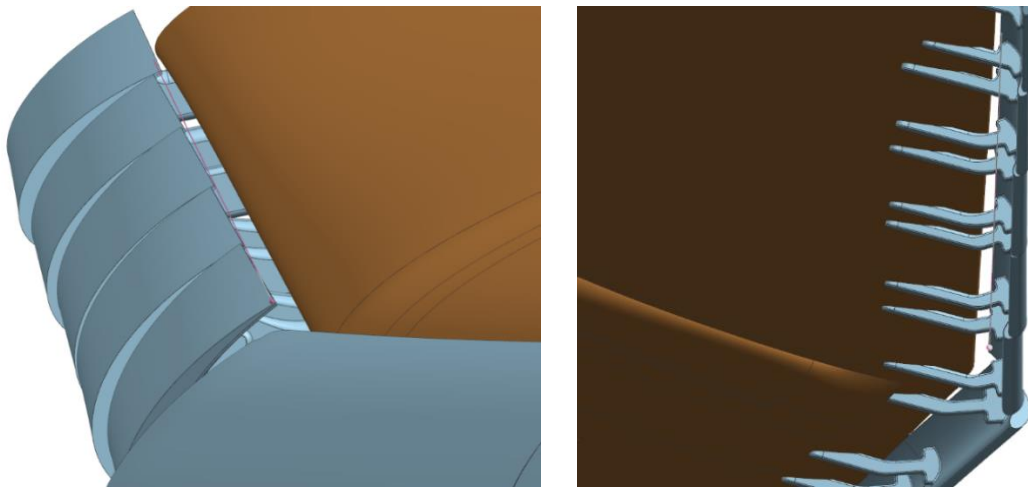


Fig. 4 Close-up view of the TTBW model outboard leading edge VCK flap segments, highlighting differential deflection of flap elements and bluff body shape of brackets.

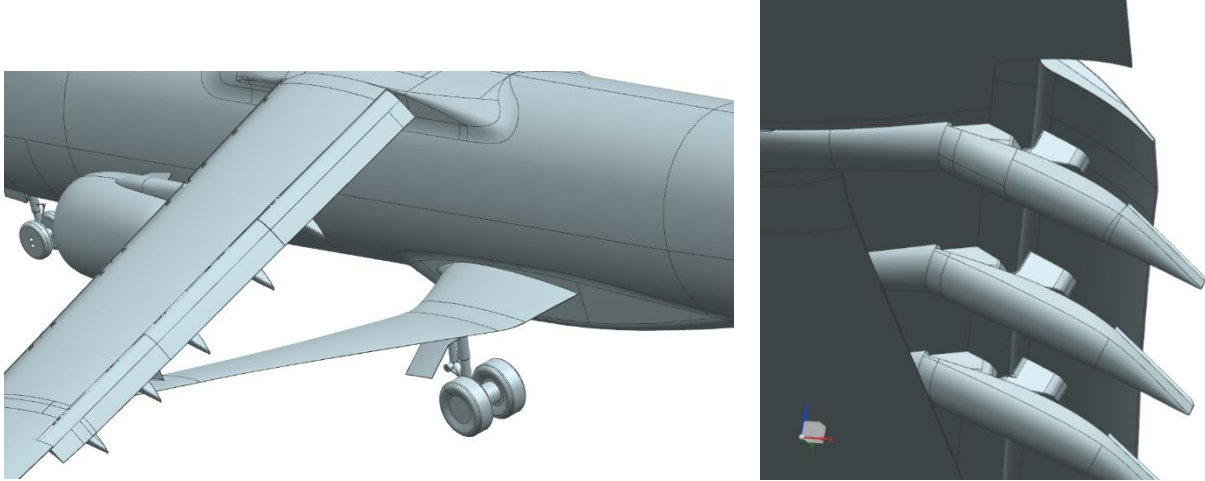


Fig. 5 Close-up view of the TTBW model trailing edge Fowler flaps and their tracks.

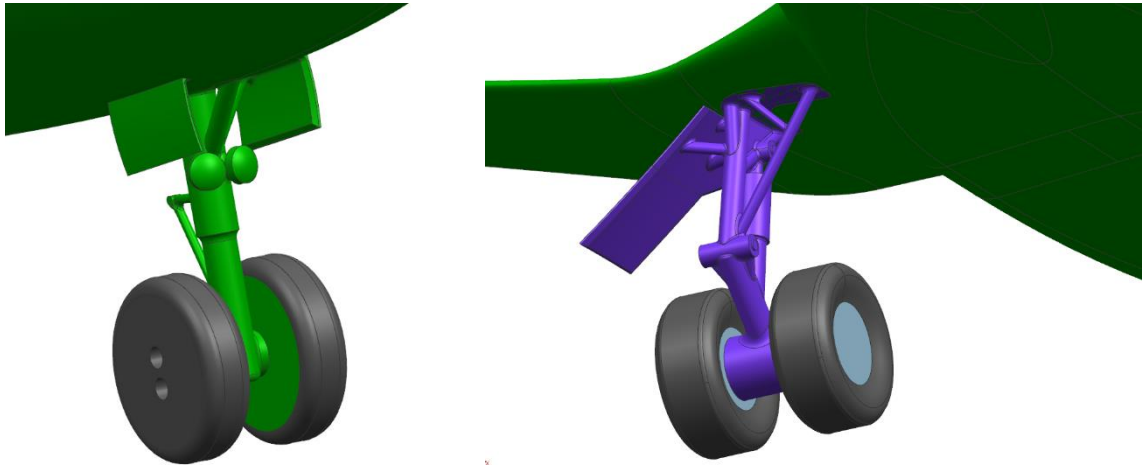


Fig. 6 Close-up view of TTBW model landing gear. Nose gear (left image) and main gear (right image).

C. Data Surfaces

An acoustic analogy approach based on the Ffowcs-Williams and Hawkins (FWH) formulation [19] was used to propagate the simulated near-field signal [18]. The computed time-dependent flow-field sampled on tailored FWH data surfaces was used as input to calculate the far-field pressure records at the array microphone locations. Data from a permeable surface was used for cruise; for comparison purposes, data from both solid and permeable surfaces were used for landing. Since a CAD geometry definition of the “as-tested” TTBW model in landing configuration was not available initially, the computational campaign [18] began with simulations of the TTBW in the clean (cruise) configuration with and without LG while an accurate digital model of TTBW in landing was being developed. Permeable data surfaces for the cruise configurations that were simulated (with and without landing gear deployed) are shown in Fig. 7. The permeable surface for the landing configuration is shown in Fig. 8. Observe that the surfaces include various end caps that are used, via averaging, to reduce the effects of hydrodynamic fluctuations exiting the surface. Notice that the FWH surfaces for the cruise configuration without LG (Fig. 7b) and for the landing configuration (Fig. 8) contain a large number of end caps. These end caps are spread over a large region downstream of the aircraft wake that contains a successively coarser mesh (variable resolution, or VR, regions). The placement and number of end caps used for averaging is aircraft-dependent and assessment of their impact on far-field noise signature is an active area of research [20]. Since the present airframe noise prediction effort is exploratory, the extent of the permeable surfaces, number of end caps, and their location relative to the VR regions used in the aircraft wake are part of ongoing work to assess the effect of these parameters on the computed far-field noise spectrum [18], particularly that obtained from single-microphone data.

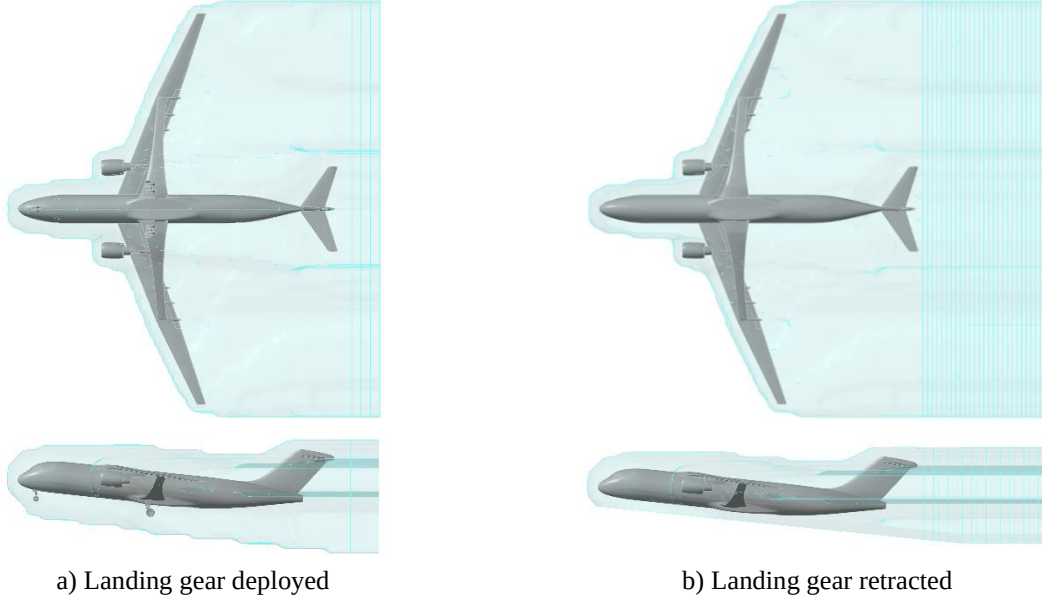


Fig. 7 Permeable FWH data surfaces (in blue) for clean configuration.

