High-fidelity sound propagation methods for evaluating engine tones of a business jet

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Introduction

Today, aerospace research is committed to move major parts of aircraft design to the virtual product development. This is based on the idea of creating a digital model of a new aircraft which allows to predict its performance before any physical models exist. The ultimate goal is being able to certify the aircraft based on the virtual product development which would require a comprehensive and highly accurate representation of its design.

The current paper investigates the status-quo of two different sound propagation methods and their capabilities to predict the noise immission at the ground during a fly-over manoeuvre. In this process, measurement data of a Gulfstream G550 serve as a reference.

Our study focuses on simulating engine tones since compared to other noise sources (see figure 1) they can most easily be compared to measurement data. From simulations point of view, engine tones are emitted from the very local region of the engine inlet which allows replacing the noise source with a simple monopole. On the measurement side, the frequencies of the engine tones are known which makes it easier to extract their contribution from the overall aircraft noise.

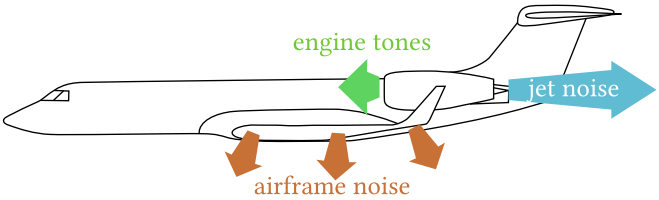

Figure 1: Very simplified sketch of the noise sources of a Gulfstream G550 aircraft.

Measurement data

The experimental data were collected by placing a number of microphones on the ground which task was to capture the pressure fluctuations during several passes of the research airplane HALO from the German Research Center (figure 2). This aircraft is a business jet of type Gulfstream G550.

For easier comparison with the simulations, the microphone data are mapped to a spherical coordinate system (see figure 3) at a constant radius of 120 m. The steps for the remapping are as follows. First, the Doppler shift is removed from the data. Then, the data is converted into the time-spectral domain by Fourier transforming short data samples of 0.25 s duration where each resulting spectrum is assigned to the corresponding spherical angles. Finally, atmospheric damping effects are estimated and removed, which allows to recompute the sound pressure level (SPL) at the target radius of 120 m.

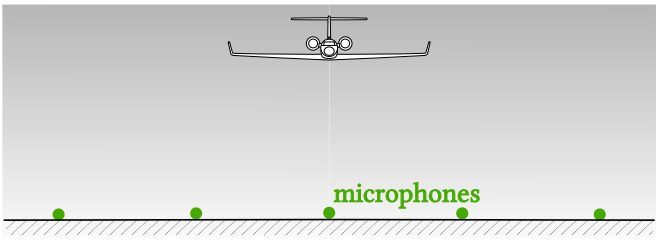

Figure 2: Sketch of experimental setup of fly-over measurement.

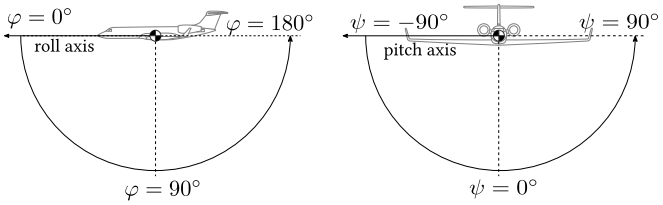

Figure 3: Definition of longitudinal angle φ and lateral angle ψ.

Figure 4 shows the remapped measurement data of a specific configuration where all available lateral positions are averaged. Here, two bright streaks represent the first and second blade passing frequency. Along the streaks, the values can be extracted over a narrow frequency band. This provides a measure of the engine tones such as shown in figure 5 for the first blade passing frequency at different flap settings. It appears, that the configuration with retracted flap is slightly quieter in the range from $\varphi \approx 30°$ to $\varphi \approx 60°$, while being louder for angles between $\varphi \approx 60°$ and $\varphi \approx 70°$.

