

Aeroacoustic Computations of a Generic Low Boom Concept in Landing Configuration: Part 2 - Airframe Noise Simulations

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Aeroacoustic simulations of a subscale, generic, low-boom supersonic aircraft model at low speeds were carried out using the Lattice-Boltzmann Very Large Eddy Simulation software PowerFLOW[®] and a Ffowcs Williams and Hawkings approach. The objective was to characterize the airframe noise signature of the configuration and determine the similarities and differences to conventional subsonic aircraft. We quantified the noise produced by the flap and landing gear by simulating the aircraft with and without deployment of these components. Mach number scaling of the far-field noise levels was examined by performing simulations at different flow speeds. We demonstrate that a solid surface formulation does not capture the aircraft acoustic field properly, while a carefully constructed permeable surface formulation yields far-field spectra that compare very favorably to results from direct probing of the simulated flow field.

I. Nomenclature

CFD	=	Computational Fluid Dynamics
FW-H	=	Ffowcs Williams and Hawkings
LBM	=	Lattice-Boltzmann method
LG	=	Landing Gear
MLG	=	Main Landing Gear
NLG	=	Nose Landing Gear
M	=	Mach number
M_{ref}	=	reference Mach number = 0.2
PSD	=	Power Spectral Density
SPL	=	Sound Pressure Level
VLES	=	Very Large Eddy Simulation

II. Introduction

At present, information of sufficient accuracy to determine properly the airframe noise footprint and levels generated by commercial supersonic aircraft during landing and takeoff does not exist. Due to the dearth of experimental data available to construct semiempirical noise prediction models, system-level, low-speed aeroacoustic

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analyses of supersonic aircraft concepts must rely on existing models that were developed for conventional tube-and-wing subsonic aircraft [1]. As a result, the airframe noise levels predicted with this approach are highly uncertain. Models with good predictive capability are crucial to the evaluation of competing aircraft concepts to identify the most viable and effective low-noise configurations. The present high-fidelity, physics-based, multiphased computational study constitutes the initial step in a targeted effort by NASA to produce the knowledge and tools that will foster accurate predictions of the airframe noise signatures generated by commercial supersonic transports during landing and takeoff (LTO) operations.

Previous studies conducted under the NASA Environmentally Responsible Aviation and Flight Demonstrations and Capabilities projects have clearly established the viability of physics-based computational simulations to accurately predict the far-field airframe noise footprints of large model-scale and full-scale subsonic aircraft in landing configuration [2-5]. Vastly different wing designs and aerodynamic performance at low speeds present challenges during the simulation of airframe noise for supersonic aircraft that are quite different from those of typical, commercial, subsonic tube-and-wing configurations. With those differences in mind, the present investigation aims to extend and tailor the computational methodology used in our previous studies to commercial supersonic aircraft concepts in order to identify the prominent airframe noise sources and to better understand the relevance of these sources to the far-field noise footprint of this transport class. As a starting point, a generic low-boom concept (GLBC) was selected as the testbed. While not a viable passenger-carrying supersonic business jet, the GLBC is a suitable configuration for exploratory airframe noise analyses. A 15%-scale model of the GLBC was tested in the NASA Langley Research Center 14- by 22-foot subsonic tunnel (14x22) to determine the low-speed aerodynamic characteristics of the configuration. The data acquired during that test provided sufficient information for us to validate predicted aerodynamic trends before commencing the more challenging and costly airframe noise simulations.

The study to assess the aeroacoustic behavior of the GLBC during LTO operations consists of three phases. The initial phase focused on accurately predicting the key aerodynamic characteristics of the model [6]. To facilitate comparisons with measured data, the wind tunnel test section and model support system were included in the simulations. The second phase, which is the subject matter of this paper, focused on airframe noise prediction by conducting simulations of several model configurations in free-air to determine the contribution of various airframe components, individually and combined, to the far-field noise footprint of the model. During this phase, extensive work was performed to determine the most appropriate data surface to use during propagation of near-field pressure to the far-field. Description and tabulation of available experimental data, validation of the predicted aerodynamic trends, and analysis of synthetic phased microphone data for identification and ranking of the simulated airframe noise sources were performed during the third phase [7].

A full account of the airframe noise simulations performed in phase two is provided in this paper. Detailed descriptions of the approach and subtle, yet important, computational issues unique to supersonic aircraft configurations are discussed as well.

III. Simulated Cases

The digital model of the GLBC is described at length in phase one of this study [6]. The present simulations were carried out in free air conditions to eliminate reflections from tunnel walls and allow the acoustic waves to propagate properly. Additionally, gaps near the ailerons, flaps, rudder, and stabilators were closed, as they created considerable noise, while not being realistic in size when compared to gaps in flying aircraft. The only other modification to the geometry was the removal of the wind tunnel sting, leaving a blunt face where the engine exhaust would be. We used a cubic domain of 100 fuselage length sides and removed the model support system holding the aircraft in the wind tunnel. The aircraft remained in model scale (15%) and the Reynolds number (based on mean aerodynamic chord) and Mach number were 4.4×10^6 and 0.2, respectively. The angle of attack was fixed at 9° , representative of landing conditions. We varied the flap deflection angle from retracted (0°) to deployed for landing (30°) and for each flap angle, we simulated landing gear deployed (LGon) or stowed (LGoff). Hence, four different geometries were considered, as listed in Table 1.

Table 1. Configurations studied.