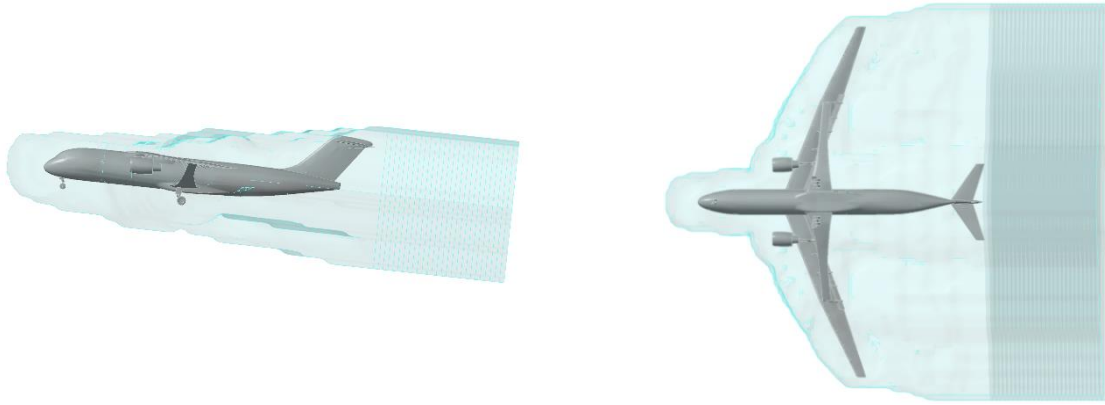


Fig. 8 Permeable FWH data surface for landing configuration.

B. Synthetic Phased Array

Phased microphone arrays are powerful tools used to identify the location of prominent airframe noise sources and determine their strength. A non-redundant synthetic phased array with 800 microphones (previously developed for analysis of various aircraft, see Refs. [17] and [21]), was scaled to obtain the desired source resolution for the 8%-scale TTBW model. The array was placed in the flyover direction at a distance equivalent to 120 m (394 ft) full-scale, representative of aircraft certification conditions for landing. Accordingly, this array is referred to as the flight test array (FTA). Schematics of the FTA in the non-convected position relative to the model and the microphone pattern are shown in Fig. 9. To compensate for flow convection effects during the propagation phase, the array was moved downstream to emulate an emission angle of 90° between the aircraft main landing gear (MLG) and the center of the array.

For acoustic analysis, the simulated pressure records from FWH surfaces were beamformed in the frequency domain and deconvolved using the CLEAN [22] algorithm as implemented in AVEC's phased array software suite [23]. Diagonal removal was applied, and flow convection effects were taken into account. A hyperbolic tangent-based shading algorithm, previously used by the authors in several studies (including Refs. [17], [21], and [24]) and later described in Ref. [25], was employed to improve array resolution while preserving a good array signal-to-noise ratio (SNR) for all frequencies of interest. The array resolution using conventional beamforming is less than 0.2 m at 3 kHz, with the typical doubling with frequency observed below ~ 7 kHz (i.e., limited by the array aperture). Shading keeps the array resolution relatively constant (~ 0.05 m) for frequencies above ~ 10 kHz. Array resolution is improved further

by applying CLEAN. The reduction in aperture caused by array shading at high frequencies (needed to keep resolution constant) results in a decrease in SNR from ~ 18 to ~ 15 dB between 10 and 50 kHz (corresponding to 800 Hz and 4 kHz full-scale frequencies). Below 10 kHz, the array SNR is reduced (although always remaining above 15 dB) due to the smaller number of microphones used to improve resolution at low frequency.

The beamform maps were generated on a planar grid (with a 0.025 m resolution in both directions) covering the entire aircraft. The extent of the grid downstream of the aircraft was adjusted for each aircraft configuration to ensure that all the end caps were within the grid. This allowed identification of potential spurious sources at the end caps and/or VR transition regions. To reduce parallax effects – sources appearing at a location different than the actual – multiple 2D planar grids were defined; 3D grids surrounding the entire aircraft (not shown here) were also implemented to determine the accuracy of the computed results based on the 2D grids. We determined that results from the 2D grids provided ample fidelity for this initial acoustic analysis. The slight reduction in accuracy (in terms of levels and location of sources) is a good trade-off to reduce computational time and simplify the visualization of results. The three beamform grids positioned at the landing gears, “mid”, and wing sections of the TTBW model are shown as red 2D planes in Fig. 10 for the landing configuration. “High-resolution” maps were also generated for a half-span grid aligned with the starboard wing (see Fig. 11), in this case using a 0.005 m resolution in both directions. As will be shown later, this grid was used to identify/separate sources that are clustered around the VCK junctions and brackets.

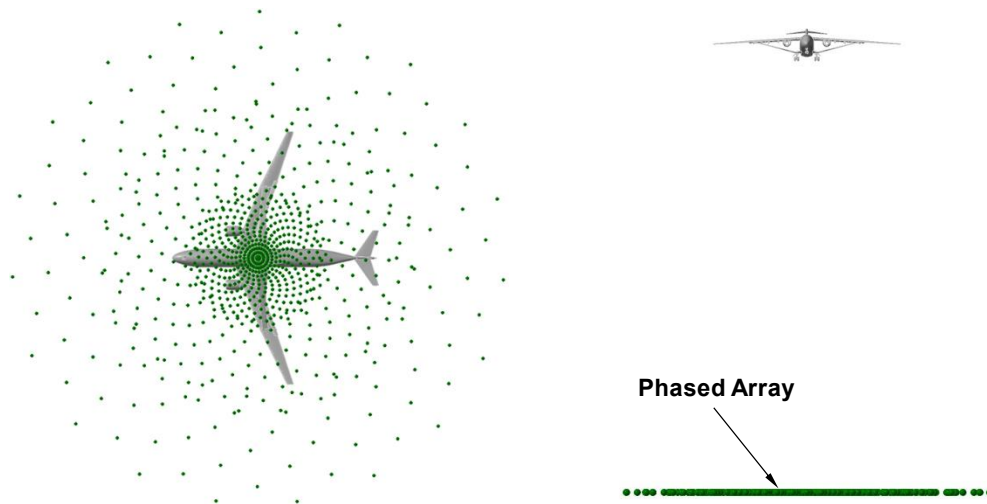


Fig. 9 “Flight test” microphone phased array (FTA) shown in its non-convected location.

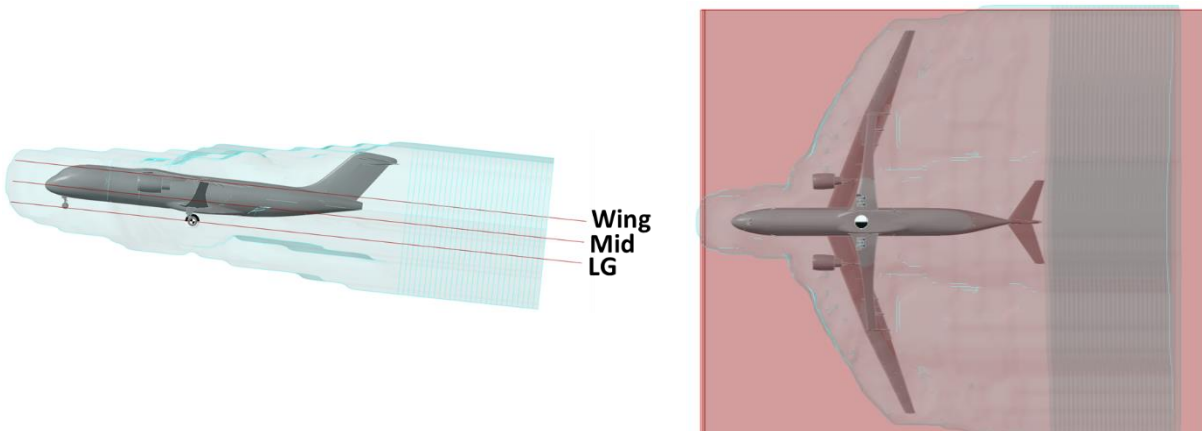


Fig. 10 Two-dimensional (2D) beamforming grids for landing configuration.

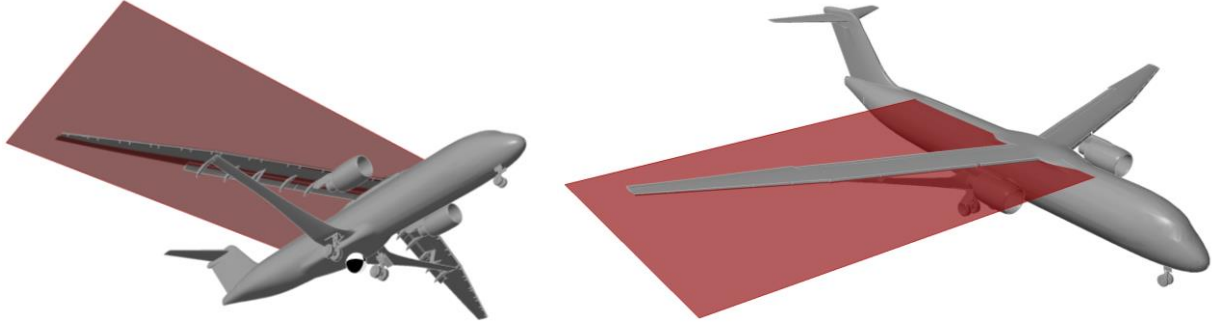


Fig. 11 Half-span, 2D grid used for “high-resolution beamforming”.

