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Sticchi, E., Casalino, D., Ragni, D., & Avallone, F. (2026). The Ffowcs-Williams and Hawkings Analogy for Full Aircraft Noise Prediction. In E. Carrera, & M. Filippi (Eds.), *CEAS - AIDAA Conference 2025 - Proceedings of the 10th CEAS Aerospace Europe Conference 28th AIDAA International Congress* (pp. 308-313). (Materials Research Proceedings; Vol. 69). Association of American Publishers. https://doi.org/10.21741/9781644904251-55

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Materials Research Proceedings 69 (2026) 308-313 https://doi.org/10.21741/9781644904251-55

The Ffowcs-Williams and Hawkings Analogy for Full Aircraft Noise Prediction

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Keywords: Aeroacoustics, Acoustics Analogy, Aircraft Noise

Abstract. This study investigates the influence of different Ffowcs Williams and Hawkings (FW–H) formulations on far-field noise prediction for a propeller-driven strut-braced wing aircraft. High-fidelity flow data were obtained using the Lattice–Boltzmann Very-Large-Eddy Simulation (LB-VLES) solver PowerFLOW®, and acoustic predictions were carried out using the permeable-surface, solid-surface, and volumetric FW–H analogies included in the $Opty\partial B$™ toolkit. Results show that the permeable formulation reproduces both the amplitude and directivity of the dominant tonal lobes in good agreement with the noise directly extracted from the CFD simulation. The solid formulation, instead, exhibits discrepancies in regions exposed to the impingement of propeller-generated sound waves, where pressure fluctuations are detected but not correctly propagated. The volumetric approach, while computationally demanding, provides valuable physical insight by confirming the absence of actual radiating sources on that part of the fuselage. For similar configurations, the permeable formulation represents the most reliable and computationally efficient choice for predicting far-field noise.

Introduction

The prediction of far-field aircraft noise has become a critical component in the design of next-generation low-noise aircraft. Most aeroacoustic simulations rely on acoustic analogies, with the Ffowcs Williams–Hawkings (FW-H) method being a standard in both academia [1] and industry [2].

Two main formulations of the FW-H method are commonly employed: the solid surface formulation, which records pressure fluctuations on the aircraft surface, and the permeable surface formulation, which samples the data on a surface located within the flow, enclosing the entire noise-generating region, and capturing both surface and volume sources [3]. Each has its own practical advantages and theoretical limitations. Recent studies have provided valuable insights into the performance of both approaches. For instance, Spalart et al. [4] emphasized the sensitivity of the permeable formulation to numerical errors and surface placement, while Ribeiro et al. [2] showed that even in large-scale simulations, solid surface methods can lead to overprediction or misidentification of key sources, particularly in the presence of shielding and complex geometries.

In this context, this work aims to assess the performance of the solid and permeable FW-H formulations when applied to a high-fidelity simulation of a propeller-driven regional aircraft with a strut-braced wing configuration. The simulation is carried out using the LBM-VLES solver PowerFLOW®, and results are assessed in terms of their acoustic directivity, spectral content and noise source density.

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The manuscript is organized as follows: first, the methodology is described; next, the results of the analysis are discussed; finally, the main conclusions are presented.

Methodology

The flow field was computed using the flow solver PowerFLOW®, version 6-2022-R3 from 3DS Dassault Systèmes, which implements the Lattice-Boltzmann Method (LBM). The software used has been extensively used to accurately predict noise generated in complex flow problems, including full-vehicle configurations [5], and propulsion systems [6] [7]. A detailed description of the solver can be found in Ref. [8]. For the present computation, the high-subsonic solver, extended to transonic regime, is used.

Far-field noise predictions were obtained using three approaches: the permeable-surface formulation of the FW–H analogy ($Opty\partial B$-FWHFREQ™), the solid formulation ($Opty\partial B$-SOLID™), and the complete volumetric analogy ($Opty\partial B$-LIGHTHILL™). The solid surface consisted in the aircraft surface. The permeable surface was defined as an offset from the aircraft plus a cylinder, which includes the propeller's wake, to reduce spurious noise sources. Three equally shaped FW-H surfaces, placed 25 cm apart, were used to average noise signals. For the full volumetric formulation, the integration domain corresponds to the volume enclosed by the previously defined permeable surface. The tailored Green's function was obtained using the quasi-Dirac pulse method described in Ref. [9]. Since acoustic reciprocity does not hold in a rotating frame, the local rotating frame (LRF) associated with the propeller was excluded from the volume integral and accounted for through an additional permeable surface surrounding the LRF. The additional Green's-function simulation required about 5k CPU-h compared to the 70k CPU-h for the main run. The subsequent volumetric FW–H calculation, performed for one microphone over a narrow frequency range, lasted around three hours on a fat node of the Dutch national supercomputer Snellius (dual AMD EPYC Rome 7H12 @ 2.6 GHz, 128 cores, 1 TiB RAM). Consequently, the full spectrum is not shown in the next section, and only source-localization results are presented for this case.