Numerical methods

Two distinct numerical methods are investigated concerning their capabilities of reproducing the measurement results. A fast boundary element method which requires a surface mesh of the airplane geometry and a discontinuous Galerkin method relying on a volume resolved mesh. Typical meshes are depicted in figure 6.

Before going deeper into the description of the methods, it is worth considering what sound propagation effects are important for this test case. Figure 7 gives an overview of the major effects: *reflection* on surfaces, *diffraction* around edges and *refraction* in spatially varying mean flows.

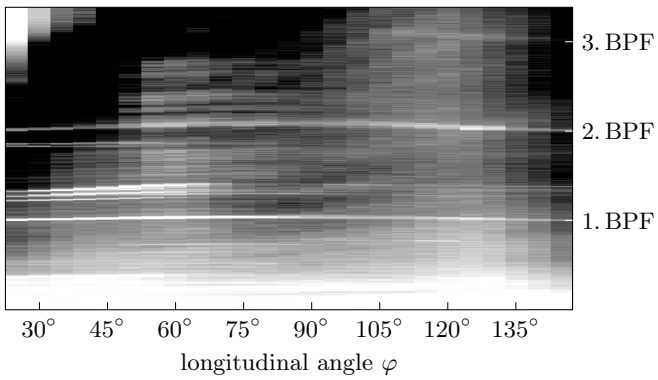

Figure 4: Spectral visualization of the sound pressure level over the longitudinal angle φ for the engine setting $N_1 = 80\%$ and deflected flaps. Black means quiet, white means loud.

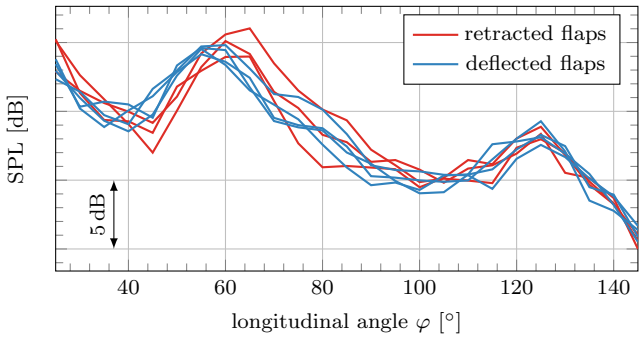

Figure 5: Sound pressure level of the first blade passing frequency for the engine setting $N_1 = 80\%$ and different flap settings. Lines of same color represent various fly-overs with same settings.

All effects are taken into account by the volume resolving approach as used within the solver DISCO++[2]. It adopts a discontinuous Galerkin method in order to solve the Acoustic Perturbation Equations[1] on a tetrahedral mesh. In each tetrahedron the solution is represented with a third order polynomial. Time integration is performed with a fourth order Runge-Kutta method. Due to the very high computational cost, this method is not suited for the sound propagation to the farfield. Instead, it is coupled to a Ffowcs-Williams-Hawkings method, which records the solution close to the outer boundary of the volume mesh and from there performs an extrapolation step to the farfield.

The surface discretization based software to be investigated goes by the name of Fast Multipole Code for Acoustic Shielding (FMCAS)[3]. It is a fast implementation of the boundary element method which solves the wave equation in the frequency domain. Due to its underlying fast multipole algorithm this solver is highly efficient for processing up to 40 million surface elements on a very small computer cluster. However, FMCAS cannot account for refraction effects and its current implementation allows for constant mean flows at low Mach number only.

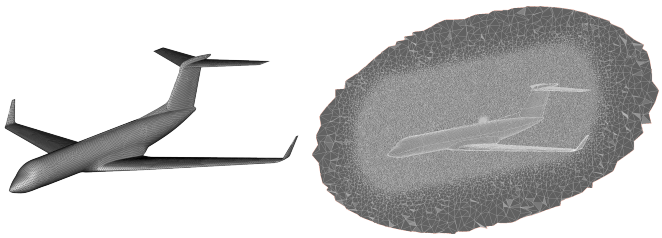

Figure 6: Surface mesh for boundary element method (left) and volume mesh for discontinuous Galerkin solver (right).