	Flap Angle	Landing Gear
Flap0-LGoff	0°	Stowed
Flap30-LGoff	30°	Stowed
Flap0-LGon	0°	Deployed
Flap30-LGon	30°	Deployed

Configuration Flap0-LGoff corresponds to an aircraft in cruise and represents the quietest possible (baseline) configuration, while Flap30-LGon corresponds to a landing scenario, shown in Fig. 1. Configurations Flap30-LGoff and Flap0-LGon serve to isolate the effects of flaps and landing gear, respectively, on far-field noise.

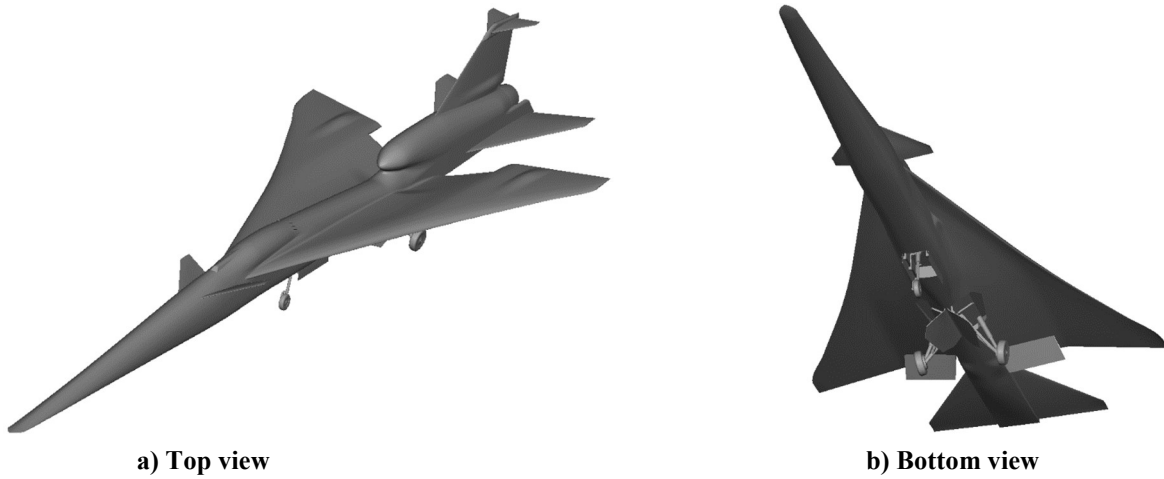


Fig. 1 Generic Low Boom Concept aircraft with flaps and landing gear deployed.

The flow field on the upper surface of the wing was resolved with a mesh distribution very similar to that used in phase one [6] of this study. Additional spatial resolution was placed in the vicinity of the landing gear, flap-side-edges, and wakes to capture the aeroacoustics of these components. Lessons learned from previous work [2-4] were used as best practices to guide the resolution requirements for the GLBC.

Three meshes were used in this study to investigate grid sensitivity. Determination of mesh resolution effects is particularly relevant for this case, as currently no acoustic data exist for the GLBC. The three meshes have the same underlying structure and were refined by dividing the cells by a factor of 1.5 from coarse to medium and medium to fine. The exact number of cells in the meshes depends on the model configuration and whether the flaps and LG are deployed. A summary of the meshes used for Flap30-LGon, representing the most computationally intensive configuration, is shown in Table 2.

Table 2. Meshes used for Flap30-LGon.

Resolution	Smallest cell size (mm)	Number of cells
Coarse	0.13	1.5×10^9
Medium	0.09	5×10^9
Fine	0.06	17×10^9

We evaluated the noise spectrum at several locations to gain insight into different aspects of the aeroacoustic behavior of the model. For validation of the FW-H approach (section V-A) we used a location near the aircraft, so that the sound levels could be extracted directly from the simulated fluctuating pressure field without incurring significant numerical diffusion. For the other studies, we used an overhead microphone located 5.334 m below the aircraft. This microphone is at the center of the overhead synthetic microphone array used in phase three of this study [7] and is displaced downwind to account for convection effects. Finally, microphones positioned along two circular arcs were used to evaluate the directivity effects in the flyover and sideline directions. These arcs are centered on the aircraft and have radii of 15 m (or 100 m in full-scale). Figure 2 illustrates the location of all aforementioned microphones. All simulations were run long enough beyond the transient stage to record pressure at the various microphone locations for 0.06 s of simulated time (0.4 s full-scale), to provide sufficient resolution at low frequencies and an adequate number of samples for spectral analysis and averaging.