Results

An overview of the instantaneous flow field is provided in Fig. 1, which shows a λ_2 isosurface coloured by the velocity magnitude and normalized by the freestream value. The insets in the top-left and top-right corners highlight the interaction of the tip vortices with the wing and the strut, respectively. This visualization intends to introduce the reader to the aerodynamic features underlying the acoustic mechanisms under investigation. A more detailed flow analysis is intentionally omitted to comply with the page limitations and to maintain focus on the acoustic analogy assessment.

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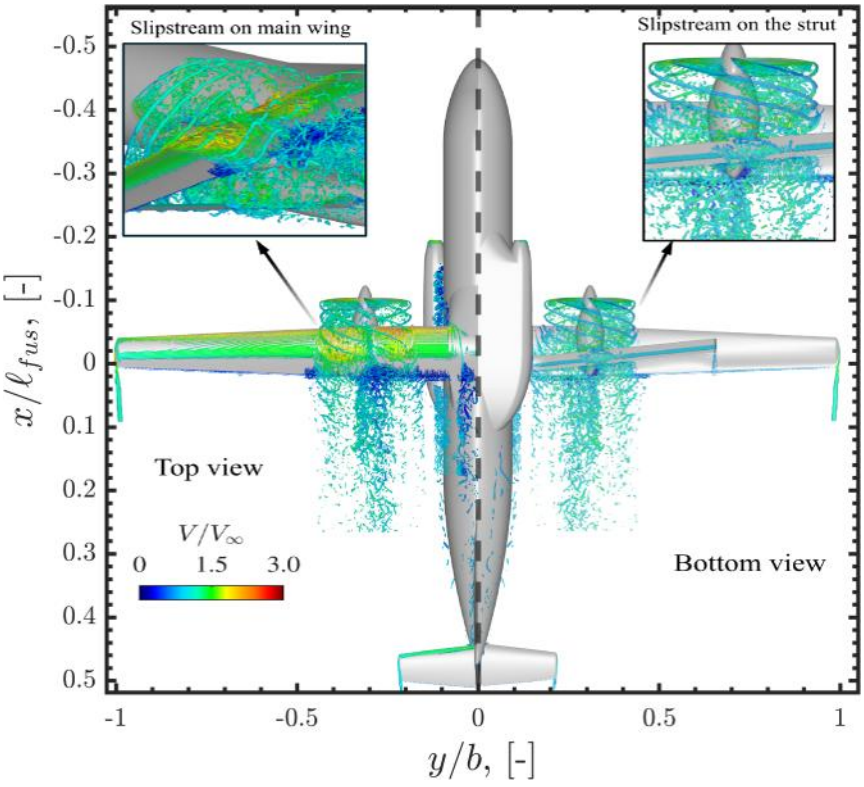


Figure 1: Isosurface of λ_2 colored by the magnitude of velocity, V, normalized by the cruise speed, V_∞.

Figure 2(a) shows the aircraft geometry, the FW–H integration surface, and the microphone array used for the acoustic analysis. The Overall Sound Pressure Level (OASPL) at the microphone locations for both FW–H formulations, compared with the direct noise extracted from the simulation, is displayed in Fig. 2(b). The permeable formulation shows good agreement with the direct results, except in the angular regions upstream and downstream (grey areas in the Fig. 2(b)), likely due to the impingement of the propeller wake on the FW–H surface. Despite these local deviations, the overall agreement is very satisfactory, confirming the reliability of the results obtained with the permeable formulation. In contrast, the solid formulation exhibits a marked discrepancy, particularly at $\theta = 250°$, where it fails to reproduce the acoustic lobe. To investigate this discrepancy, Fig. 3 shows the sound pressure spectra at the microphone located at $\theta = 250°$. The results obtained with the permeable formulation are compared with those from the solid formulation, which is also decomposed into its individual surface contributions. The spectra show that the solid formulation underpredicts both the first and second Blade-Passing-Frequency (BPF) tones. Focusing on the first BPF, it can be seen that the fuselage contribution has an intensity comparable to that of the propeller. A phase analysis, not shown here for conciseness, shows that these two signals are nearly out of phase at the first BPF, resulting in a destructive interference between the fuselage and propeller contributions.