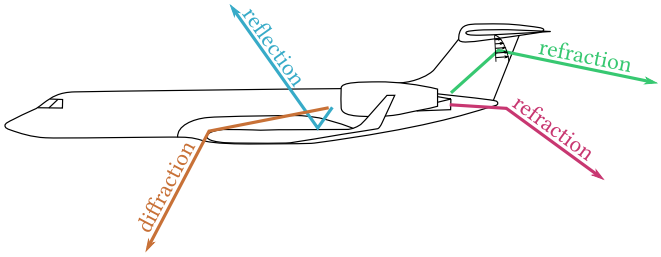

Figure 7: Mechanisms leading to deflection of sound waves.

The computational cost of the two methods is shown in table 1. Considering the 1 kHz rows, a vast cost difference can be seen between the volume-resolved method DISCO++ and the surface-based method FMCAS. In fact, the DISCO++ setup for 1 kHz is close to the maximum limit of resources available to the authors. This poses a problem since the first blade passing frequency is well above 2 kHz and the expected computational efforts grow with the fourth power of the frequency. On the other hand, the surface based method can be efficiently employed to frequencies of 6 kHz and more.

The following strategy is applied to address the above stated problem: Compare the results of the two different solvers for frequencies that can well be resolved by DISCO++ and subsequently only compare the surface based solver with the measurement data.

Table 1: Approximate problem sizes for the investigated solvers at two frequencies.

	FMCAS	**DISCO++**
$f = 1\,\text{kHz}$		
Number of elements:	600 000	80 000 000
Cost in core hours:	≈ 50	$\approx 230\,000$
$f = 6\,\text{kHz}$		
Number of elements:	25 000 000	-
Cost in core hours:	$\approx 10\,000$	-

Computational setup

In this work a simplified setup is used where both engines are omitted and instead a monopole source was placed at the engine inlet on one side of the aircraft (see figure 8). With such a setup, it is no longer possible to compare the sound pressure levels over the longitudinal angle e.g. as shown in figure 5. Rather, it must be focused on comparing shielding effects of the aircraft geometry since here the source radiation pattern of the engine cancels out.

This advantage allows for an improved sound propagation comparison without the additional concerns of having to accurately reproduce the acoustic sources.

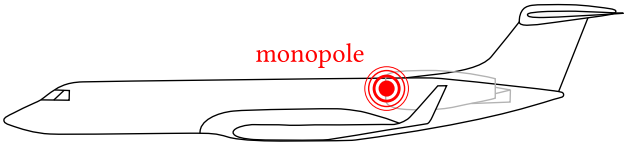

Figure 8: Position of monopole in numerical setup.

The simulation results are sampled in form of pressure fluctuations on a microphone array 51 m below the aircraft. This allows getting a first impression of how an observer on the ground would experience the fly-over. Additional sampling points are added in accordance with the measurement locations. Note, that all sampling points are defined twice to also account for those mirrored at the symmetry plane of the aircraft. Summing up the sound energy of both, the original sampling points and the mirrored sampling points emulates a two-engine aircraft.

Unless stated otherwise, the volume resolving simulations use a CFD mean flow as basis for the sound propagation. In contrast, the surface based simulations use a constant mean flow based on the airplane velocity. The applied Mach number of $Ma = 0.35$ is set in accordance with the measurement conditions.

Numerical results

As stated in the previous section, the evaluation focuses on the engine source shielding effects by the given aircraft geometry. The shielding level is defined as follows

$$\gamma = SPL - SPL_{\text{ref}} \tag{1}$$

where SPL is the sound pressure level of a specific aircraft setup and SPL_{ref} is the sound pressure level of a reference configuration. Here, the reference is defined as the result of an isolated monopole without the aircraft.