Beamforming in narrowband (with a bandwidth of 100 Hz) was used to obtain maps in $1/24^{\text{th}}$, $1/12^{\text{th}}$ and $1/3^{\text{rd}}$ octave bands. The acoustic results presented in this paper are based on the CLEAN beamformed maps, and the corresponding integrated far-field spectra obtained from synthetic pressure records for the FTA. The CLEAN acoustic maps presented here correspond to $1/12^{\text{th}}$ -octave bands, with a range of 15 dB in the contour levels. For visualization purposes only, the maps were generated using an artificial resolution of 0.05 m and 0.02 m for the standard and “high resolution” processing, respectively. However, integration of the CLEAN maps was performed with “zero-resolution” to improve accuracy and avoid the need for normalization. Although narrowband integration was computed for several individual airframe components, the results presented in this exploratory work only include those for the entire aircraft, the wing leading edges, and the landing gear. The reason for this will be explained in the next section. The extent of the three selected integration regions is shown in Fig. 12. A 15 dB integration cutoff was used for the aircraft region to capture the contribution from secondary sources. CLEAN integrated levels for all other regions were obtained with a 10 dB cutoff. This is our typical approach to guarantee that integration around regions of non-dominant sources is not contaminated by spurious sources.

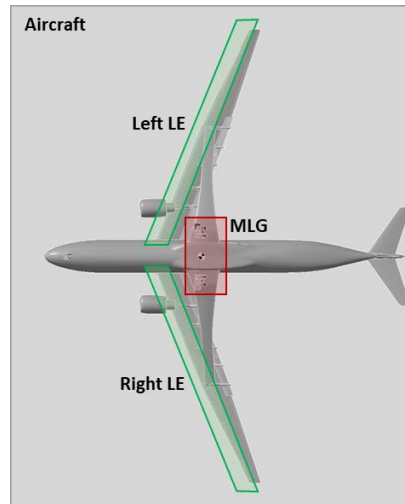


Fig. 12 Tailored integration regions for the TTBW model in landing configuration used to determine contributions to far-field noise spectrum from full aircraft, MLG, and leading edges (LEs).

IV. Results

Representative acoustic predictions of the TTBW aircraft in cruise based on permeable surface data are presented first. Only results from the case without landing gear (clean) are shown, as landing gear deployment masked the noise generated by the rest of the airframe and diminished the level of insight that could be obtained from the clean configuration. The clean condition represents the quietest airframe configuration and is used typically as noise floor in the assessment of contributions from high-lift devices and aircraft undercarriage. Following the cruise results, we present and discuss the primary and secondary airframe sources observed on beamformed (source localization) maps and the resultant integrated far-field spectra for the landing configuration. All frequencies included in this paper (e.g., beamform maps, spectral plots) represent model-scale values.

In our previous studies of other aircraft configurations, we established the need to evaluate spatial resolution convergence of the overall noise signature as well as that of individual aircraft components [21]. This is of particular importance in the presence of elements with different geometric complexities. In such scenarios, the spectrum of a component with a relatively simple geometry is likely to “converge faster” than those of more complex elements with finer details. Since most of our work focuses on noise source identification using data from permeable FWH surfaces, integration of acoustic maps is our preferred tool to determine convergence and will be used here. Although directivity effects over the array would inherently affect the levels output by the array integration process, we have found that the aircraft integrated levels follow very closely the trends and levels of the average spectra of all the microphones in the array. At the same time, phased-array results have the added advantage of rejecting any potential spurious/numerical sources.

A. Cruise Configuration

The results shown in Fig. 13 correspond to the aircraft integrated spectra (from CLEAN maps) for coarse, medium, and fine resolution simulations of the cruise configuration obtained with the original, as-tested CAD model geometry. Observe in Fig. 13 that the far-field spectrum of the clean configuration contains several prominent tones and broad peaks, with their overall character and frequency changing significantly with mesh refinement. These results do not show the expected convergence behavior with increased spatial resolution: based on our previous studies of other aircraft (see Refs. [16], [17], and [21]), we were anticipating a converged spectrum far beyond the 10 kHz frequency range for the finest resolution attempted. To understand the underlying cause of this lack of convergence, a careful examination of the acoustic maps at each spatial resolution was undertaken. We noted that some of the major tonal sources resided along the trailing edges (TE) of the wings, wingtips, and struts. The location and strength of these sources varied with frequency, typically moving from the inboard wing section toward the wing tip as frequency increased, causing broad peaks instead of multiple sharp tones. At the highest frequencies being resolved, sources around the wing tip were highly dominant. Sample acoustic maps from the medium resolution simulation illustrating these sources for the original model geometry are shown on the left column of Fig. 14 for two different 1/12th-octave band frequencies. The appearance of these sources was deemed to be the result of vortex shedding from the variable and thicker-than-normal TEs of the TTBW model geometry being simulated. Recall that this geometry corresponds to the physical model that was tested in the LaRC 14x22 tunnel. Most likely, the TEs were thicker than would be expected from scaling a full-size vehicle to facilitate fabrication of the 8%-scale test model.

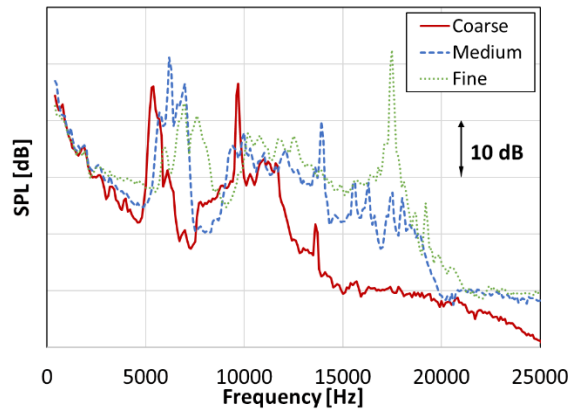


Fig. 13 CLEAN integrated noise spectrum of TTBW model in cruise configuration (LG retracted) for aircraft with original trailing edges. Results obtained at three different resolutions.

To determine the correctness of our assessment, new simulations were performed for a TTBW model with much thinner and uniform TEs that are more representative of an actual full-scale aircraft. These simulations produced acoustic maps without dominant tonal sources along the wing trailing edge and wing tips. The elimination of these tones allowed identification of sources that were being masked. The corresponding maps from medium resolution simulations obtained with the thinner TEs are shown in the right column of Fig. 14. Notice that at 6.7 kHz the peak level in the map for the thinner TE configuration is ~23 dB below that for the original TE configuration. At this frequency, sources are also observed downstream of the tail. These spurious sources are associated with the VR transition region and/or end cap configuration used. Although these spurious sources would contaminate the single-microphone spectra, the use of beamforming and tailored integration regions precludes their effect on the overall noise levels. Detailed explanations of this phenomenon for different aircraft configurations can be found in Ref. [20]. A

method to remove the contribution of these spurious sources from the spectra of single microphones is being developed by our group and will be presented in future publications. For 16 kHz (bottom row of Fig. 14), the peak level in the map for the thinner TE is only 1.4 dB lower than that for the original TE configuration, as indicated in the corresponding contour ranges. Notice also that the sources at the wing tips are no longer present.

The substantial impact of trailing-edge thickness on the noise spectrum becomes very evident when integrating the acoustic maps over the aircraft region. Fig. 15 compares original and thinner trailing edges for coarse (left) and medium (right) resolution results. For both sets of results, observe that the lower-frequency peak (due to sources in the inboard TE) disappears when TE thickness is decreased. However, although the broad “hump” around 10 kHz disappears for coarse resolution results, it is still present for medium resolution (albeit at slightly higher frequencies). The increase in noise between 10 and 14 kHz for the medium-resolution, thinner-TE spectrum and some dominant peaks still observed for both resolutions are related to sources at the engine chine (see Fig. 16), whose thickness was not altered. Based on the cruise configuration results, similar alterations to the thickness of various TEs (including those associated with the chines) were made to the geometry for the landing configuration. These modifications are described in the next section.