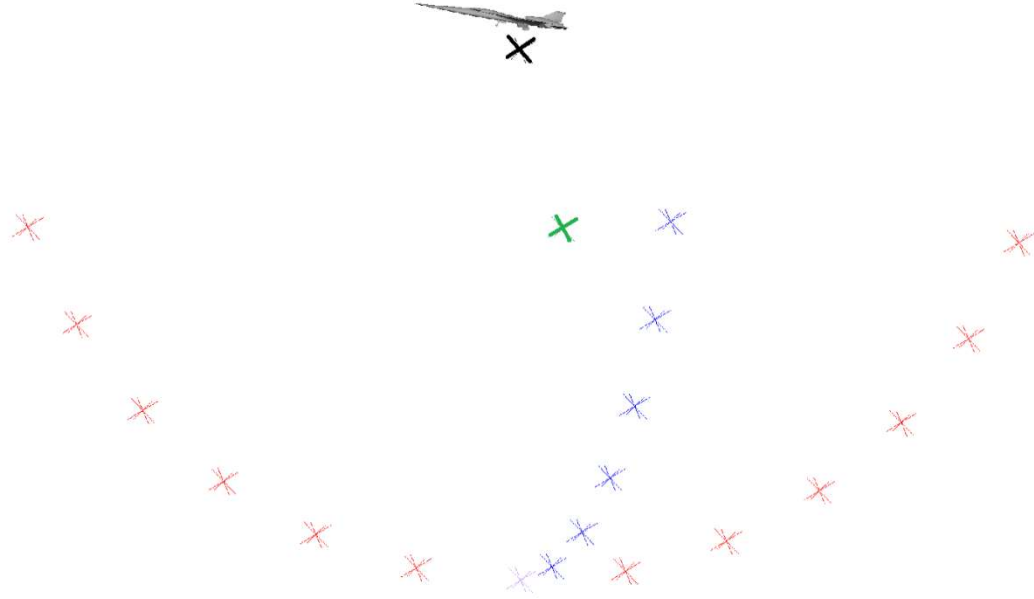


Fig. 2 Microphone locations. Direct probe in black, center of beamforming array in green, flyover directivity arc in red, sideline arc in blue, microphone common to both directivity arcs in purple.

IV. Numerical Methods

The lattice Boltzmann code PowerFLOW 6-2019-R2 was used to simulate the results presented in this paper. A description of the numerical methods is provided in phase one of this study [6]. Although the flow solver can compute propagating noise directly from the unsteady flow simulation, this is computationally prohibitive due to the broadband nature of airframe noise. Therefore, we used PowerACOUSTICS® 2020-R1 for the propagation of acoustic waves to the far field. This is achieved with a Ffowcs Williams and Hawkins (FW-H) approach [8], based on Farassat's formulation 1A [9]. The free-stream convective effects are taken into account directly in the integral formulation [10].

The choice of data surface used to propagate near-field acoustic waves has major implications on the accuracy of the predicted far-field spectra and computational cost of the simulations. In this paper, we compared the solid and permeable data surface [11] FW-H formulations to demonstrate the ramifications of an inappropriate data surface choice. As there is no generally accepted standard for building a permeable FW-H surface, we rely on experience from previous work. We built the permeable surface as a convex wrap of the aircraft, user-defined boxes, and isosurfaces of turbulence kinetic energy and velocity magnitude. The surface does not cross any regions where the fluid velocity differs from the freestream by more than 5%, while it also avoids regions with resolved or modeled fluctuations. The effects of vortices crossing the permeable data surface at its downstream end can be mitigated by using end caps, each generating its own acoustic signal. These signals can be averaged a posteriori. The effects of the end caps are discussed in phase three of this study [7]; following the findings described in phase three, no end caps (open surface) were used for the results shown in this paper. Two-dimensional views of the permeable data surface and its end caps are shown in Fig. 3.

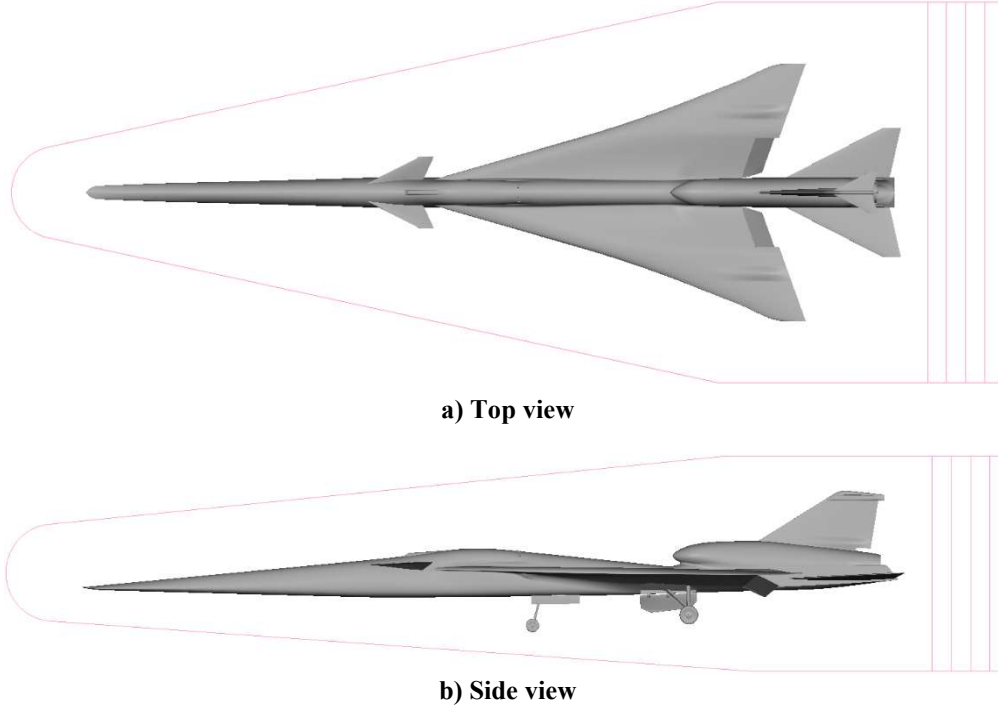


Fig. 3 Permeable FW-H surface.

V. Simulation Results

Phase one [6] and three [7] of this study investigate the aerodynamics of the GLBC in detail. Here, we focus on the acoustics. We present analyses of solid vs. permeable FW-H surfaces, mesh refinement effects, flaps and LG deployment on airframe noise signature, and far-field noise velocity scaling in this section. All results are provided in model-scale.