Figure 9 shows three computations for the same flight condition for a low frequency of 900 Hz. The topmost picture shows the fully featured solution of the volume resolving method with CFD mean flow, the middle picture shows the result achieved with a constant mean flow and the bottom picture shows the result of the surface based method. It is expected for the results' quality to lower with the decrease in fidelity, i.e. when moving from the top to the bottom picture. In this instance, the surface based method is in good agreement with the constant flow result of the volume resolved method, which sound propagation was based essentially on the same flow assumption. The low Mach number limitation of the surface based FMCAS solver appears not to be strongly violated. The solution employing the CFD mean flow looks notably different, especially when closely examining the interference pattern. Being the only computation which takes refraction effects into account this is not surprising. But since the overall picture is still very similar, the surface based method seems a promising choice for being validated with the measurement data.

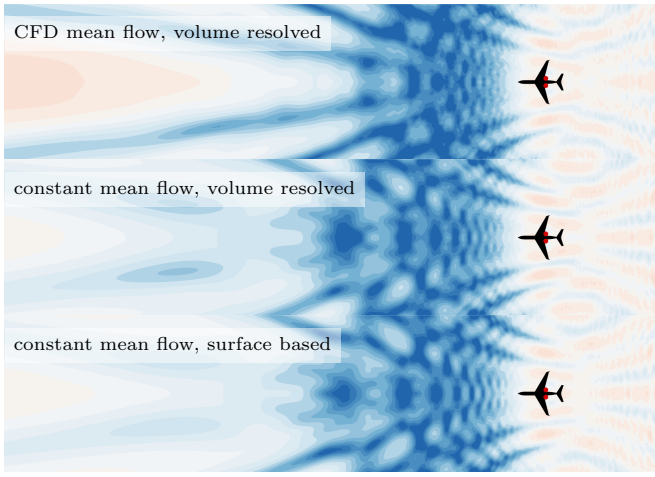

Figure 9: Contour plot of shielding level γ for retracted flap at a frequency of 900 Hz for different mean flows and methods. (legend: quiet, loud)

Figure 10 shows the differences between the retracted and deflected flaps. There are minor visible differences and only a close inspection of both figures reveals a slight downstream shift of the quiet blue region in front of the aircraft. Even minor in appearance, these fine differences may prove to be significant when compared to the measurements.

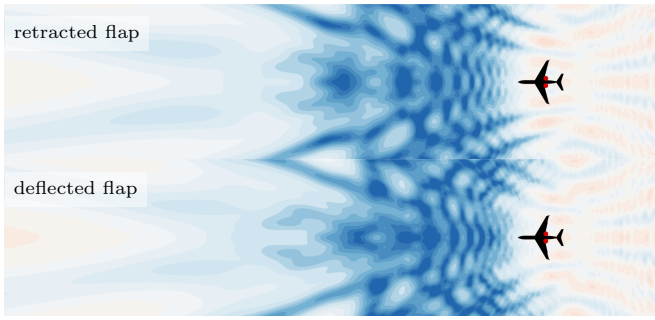

Figure 10: Contour plots of shielding level γ for retracted flap and deflected flap at a frequency of 900 Hz both computed with surface based method. (legend: quiet, loud)

Comparison of numerical solutions to measurements

In order to compare the numerical results to the measurements, the surface based method is employed to solve for the first and second blade passing frequencies of the engine with retracted and deflected flaps, respectively. Afterwards, the shielding levels are computed similar to equation (1) with the difference, that the deflected flap is compared to the retracted flap:

$$\gamma_{\text{flap}} = SPL_{\text{defected flap}} - SPL_{\text{retracted flap}} \tag{2}$$

The calculated SPL difference γ_{flap} can be interpreted as the flap shielding. The results are evaluated at the same positions as within the measurements and averaged over all available lateral positions and fly-overs with the same configuration.

The final confrontations are shown in figures 11 and 12.

Positive shielding levels γ_{flap} mean that at a given position the aircraft with deflected flap is louder then the one with retracted flap, negative levels γ_{flap} mean that it is quieter. The overall shape and levels of the numerical results and of the measurement data is quite similar but the numerical data seem to shifted by about 20°. While it seems unlikely that this is the effect of the constant velocity or exceeding the small Mach number limit ($Ma = 0.35$), it is possible that the monopole position does not correspond exactly to the engine tone source position of the aircraft. For example, shifting the monopole backwards could move the shielding pattern to smaller angles.