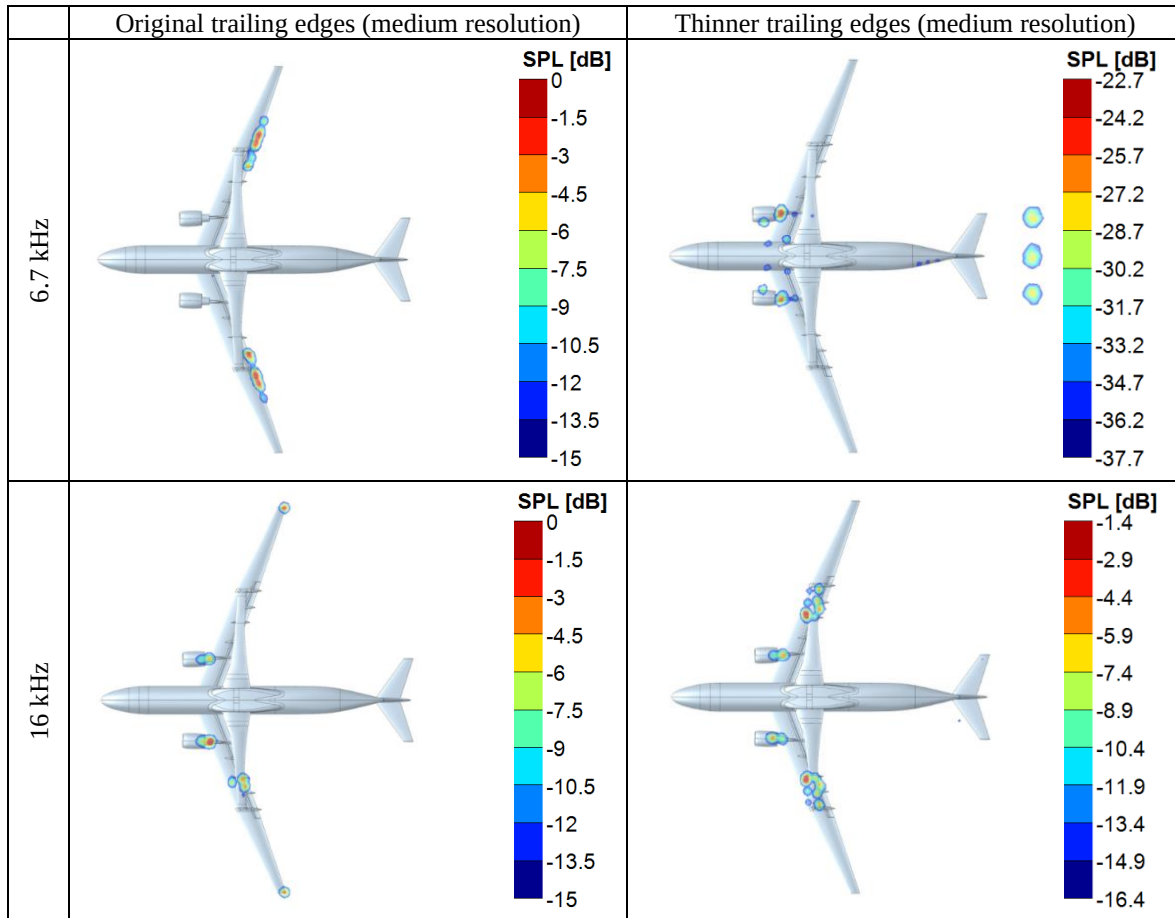


Fig. 14 CLEAN acoustic maps (in 1/12th-octave bands) of TTBW model in cruise configuration (LG retracted) obtained from medium-resolution synthetic pressure records. Peak levels in contour range for thinner TE (right column) are shown relative to peak for original TE (left column), at the corresponding frequency.

With a revised trailing-edge geometry, convergence of the spectral content with increased resolution can be revisited. Results for coarse and medium resolution for the thinner-TE geometry are shown in Fig. 17. Although full convergence is yet to be achieved, a better convergence behavior of the spectrum for frequencies below 10 kHz is observed. In addition, the medium-resolution results show significantly increased levels for most frequencies between ~9.5 and ~18 kHz. As mentioned before, the broad “hump” around 12 kHz is associated with the engine chine. The tones observed between 15 and 18 kHz are caused by sources at the engine pylons. Narrowband maps in that range show dissimilar tone frequencies (and hence levels) between the port and starboard pylons. Most likely, some of this

tonal content is associated with vortex shedding from the nacelle TE, whose thickness remained unaltered for the cruise configuration. Clearly, the presence of these sources and their impact on the spectra complicate the process of determining the frequency range for which convergence was achieved.

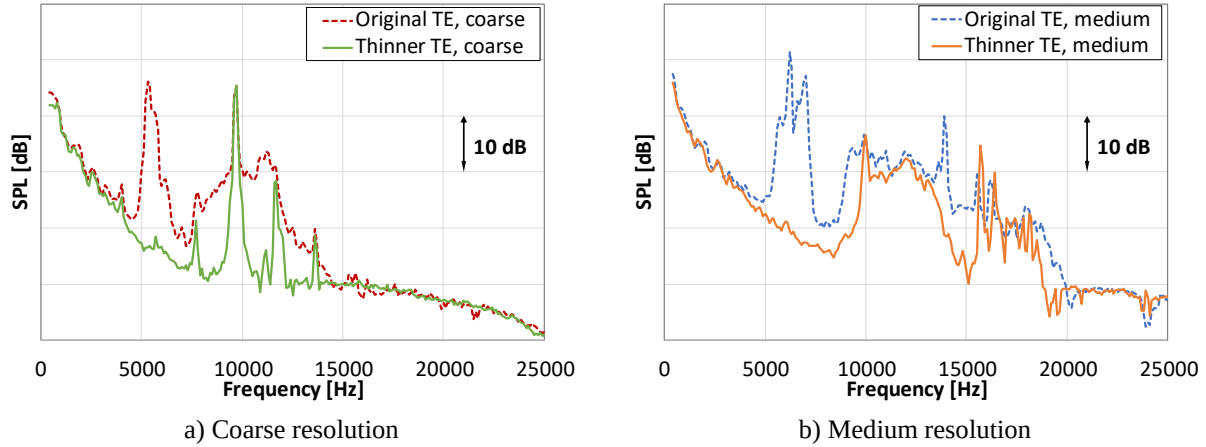


Fig. 15 Comparison of CLEAN integrated spectrum of TTBW model in cruise configuration (LG retracted) with original and thinner trailing edges from coarse (left) and medium (right) resolution simulations.

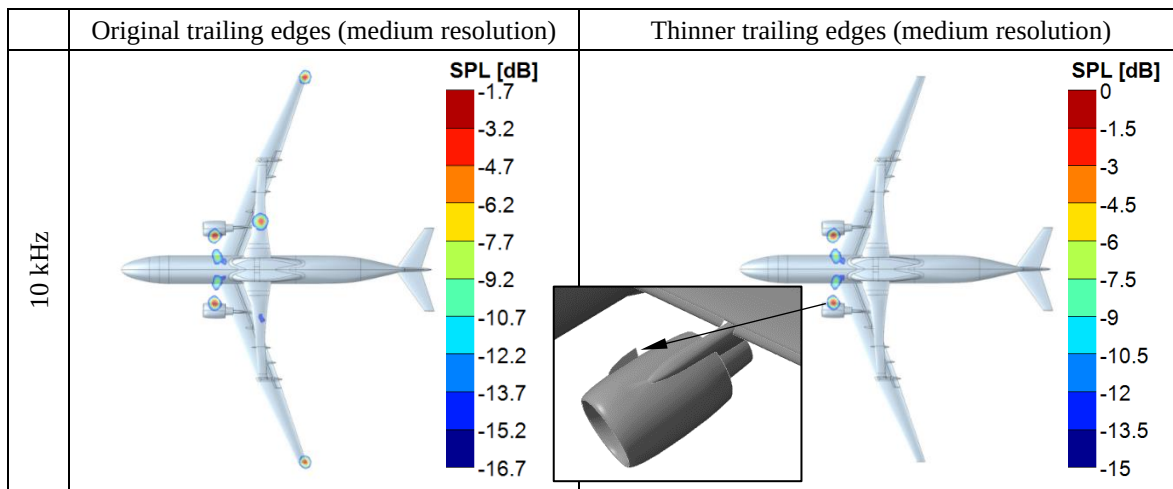


Fig. 16 CLEAN acoustic maps (1/12th-octave band) of TTBW model in cruise configuration (LG retracted) at 10 kHz, showing dominant sources at the engine chine. Results from medium-resolution simulations.

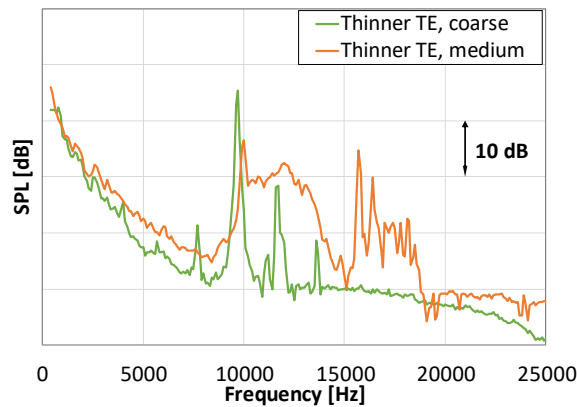


Fig. 17 CLEAN integrated noise spectrum of TTBW model in cruise configuration (LG retracted) with thinner trailing edges. Results shown for two spatial resolutions.

B. Landing Configuration

Leveraging the insights gained from the cruise configuration, the CAD geometry for the landing configuration was carefully modified to eliminate the anticipated unrealistic tonal sources, resulting in a TTBW model with much thinner and uniform TEs that are more representative of an actual full-scale aircraft. Thinning the trailing edges required modifications to various airframe components such as the wing, flap, main strut, jury strut, nacelle, and chine. Only the TEs of the VCK flap segments located on the wing LE were untouched. Validation of simulated aerodynamic results against 14x22 measurements [18] clearly demonstrates that thinning the TEs has a negligible impact on the aerodynamic characteristics of the model. Therefore, all airframe noise simulations for the landing configuration and the associated acoustic results presented here were accomplished using the CAD model with thinner TEs.