A. FW-H Surface Effects – Solid and Permeable

The FW-H approach supports two types of data surfaces: solid and permeable. The solid surface is simply the geometry of interest, which in this case is the entire aircraft. Solid surfaces have several advantages, namely, ease of definition, the topological consistency of being closed, and, for PowerFLOW specifically, the fact that due to local time stepping in the solver, they are typically located in regions with very high temporal and spatial resolution, allowing calculation of synthetic microphone records up to very high frequencies.

Permeable surfaces have the great advantage of capturing quadrupole effects, which are ignored by solid surfaces. However, they come with some disadvantages. One of them is the complex task of enclosing the regions of high flow fluctuations and/or mean flow variations encountered in wakes. This requires having an open surface (which is not mathematically consistent) or performing end-cap averaging (which increases the size of the permeable surface). Another important disadvantage is the potential for noise generated on solid surfaces to dissipate before reaching the permeable surface, causing the noise levels calculated from permeable surfaces to have an earlier frequency cut-off. Critically important is the significant increase in computational cost associated with the use of permeable data surfaces, as the spatial resolution must be sufficient to avoid said early cut-off.

Previous studies [12-13] have shown that noise propagation based on the solid surface approach can also miss shielding effects altogether, making these surfaces less reliable for applications with complex geometries. Figure 4 shows a sample comparison of the spectrum extracted at the direct probe with those computed from solid and permeable FW-H surfaces. We observe that the solid surface tends to overpredict noise levels, while the permeable surface accurately matches the direct probe up to 20 kHz, beyond which roll-off due to insufficient spatial resolution starts. Although not shown, similar overprediction for the solid surface occurred at other probe locations. The third phase of this study [7] will demonstrate that the solid formulation misses important shielding effects, which can be inferred from the results of Fig. 4. The larger discrepancy in the clean case (Flap0-LGoff), where the major noise sources are above the wing, compared to the landing configuration (Flap30-LGon), where the major sources are below

the aircraft, indicates that shielding effects are a likely source for discrepancy. Thus, for the rest of this paper, we use exclusively the permeable FW-H data surface approach to predict far-field noise spectra.

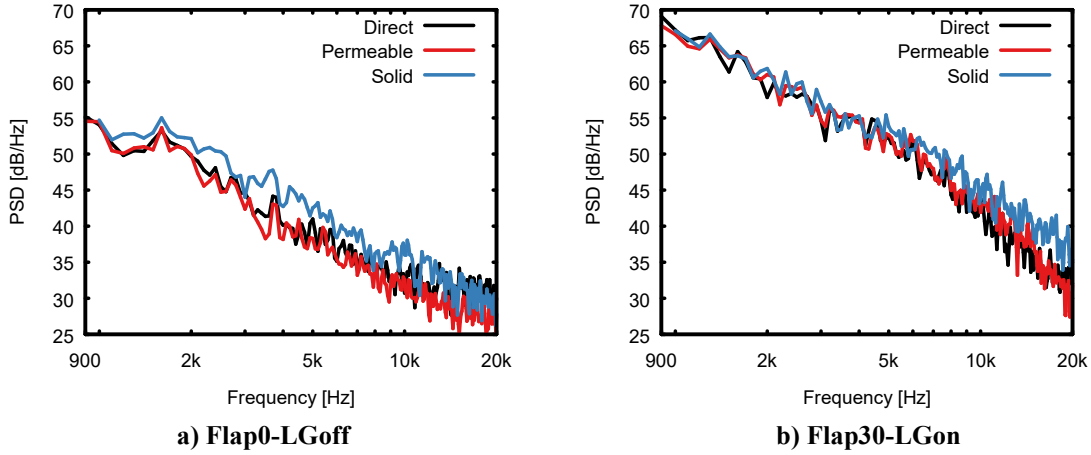


Fig. 4 Direct measurement comparison to solid and permeable FW-H surfaces. Medium resolution.

Another noticeable feature in Fig.4 is the flattening of the noise curves for Flap0-LGoff at high frequencies. This is investigated further in subsection D.

B. Resolution Effects – Coarse, Medium, and Fine Meshes

We used the quietest (Flap0-LGoff) and loudest (Flap30-LGon) configurations to investigate mesh sensitivity of the GLBC. We compare the noise computed for the overhead microphone in Fig. 5. Flap30-LGon results include all three resolutions, while Flap0-LGoff does not include the finest grid due to time constraints. High frequency (above 10 kHz) noise increases with resolution for Flap30-LGon, as expected, while Flap0-LGoff shows less grid sensitivity (high frequency noise for the clean configuration will be explained in subsection D). Overall, the noise levels and spectral shapes seem to be captured by the medium resolution grids fairly well up to frequencies of 15-18 kHz. Therefore, unless stated otherwise, we use medium grid results for the rest of the paper. Further investigations on mesh sensitivity, including effects on aerodynamics, are shown in phases one [6] and three [7] of this investigation.