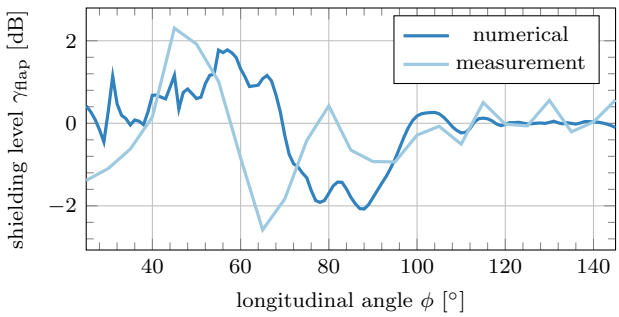

Figure 11: Comparison of measurement data against the results of the surface based method for flap shielding γ_{flap} of first blade passing frequency.

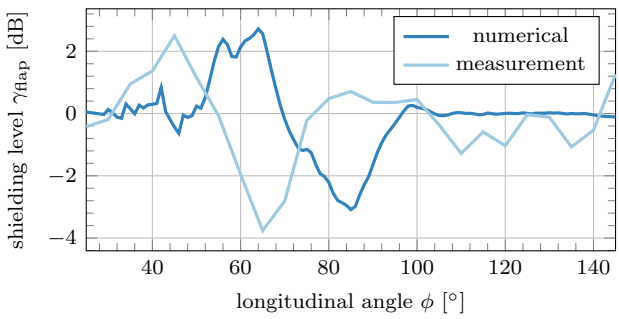

Figure 12: Comparison of measurement data against the results of the surface based method for flap shielding γ_{flap} of second blade passing frequency.

Conclusion

The goal of this paper was to validate high-fidelity sound propagation methods. Two methods, a volume resolving discontinuous Galerkin method and a surface based fast boundary element method were investigated. In short, the volume resolving discontinuous Galerkin method remains too expensive for predicting the blade passing frequencies of a large-scale aircraft. The surface based method in question may provide a competent alternative. The investigated fast multipole boundary element method manages to resolve frequencies of 6 kHz and higher when applied to a large-scale aircraft. The downside, however, is that diffraction effects are neglected and it is limited to small Mach numbers. Nevertheless, the surface based method simulations are in good agreement with the results of the volume resolving method, which however, are only available for the lower frequency range. When comparing to measurement data, the surface based method exceeded the expectations in terms of accuracy. The overall shape of the flap shielding over the longitudinal airplane angle matches very well with the exception of the significant shift towards larger longitudinal angles consistent for all numerical results. This could have resulted from a misplaced monopole source in relation to the source origin of the real aircraft. This monopole source is currently replacing the real engine and leads to the restriction, that only shielding effects of the aircraft geometry onto the engine radiated sound can be compared.

In order to move forward, a more realistic sound source is needed with the engines in place. The advantages would be twofold. Firstly, this would enable the numerical and experimental data comparison of the sound pressure level versus the longitudinal aircraft position. Up to now, this was only possible for flap shielding. Secondly, the source position would no longer have to be estimated. However, these advantages will come at the sacrifice that the surface based method becomes more difficult to apply because the local flow velocity at the engine inlet is relatively high. For these conditions the constant mean flow assumption will most probably result in significant errors. Also, keeping velocities low is not an options since several acoustic modes in the inlet duct will be cut-off which become active again only when subjected to high local velocities. One potential for overcoming the limitation will be to couple the volume resolving method to the surface based method. The idea is to apply the volume resolving method locally to the engine inlet and communicate the data to the surface based method just outside the engine. This procedure will allow to efficiently compute for high frequencies in a highly restricted volume domain. The surface based method can then propagate the sound to the observer through a mean flow with small to moderate Mach numbers.

Acknowledgement

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