Synthetic pressure records for the FTA microphones using permeable and solid FWH data surfaces were generated for the landing configuration. A comparison of the CLEAN integrated spectra between both types of surfaces is shown in Fig. 18 for coarse (left) and medium (right) resolution simulations. These results show that there is very good agreement at low frequencies between permeable and solid surfaces, which suggests that shielding effects are not significant below ~5 and 7 kHz for coarse and medium resolution, respectively. Above those frequencies, permeable and solid spectra start to diverge with the latter showing higher levels as expected. Any potential shielding effects at higher frequencies are addressed later.

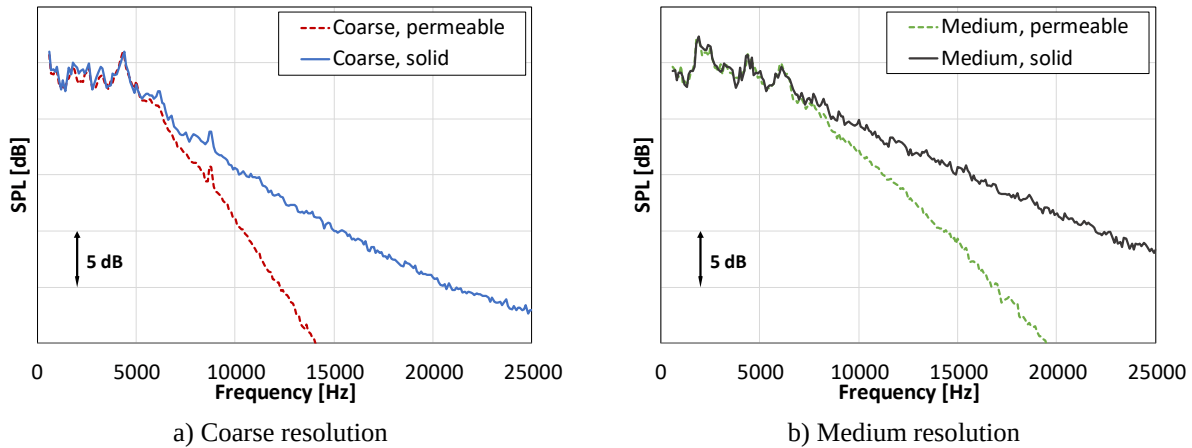


Fig. 18 CLEAN integrated noise spectrum of TTBW model in landing configuration. Comparison of results from permeable and solid FWH surfaces, shown for coarse (left) and medium (right) spatial resolution.

Convergence of the full aircraft spectra for permeable and solid surfaces is depicted in Fig. 19. Notice that both medium-resolution results show a noticeable increase in noise around 2 kHz, with two distinctive peaks in that region. Analysis of the narrowband acoustic maps (not shown here) indicates that this is caused by an increase in the noise levels of the MLG. At a given frequency, these maps also show asymmetries between the levels at each gear. This is somewhat typical in the presence of “mirrored” sources that produce tonal components with slightly different frequencies. Additional convergence results for individual components are presented later.

During analysis of the phased-array results for the landing configuration, we observed that the MLG is the dominant source for frequencies below ~4 to 5 kHz, depending on the resolution of the simulations. Sample acoustic maps (LG grid) for 3.35 kHz based on permeable surface data are displayed in the top row of Fig. 20 for coarse- and medium-resolution simulations, with contour levels shown relative to the peak level among them. As can be seen in the figure, other sources have peak levels that are more than 13 dB below those of the MLG. Above ~5 kHz, sources at the wing LE quickly become dominant, as shown in the bottom row maps of Fig. 20 for 7.1 kHz. In these maps, use of the wing grid causes a slight offset in the location of MLG and NLG sources (they appear further upstream than their actual location) due to parallax. The frequency range for which each source is dominant is easily observed in the CLEAN integration results of Fig. 21. Each chart shows a comparison of the integrated spectra for the MLG (from LG grid), wing leading edges (from wing grid) and whole aircraft (from mid grid) integration regions, as depicted in Fig. 12. Results from permeable (dashed lines) and solid (solid lines) FWH surfaces are shown in each figure for coarse (left) and medium (right) resolution. It is very clear from the spectral plots of Fig. 21 that sources on the LEs account for most of the noise above 5-6 kHz; LEs and MLG levels are similar around 4-5 kHz, and MLG sources become dominant at lower frequencies. Observe also that the combined noise from the MLG and LE devices is nearly equivalent to the total noise produced by the entire aircraft. It remains to be determined whether replacing the current

VCK brackets with more realistically shaped brackets would significantly alter the distribution and strength of the sources at the wing LE, resulting in much lower noise levels at moderate and higher frequencies.

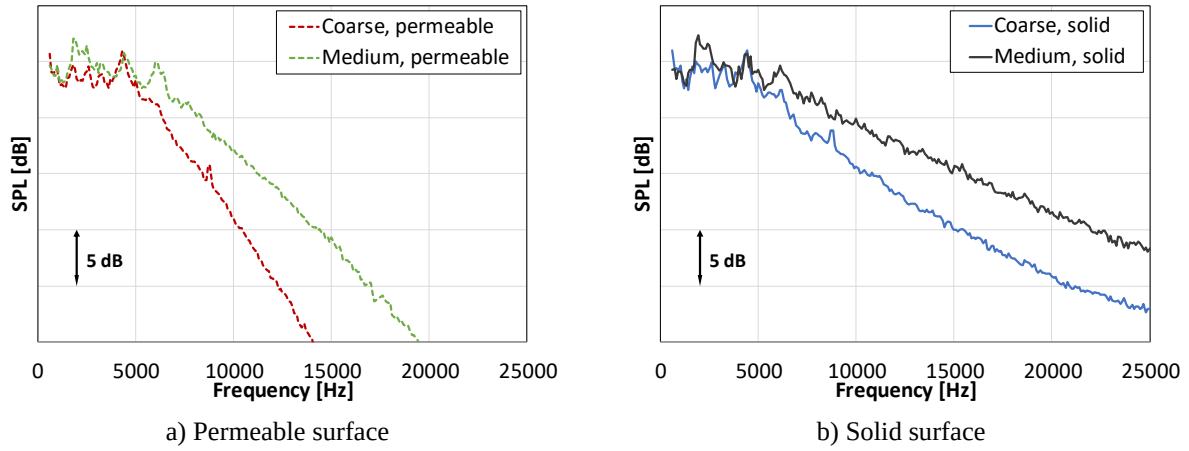


Fig. 19 CLEAN integrated noise spectrum of TTBW model in landing configuration. Convergence results from permeable (left) and solid (right) FWH surfaces for two spatial resolutions.

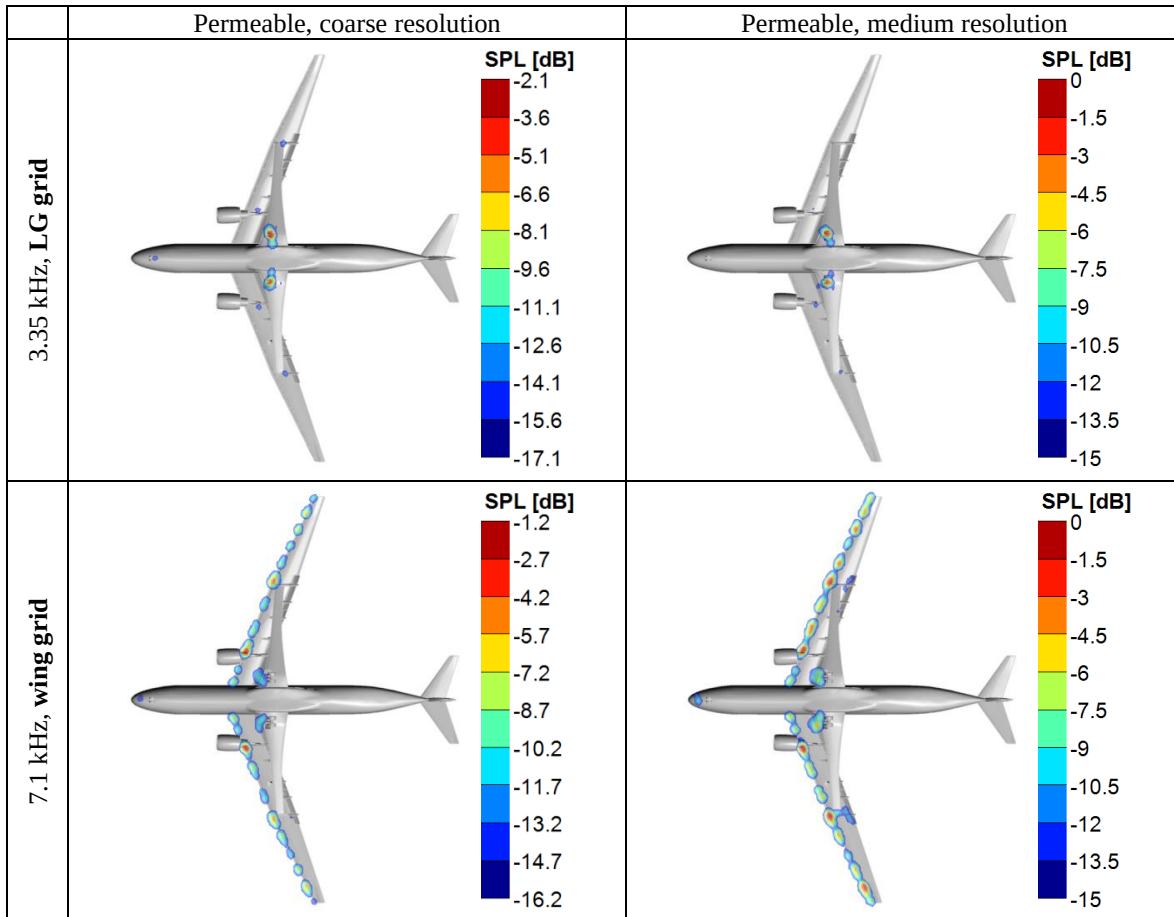


Fig. 20 CLEAN acoustic maps (in 1/12th-octave bands) from coarse (left) and medium (right) resolution. Synthetic pressure records from permeable FWH data surface. Grid and frequency indicated in the row headers.