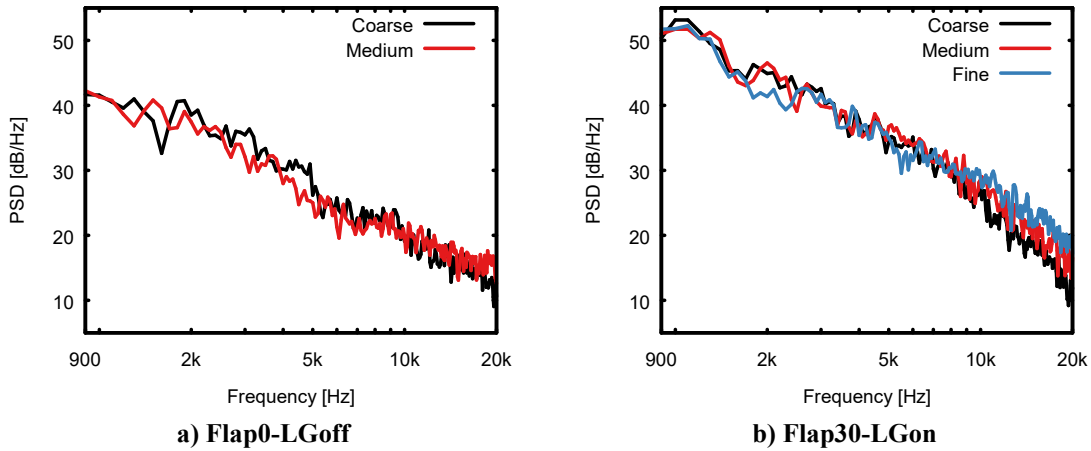


Fig. 5 Resolution effects on far-field noise at overhead microphone location.

C. Configuration Effects – Flaps and Landing Gear

Figure 6 shows predicted noise levels at the overhead microphone location for all four configurations. We observe that LG noise dominates over that from other airframe sources. However, the combined effects of the LG and flaps tend to be louder than the individual components added together, suggesting the presence of strong component interaction effects. This interaction is highlighted in Fig.7, where we compare Flap30-LGoff and Flap30-LGon results. The wake of the LG (shown with a slice of total pressure, which is hidden on the starboard side of the aircraft and in

regions where its magnitude is higher than 0.99) clearly impinges on the inboard flap-side-edge, substantially increasing the magnitude and extent of high-amplitude surface pressures in the region.

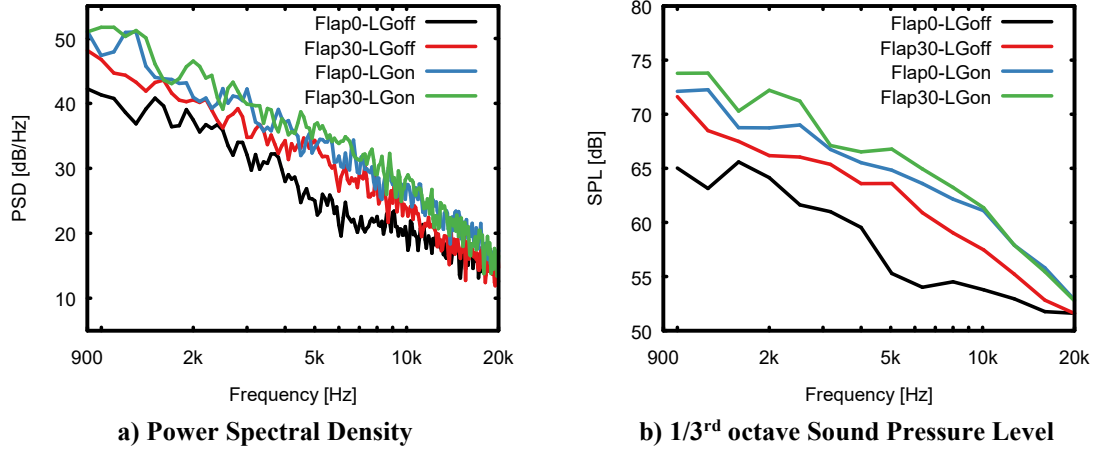


Fig. 6 Configuration effects on far-field noise at overhead microphone location.