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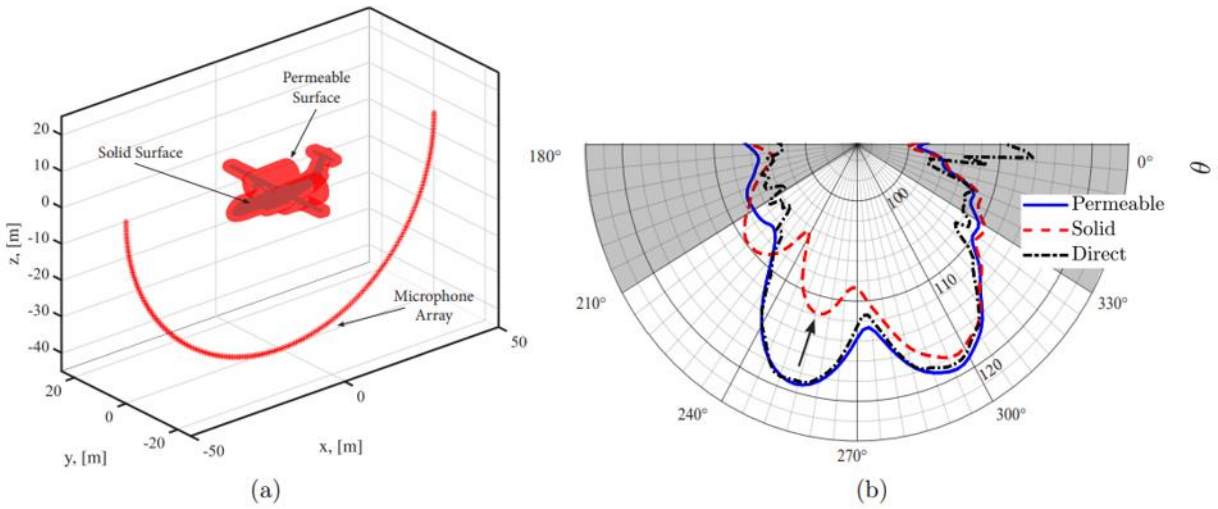


Figure 2: (a) Far-field directivity arc together with the aircraft geometry and the FWH surface used for the analyses. (b) Comparison between the noise computed by means of solid and permeable FWH formulation.

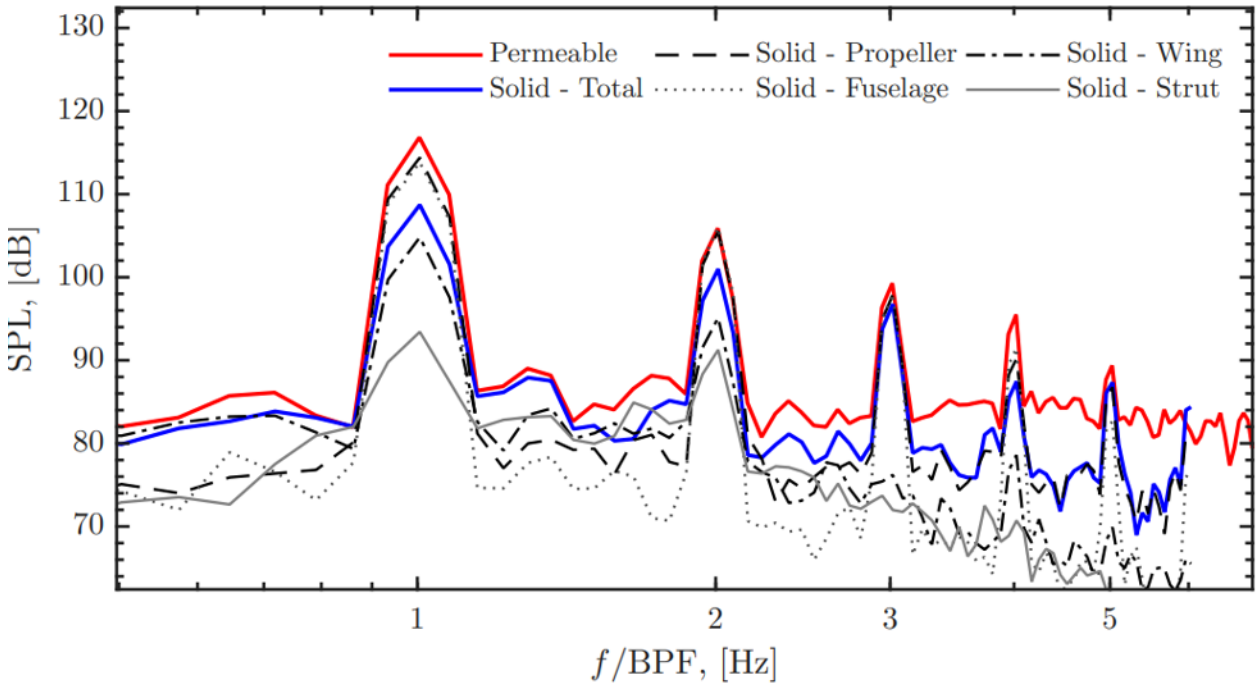


Figure 3: Sound level spectra at the microphone located at θ = 250◦ . Comparison between Permeable and Solid FWH formulation.