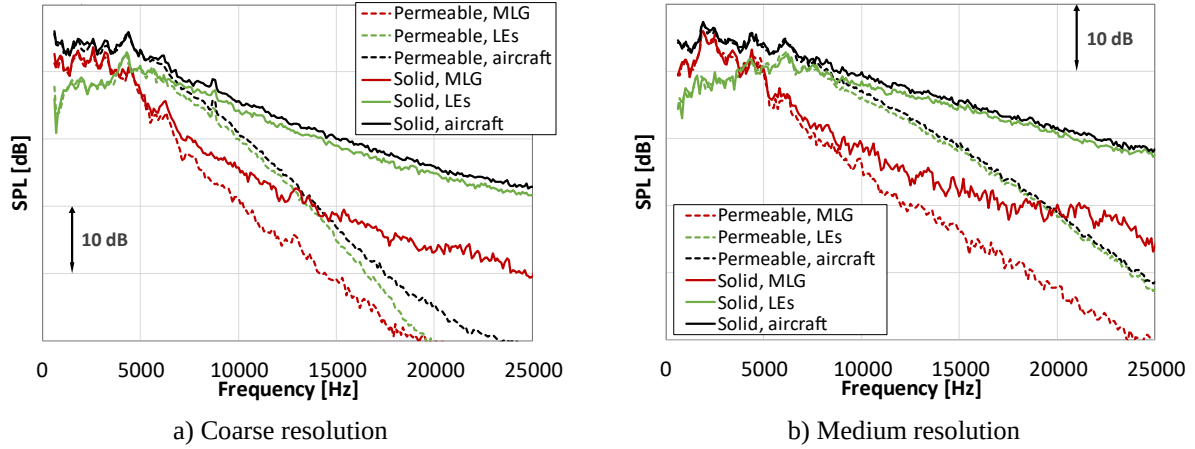


Fig. 21 CLEAN integrated noise spectrum of TTBW model in landing configuration. Spectra for different integration regions shown for coarse- (left) and medium- (right) resolution simulations.

Once the major sources of interest are identified, our goal is to analyze the convergence of their individual spectra as the resolution of the simulations is increased. We note that there are several sources with differing noise generation mechanisms in the wing LE region. However, a granular convergence analysis of those sources (and others not shown in this paper) is outside the scope of this preliminary assessment of the acoustic signature of the TTBW and will be deferred to a later study. Fig. 22 shows convergence of the integrated spectra obtained from the MLG and LE regions for both permeable (left) and solid (right) surfaces. Unlike previous figures, notice that the frequency range shown in the plots is limited to 15 kHz to emphasize those frequencies where reasonable convergence of the predicted spectral levels was expected. Observe from the figure that the LE sources (green lines) have “fully converged” below ~5 kHz. However, spectra for the MLG region (red lines) still show some differences in that frequency range, mostly related to the tonal components around 2 kHz mentioned before (see discussion of Fig. 19). The 5 kHz range of spectral convergence observed here is unexpected. In our past studies of several aircraft, where we worked with grids of comparable resolution to those used here, we were able to demonstrate spectral convergence beyond the 10-12 kHz frequency range (e.g., see Refs. [16], [17] and [21]). For reasons yet unknown to us, the far-field noise spectrum associated with the TTBW aircraft shows a very slow rate of convergence with increasing spatial resolution. Ongoing simulations with finer grids will provide additional insights into the convergence behavior of the TTBW noise signature.

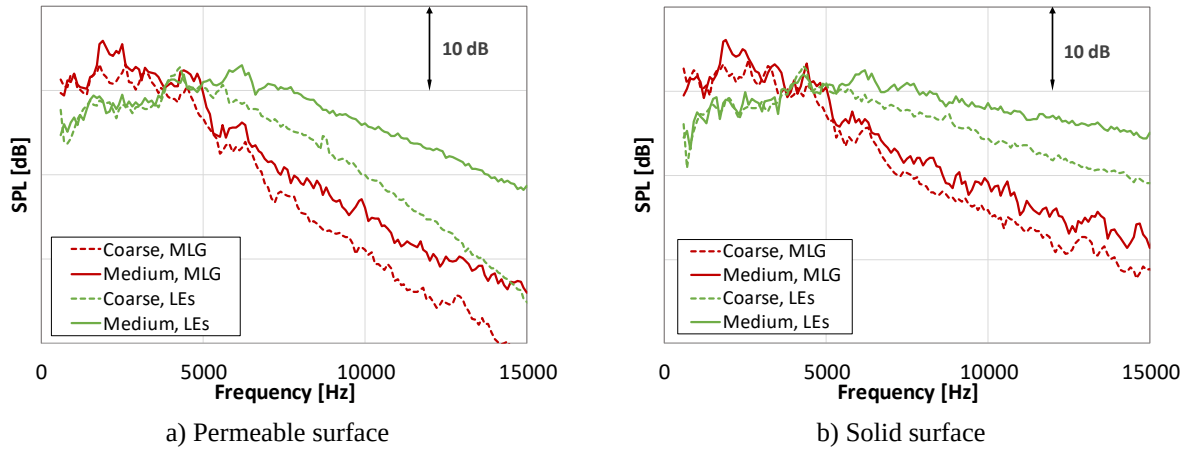


Fig. 22 CLEAN integrated noise spectrum of TTBW model in landing configuration. Convergence of MLG and LEs integrated spectra for results from permeable (left) and solid (right) FWH surfaces.

Since the VCK brackets are situated near the junction of adjacent LE flap segments, in many instances the bracket and juncture sources were manifested as single, elongated spots in the beamform maps. This necessitated improved resolution of the acoustic maps so that the VCK sources could be separated and their location determined more

accurately. Better resolution could also enhance quantification of their contribution to the overall noise levels by defining tailored integration regions around each source of interest. This task was accomplished by using the “high resolution grid” shown in Fig. 11. This grid has 5 times the resolution of our “standard” flight test array used in all the results presented so far, i.e., 0.005 m versus 0.025 m. Although the use of a finer grid increased the computational time required for beamforming and deconvolution, it was necessary to improve the noise source identification process. Sample CLEAN acoustic maps for medium-resolution simulations showing sources at the VCK brackets and junctions are presented in Fig. 23 for 7.1 kHz (same frequency shown in the lower row of Fig. 20, where the “standard” grid was used). In this and the following figures, permeable surface results are presented in the top row and the corresponding solid surface results in the bottom row. In all cases, peak contour levels for solid surfaces were higher than those for permeable surfaces. Therefore, the contour range for permeable surface maps is shown relative to the solid peak levels at the same frequency. In Fig. 23, the improved resolution of the maps – due to a finer grid and higher user-defined resolution used in CLEAN – clearly provides better separation of the desired sources, i.e., VCK brackets from junctions.

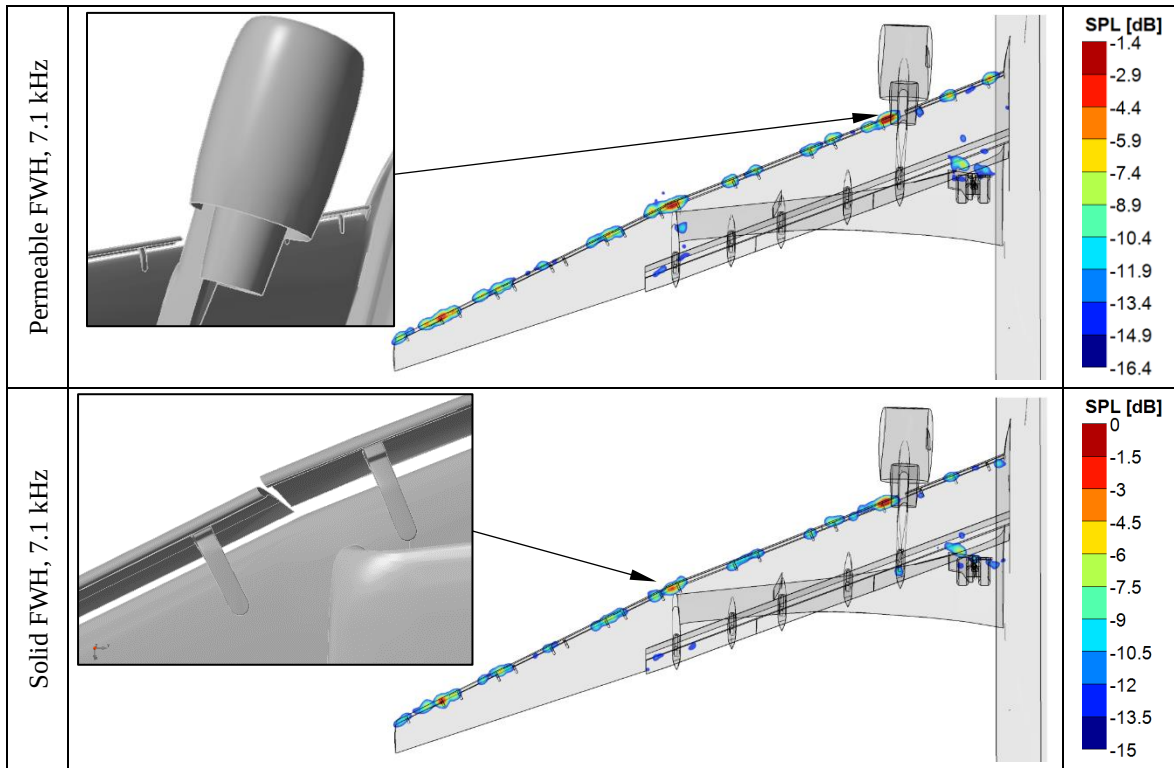


Fig. 23 “High-resolution” CLEAN acoustic maps for 7.1 kHz (in 1/12th-octave bands) from medium resolution. Synthetic pressure records using permeable (top) and solid (bottom) FWH surfaces.