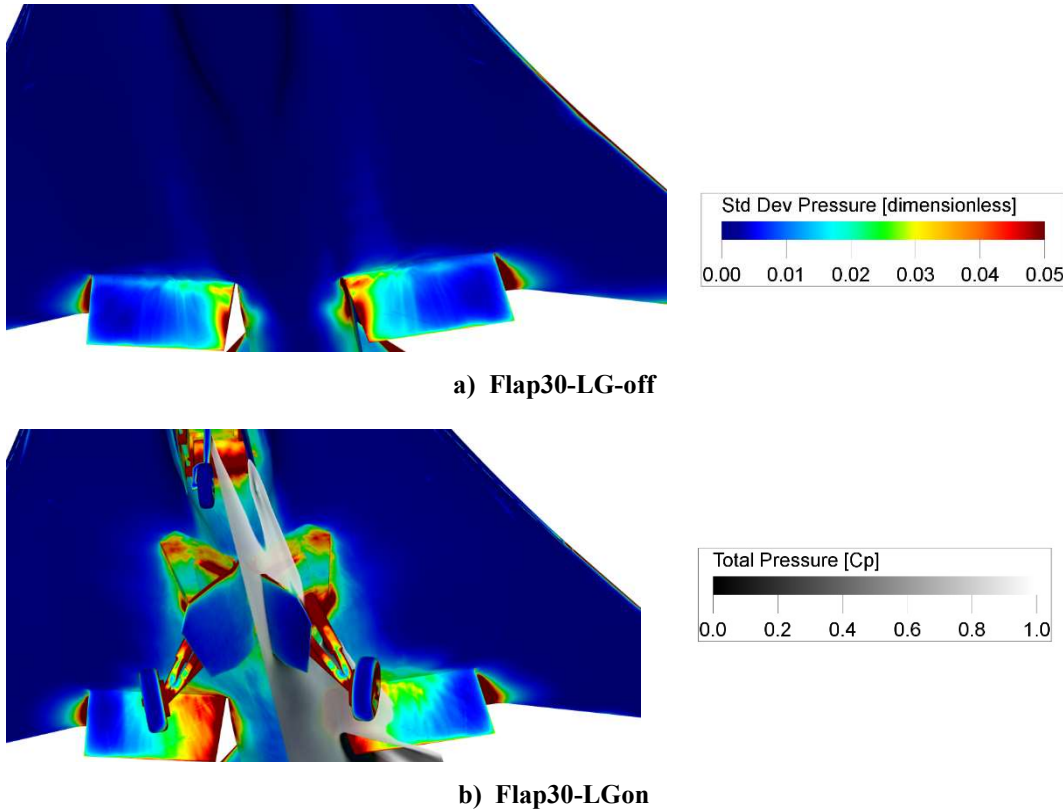


Fig. 7 RMS pressure on the aircraft surface and slice of mean total pressure on port side of LG wake.

Figure 7 also shows that the NLG wake impinges on the belly doors and that the wakes from the NLG doors impinge on the MLG struts. These interactions, which would be significant, are less likely to occur on conventional subsonic transports: for these aircraft, the distance between NLG and MLG and the separation between the two MLG are much larger than those in the GLBC or similar supersonic configurations. As a result, a diffused NLG wake reaches and passes between the two MLG with modest interaction.

Figure 8 shows directivity plots for the quietest (Flap0-LGoff) and loudest (Flap30-LGon) configurations in flyover and sideline arcs. For frequencies below 15 kHz, where we are confident of solution convergence, no prominent directivity pattern emerges for either configuration in the flyover or sideline directions. This trend is in contrast to conventional subsonic transports, where airframe noise is clearly dominant in the forward emission angles in the flyover direction. The difference in directivity patterns between the two classes of transport may be attributed, at least partially, to the extremely simplified LG geometries of the GLBC model.

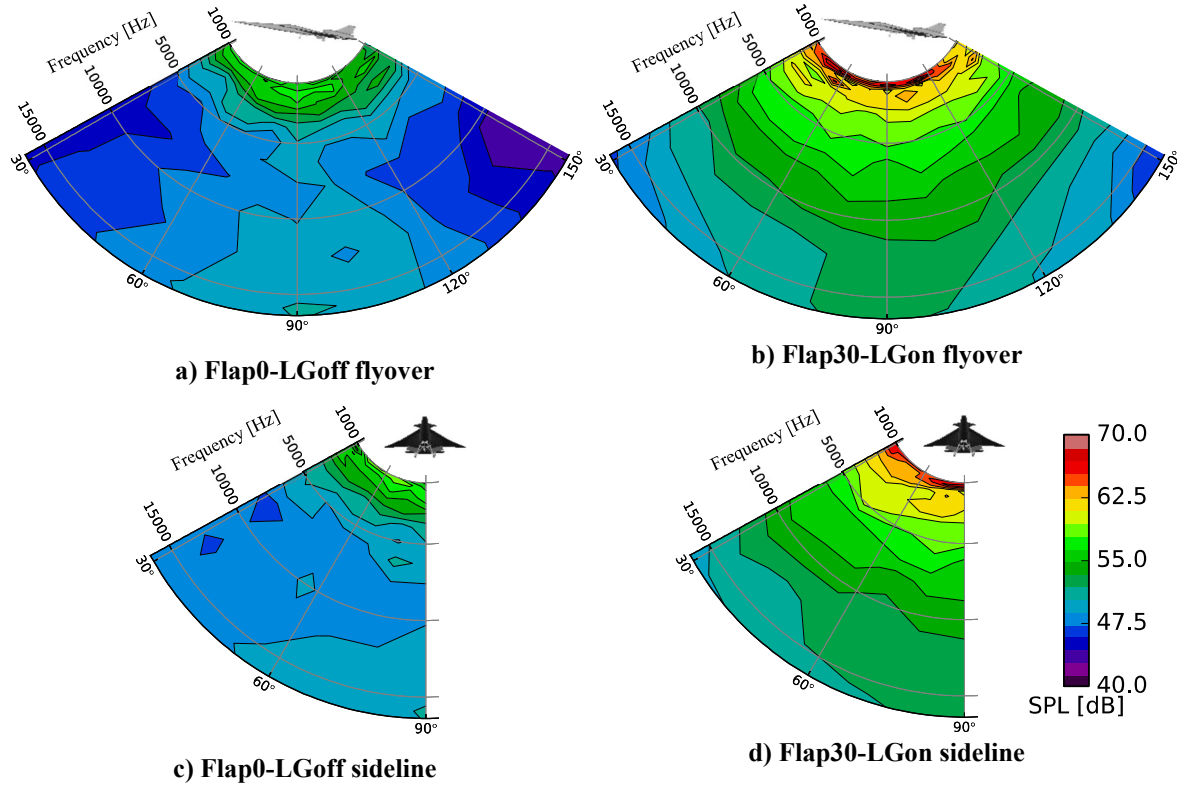
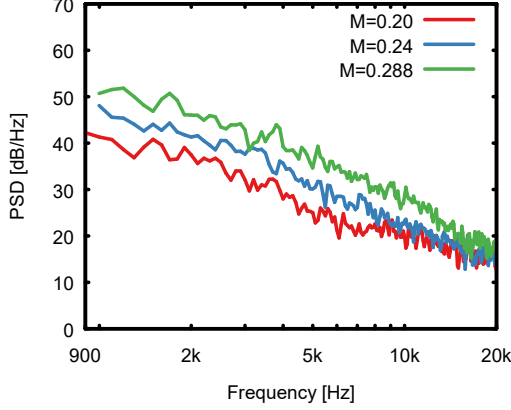


Fig. 8 Directivity plots for flyover and sideline.