Furthermore, the inspection of the acoustic source amplitude per unit area obtained with the solid formulation (see Fig. 4(a)) shows that this contribution originates from the upper side of the fuselage sponson. In fact, the fuselage sponson is exposed to the impingement of the propeller-generated sound waves during rotation, resulting in high pressure fluctuations sampled on the solid surface.

Figure 4(b) shows the noise sources computed using the volumetric FW–H analogy at the first BPF. According to this formulation, the main source is the propeller. However, this contribution is not shown in the Fig. 4(b) since the local rotating frame is excluded from the integration volume (see Sec. Methodology). The secondary volumetric sources, displayed as isosurfaces of noise

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source amplitude per unit volume, show pronounced distortion effects on the wing and strut, while no contribution from the fuselage sponson is observed. This comparison suggests that the solid formulation identifies apparent sources on surfaces affected by the impingement of acoustic waves, as its propagation model does not account for local flow refraction. In contrast, the permeable and volumetric formulations correctly interpret these fluctuations as non-radiating. In addition, it is worth noting that no source appears on the lateral side of the fuselage in Fig. 4(a), indicating that the discrepancy occurs only when the reflecting surface is oriented with its normal in the observer direction.

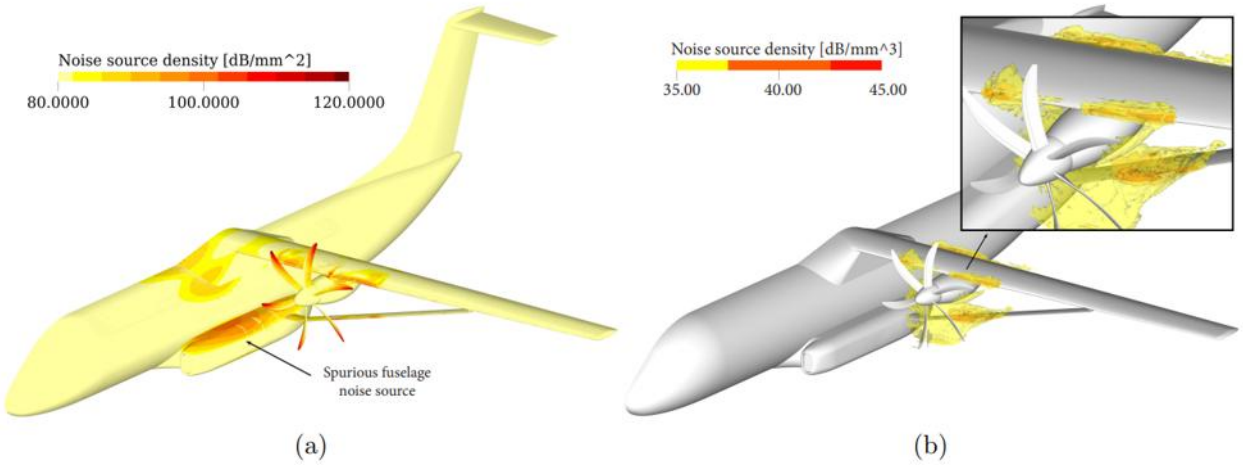


Figure 4: Noise source density at the first BPF computed with (a) solid FW-H formulation and (b) the volumetric acoustic analogy.

Conclusion

The study presented a comparative assessment of three acoustic analogy formulations: permeable FW–H, solid FW–H, and volumetric FW-H applied to the prediction of far-field noise from a propeller-driven strut-braced wing aircraft. The flow field was computed using the Lattice–Boltzmann solver PowerFLOW®.

The results show that the permeable formulation provides a consistent agreement with the noise extracted from the CFD simulation, accurately reproducing both the directivity and amplitude of the dominant acoustic lobes. The solid formulation, instead, exhibits discrepancies in regions influenced by the impingement of sound waves generated by the propeller, such as on the fuselage sponson. In these areas, pressure fluctuations are detected but are not correctly propagated as acoustic waves, since the underlying propagation model does not account for local flow refraction. This interpretation is supported by the volumetric FW–H analysis, which confirms that no actual radiating sources are present in those regions.

Although the volumetric approach offers valuable physical insight, it is computationally expensive and not feasible when many microphones or frequency bands are of interest. The permeable formulation is therefore recommended for practical far-field predictions, while caution should be exercised with the solid formulation in regions affected by strong mean-flow gradients or acoustic reflections.

Acknowledgments

The authors gratefully acknowledge financial support from the Clean Aviation Joint Undertaking under the HERWINGT project (grant agreement No. 101102010).

The authors also thank SURF for the support in using the National Supercomputer Snellius (grant no. EINF-13850).

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