Fig. 24 depicts maps for 11.2 kHz, where the location of sources for solid and permeable surfaces is similar, but differences in peak levels are now larger. These differences in source amplitude could be related to two distinct effects. First, the lower amplitudes of the permeable surface sources are caused by 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. Second, the higher amplitudes of the solid sources may be caused by the inability of the solid surface approach to account for shielding at higher frequencies. We hope our ongoing simulations at finer resolutions will allow us to distinguish which effect is more prevalent. To illustrate the latter effect, notice that noise sources generated at the outboard edge of the first VCK flap segment and inboard edge of second VCK segment (these two side edges reside above the nacelle) are visible in the solid surface maps but are, correctly, absent in the permeable maps. This indicates that noise shielding effects are not being captured by the solid surface formulation. Although not shown here, sources around the same location (VCK side edge and gap in the nacelle region) were also observed at ~4.25 kHz. These sources become more dominant for solid results at frequencies above 20 kHz, frequencies for which acoustic maps from permeable data are no longer reliable due to insufficient spatial resolution. Notice also that Fig. 24 shows a source at the outboard edge of the third flap segment. This flap side-edge source is also observed at frequencies

between 8 kHz and 12 kHz, and around 3 kHz (not shown here). In conventional tube-and-wing aircraft, flap side edges are primary sources of airframe noise. Most likely, their importance relative to other TTBW airframe sources is greatly impacted by the dominance of VCK bracket noise.

Synthetic pressure records based on medium-resolution simulations are likely not fully resolved at frequencies above ~12-13 kHz. Therefore, as frequency increases, we expect that the levels from permeable surfaces would decay faster than those for solid surfaces. This trend can be observed in the results for 16 kHz, shown in Fig. 25. Note that the peak levels from the permeable surface are 5.1 dB lower than those for solid data, and that the relative strength of sources along the LE is different in the two maps. That is, the permeable surface map shows stronger sources residing towards the wing tip, while the solid map shows similar levels for most brackets/sources along the span. Further discrepancies in terms of relative levels along the span are also present at higher frequencies. Beamform maps at 20 kHz, shown in Fig. 26, illustrate this observation. Notice that for solid surfaces, VCK brackets in the inboard and mid span sections of the wing are now louder than those towards the wing tip. However, permeable surface results indicate that sources towards the wing tip are strongest, with the LE sources from the VCK side edges adjacent to the nacelle seemingly shielded. Although results obtained from the permeable surface at this frequency are not fully resolved, it is still informative to see the impact of using this surface on different sources along the span.

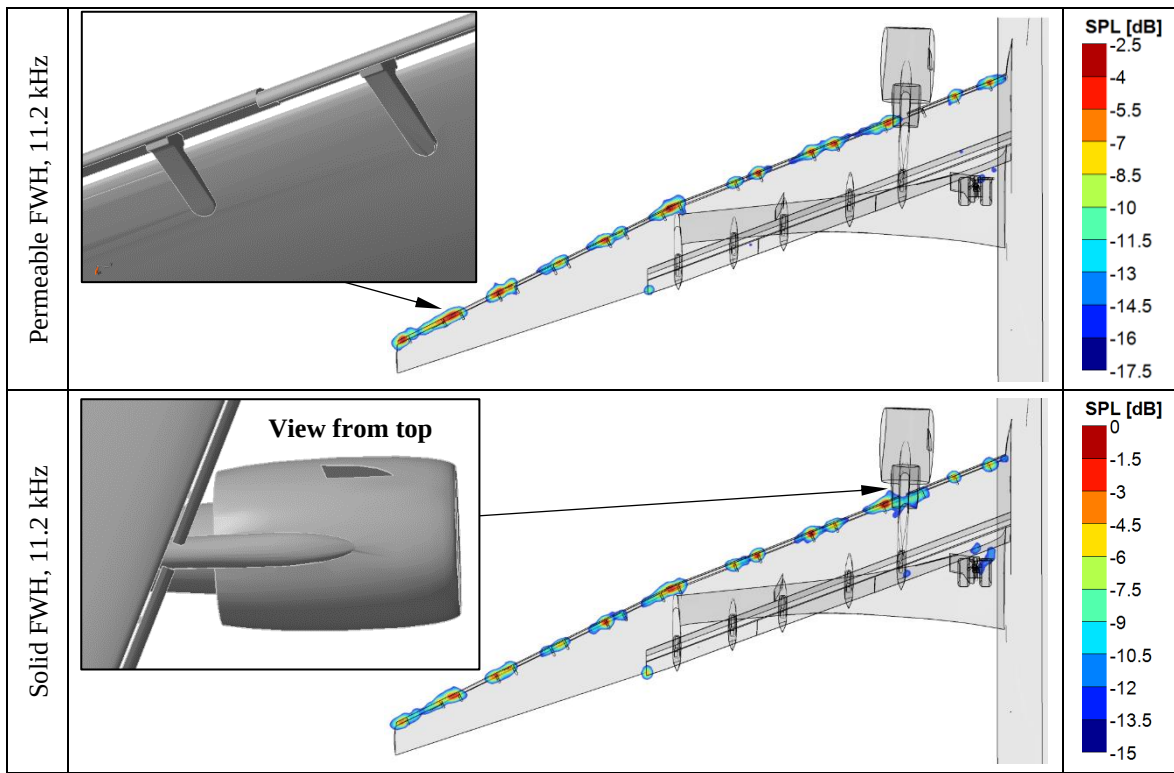


Fig. 24 “High-resolution” CLEAN acoustic maps for 11.2 kHz (in 1/12th-octave bands) from medium resolution. Synthetic pressure records using permeable (top) and solid (bottom) FWH surfaces.

We also compared the aircraft integrated noise spectrum of the TTBW model in cruise (LG retracted) and landing configurations. Results for medium resolution simulations using permeable FWH surface data are shown in Fig. 27. For the landing configuration, this figure also includes integrated levels for the MLG and LE regions. The plotted spectra show that once landing gear and high-lift devices are deployed, the landing configuration is 15 to 40 dB louder than cruise for frequencies below ~15 kHz. In that same frequency range, the noise from the MLG alone is significantly higher than the noise produced by the entire aircraft in the cruise configuration. Since the increase in noise that starts around 10 kHz for the cruise configuration is related to chine sources, we expect that future simulations with thinner TEs in all relevant components (as was done for the landing configuration) would also render levels ~30 dB quieter than the landing configuration in the 10-15 kHz range. Finer resolution simulations should allow us to determine the spectral trends above the 15 kHz frequency range.