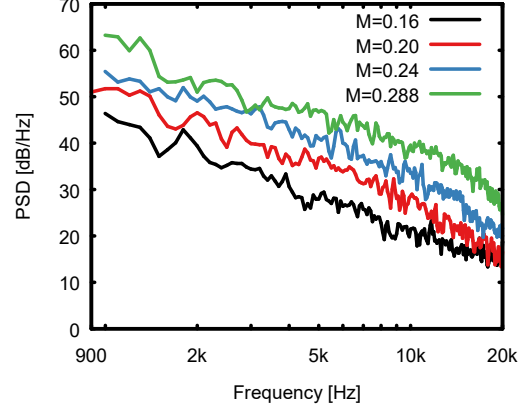
D. Velocity Effects – Mach Number Scaling

Supersonic aircraft with delta wings have lower aerodynamic efficiency at low speeds than conventional subsonic transports, potentially leading to higher angles of attack and landing speeds. With airframe noise typically scaling with M^6 , increasing the landing speed by only 10% translates to an increase of 2.5 dB in far-field noise levels. Therefore, it is crucial to understand the scaling laws for this class of transports. In order to verify M scaling, we simulated Flap30-LGon at four different speeds, corresponding to $M = 0.2$ (the baseline condition used in previous sections), $M = 0.16$, $M = 0.24$, and $M = 0.288$. We also simulated Flap0-LGoff at $M = 0.20$, 0.24 , and 0.288 . We compared these cases on the microphone at the center of the flyover array. The microphone was shifted based on flow velocity to account for convection effects and obtain a consistent comparison.

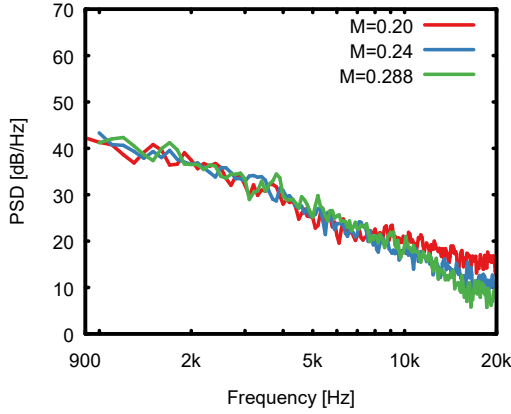
Figure 9 shows the effects of increasing M on the far-field noise levels. In order to compare the different cases, we applied M^6 scaling by adding $60\log(M_{ref}/M)$ to the noise levels, where M_{ref} is the reference $M = 0.2$ used throughout this paper. We also applied frequency scaling (or Strouhal scaling) by multiplying the frequencies by M_{ref}/M and subtracting $10\log(M_{ref}/M)$ from the noise levels, as the spectra are shown in dB/Hz. Airframe noise measurements from previous model-scale wind tunnel and full-scale flight tests [14-16] have clearly shown that frequency scaling is not required for a tube-and-wing subsonic aircraft with flaps and landing gear deployed, since M^6 scaling alone collapses the far-field spectra. The results presented in Fig. 9 indicate a somewhat similar trend: M^6 scaling collapses the data; frequency scaling seems to have a negligible effect at low and mid frequencies, and increases data scattering at high frequencies.



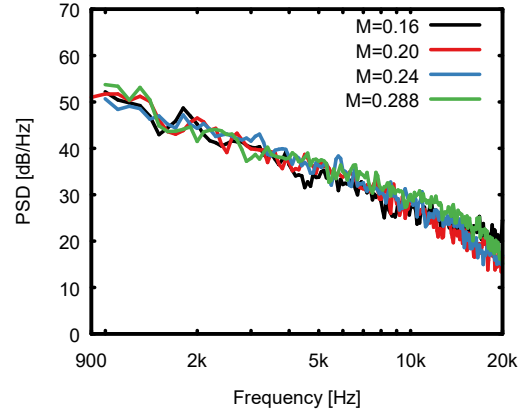
a) No scaling, Flap0-LGoff



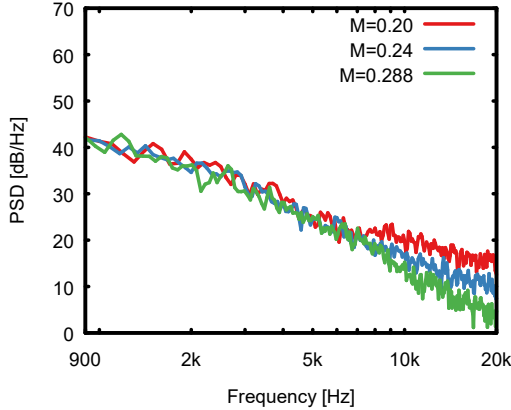
b) No scaling, Flap30-LGon



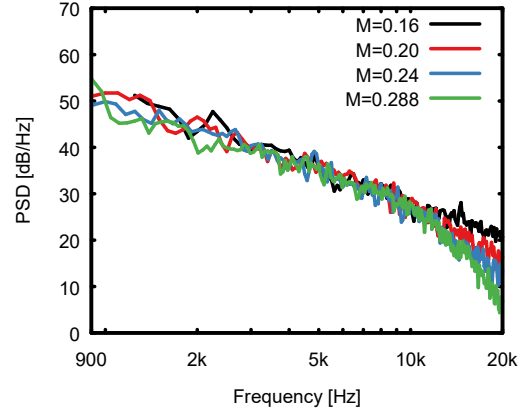
c) M^6 scaling, Flap0-LGoff



d) M^6 scaling, Flap30-LGon



e) M^6 and frequency scaling, Flap0-LGoff



f) M^6 and frequency scaling, Flap30-LGon

Fig. 9 Mach number effects on overhead microphone noise.

High frequency noise (10-20 kHz) seems to have a different M scaling from other frequencies. In particular, Flap0-LGoff appears to have a noise floor. This is also present for Flap30-LGon at $M = 0.16$. Since these simulations are the quietest, we investigated the possibility that numerical background noise is the source of this effect. Airframe noise simulations with PowerFLOW are typically run in single precision, as the LBM is able to capture pressure fluctuations without noticeable truncation errors. In contrast, simulations of quieter aeroacoustics phenomena, such as the noise generated by air conditioning ducts or small fans, require double precision. A previous study of direct numerical simulations of trailing edge noise [17] demonstrated that spurious noise can be present in single precision for quiet

cases. Hence, we compare in Fig. 10 the noise spectra obtained from single and double precision coarse resolution simulations at $M = 0.2$. The noise floor seen previously disappeared by reducing the truncation errors. We can now see the frequency cut-off near 15 kHz, which was previously masked by the noise floor. These results confirm the need for double precision for Flap0-LGoff (and low M for other configurations) and will require further study. Thus, the acoustic trends shown in previous plots for power spectral densities below 20dB should be viewed with caution. Note that the other analyses in this paper used medium grid results, hence the frequency cut-off is beyond 20 kHz. Grid refinement and additional noise sources will reduce the effects of the noise floor, so by investigating the quietest configuration with the coarsest mesh, we are showing the worst-case scenario. Finally, we must note that executing a simulation in double precision doubles the computational cost and time needed to obtain a converged solution. Given the various configurations (Table 1) and grid sizes (Table 2) used in the present study, the advantages and disadvantages of such a decision must be weighed carefully.

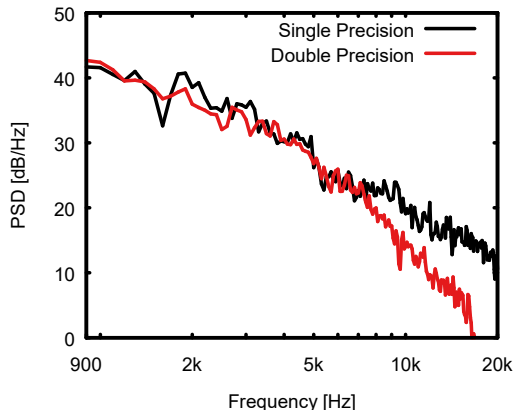


Fig. 10 Comparison of single and double precision for Flap0-LGoff at $M = 0.2$. Overhead microphone, coarse resolution.

VI. Conclusions

High-fidelity aeroacoustic simulations of a generic low boom concept (GLBC) were performed. Although not a viable passenger-carrying supersonic business jet, the GLBC is a suitable testbed for exploratory analyses of the airframe noise characteristics of delta-wing configurations during landing. The vastly different wing design and resulting vortex-dominated flow encountered during landing posed different computational challenges than those of conventional subsonic aircraft. The current study represents our first attempt at examining the differences and similarities between the airframe noise footprint of supersonic and conventional subsonic transports.

Several conclusions can be drawn from this phase of the study: first, based on the FW-H analysis, we confirmed the need for permeable FW-H data surfaces for configurations where shielding effects are relevant. This is somewhat unfortunate, as the solid formulation is significantly easier to set up, provides higher frequency content, and is computationally much more affordable. Second, we demonstrated that the acoustics for this configuration are fairly well grid-converged in our simulations. This is particularly relevant when considering the challenges in achieving grid convergence for the aerodynamics of this case, as seen in phases one and three of this study [6-7].

Third, we demonstrated that predicting airframe noise for a supersonic aircraft configuration such as the GLBC requires more attention to component interaction effects than traditional tube-and-wing aircraft, as the flap and MLG are closely spaced. Fourth, a Mach number scaling study has shown that the noise for the GLBC scales with speed in a similar fashion to traditional aircraft. Fifth, we noticed the need to run double precision simulations for the quietest cases investigated when high frequency (over 10 kHz model scale) noise is of interest.

Future work will dive deeper into permeable FW-H surface effects and noise characterization for the GLBC.

Acknowledgments

This work was supported by the Commercial Supersonic Technology project under the Advanced Air Vehicles Program of the NASA Aeronautics Research Mission Directorate. The authors gratefully acknowledge the invaluable contribution of Scott Brynildsen of Craig Technologies for his patience with the tedious task of creating the CAD definitions for the model landing gear and support system, as well as for cleaning and integrating the various aircraft components into a CFD-ready representation. All simulations were performed on the computer clusters at the NASA

Advanced Supercomputing (NAS) facility at the Ames Research Center. The logistical support provided by NAS staff, in particular Yan-tyng (Sherry) Chang, is greatly appreciated.

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