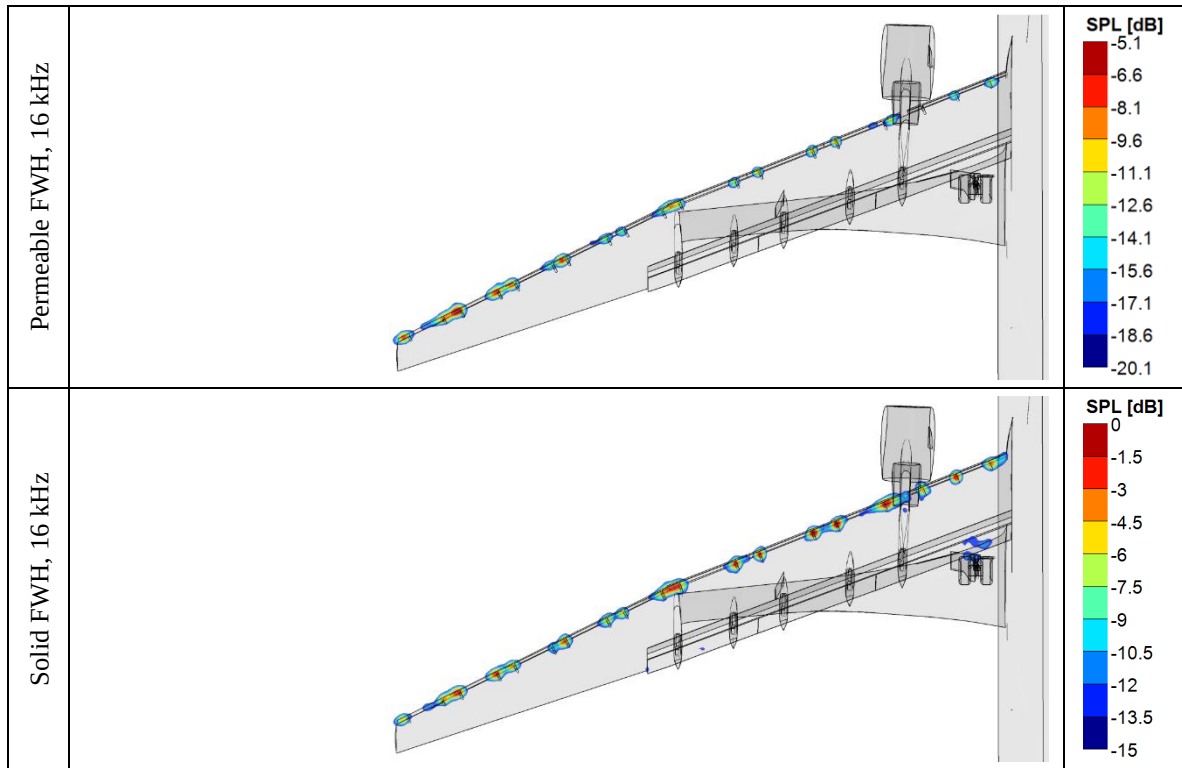


Fig. 25 “High-resolution” CLEAN acoustic maps for 16 kHz (in 1/12th-octave bands) from medium resolution. Synthetic pressure records using permeable (top) and solid (bottom) FWH surfaces.

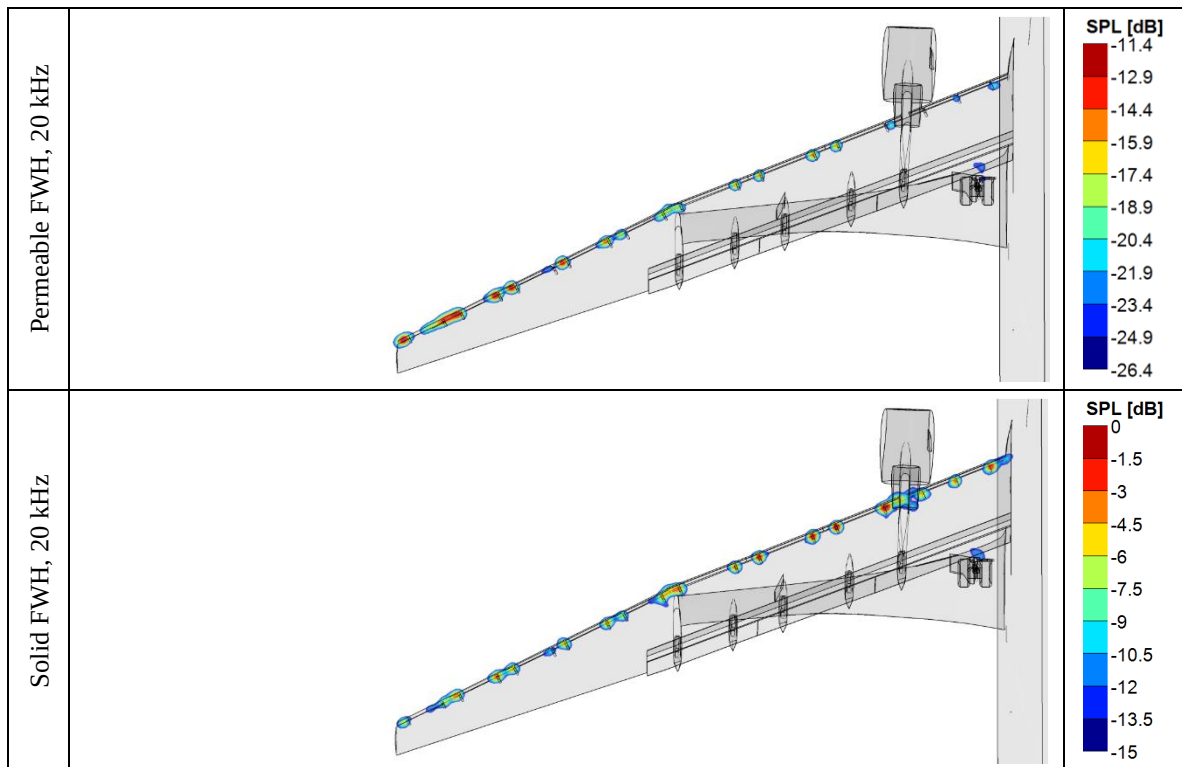


Fig. 26 “High-resolution” CLEAN acoustic maps for 20 kHz (in 1/12th-octave bands) from medium resolution. Synthetic pressure records using permeable (top) and solid (bottom) FWH surfaces.

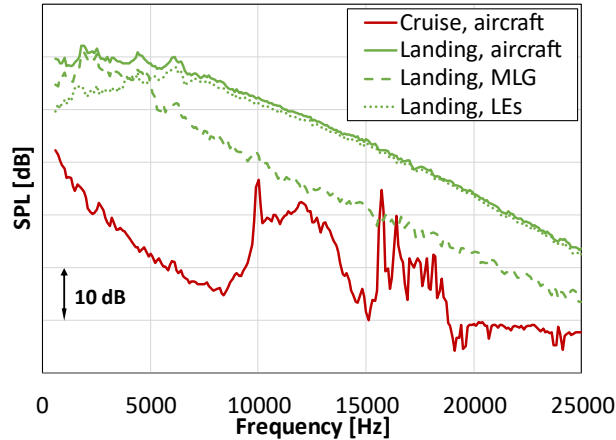


Fig. 27 CLEAN integrated noise spectrum of TTBW model in cruise (LG retracted) and landing configurations. Results from medium resolution synthetic pressure records using permeable FWH surface.

V. Summary Remarks

An initial analysis of the acoustic signature of the TTBW model in cruise (clean) and landing configurations was performed. Source localization (beamform) maps obtained from an 800-microphone synthetic phased array that mimics a flight test setup were used to examine airframe sources associated with each configuration.

For the clean configuration, integrated far-field spectra and sample acoustic maps at two spatial resolutions were generated from permeable FWH surface data. Issues in the initial simulations, arising from the model's thicker-than-normal trailing edges, were addressed and results were compared to those from new simulations with thinner trailing edges. This modification precluded dominance of trailing-edge sources caused by vortex shedding. Convergence trends for the far-field noise spectrum were established via simulations at two different spatial resolutions. However, vortex shedding from secondary components (such as engine chines) that still possessed larger than normal thicknesses resulted in the appearance of dominant tonal sources at the engine nacelle. These sources hindered the effort to extend convergence of the far-field noise spectrum for the cruise configuration to frequencies beyond ~8 kHz.

Lessons learned from the TTBW simulations of the clean configuration were applied to the landing configuration. Geometry modifications included thinning the trailing edges of various airframe components such as the wing, flap, main strut, jury strut, nacelle, and chine to either eliminate or significantly reduce the tonal noise component of the far-field noise spectrum. However, the trailing edges of the VCK leading edge flap segments were untouched. Acoustic results for the landing configuration were obtained with data from permeable and solid FWH surfaces. Synthetic flight test array results indicated that the main landing gear is the dominant noise source at frequencies below ~5 kHz. Above ~5 kHz, sources in the wing leading edge account for most of the radiated noise. These major sources mostly involve the VCK brackets as well as gaps and steps between adjacent LE flap segments. For frequencies between 4 and 5 kHz, MLG and LE sources show similar integrated levels, particularly for results from medium-resolution simulations. Results from simulations conducted at two distinct spatial resolutions were used to determine convergence of the computed far-field spectrum obtained from permeable and solid data surfaces. Convergence trends were assessed based on examination of total aircraft noise spectrum as well as spectra from two major subcomponents (i.e., LE devices and MLG). Permeable-surface results for the aircraft integration indicate that the simulations are resolved up to 12-13 kHz. A comparison of the integrated spectra for the LE region obtained from coarse and medium resolution simulations shows nearly identical levels at frequencies below ~5 kHz for both permeable- and solid-surface data, which indicates that noise for those sources has fully converged. However, a similar analysis of the coarse- and medium-resolution MLG spectra showed some noticeable differences around 2 kHz. Examination of the narrowband acoustic maps from coarse- and medium-resolution simulations identified sources of varying relative strength between the port and starboard MLG. This is typically seen when the MLG consists of multiple rod segments of varying diameter, which may result in slightly different vortex shedding frequencies for each gear. Unfortunately, the length of the time signals precludes a more accurate narrowband analysis using a higher frequency resolution. It is also conjectured that the MLG tones may appear somewhat stronger due to under resolution of the cylindrical subcomponents. Ongoing simulations with finer resolutions should allow us to support further these claims.

The use of a "high-resolution grid" in the beamforming process increased the location accuracy and separation of several sources that were clustered around the VKC brackets and nearby gaps/steps between adjacent wing LE flap

segments. For maps generated from solid surface data, use of the “high-resolution grid” helped to identify sources in the gap between LE flap segments near the engine pylon. Due to shielding effects, sources in this region had much lower strength or were not present at all in the permeable data surface maps. The VCK flap-eylon juncture sources became more dominant at higher frequencies that were not fully resolved in the current simulations. Ongoing simulations based on finer grids are expected to provide further insights on the higher frequency sources, especially those sources that may be affected by shielding.

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