Auralization of aircraft noise by means of numerical and analytical description of partial sound sources

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1 Introduction

In order to optimize concept studies of aircraft in their development phase not only with regard to expected loudness, but also with regard to their acoustic quality, auralization can be a suitable approach. In the field of auralization of aircraft noise the necessity of research on elaborated source models is evident due to increasing noise emissions that are foreseeable by technical developments of supersonic civil aircraft and tonal signal components in the radiated noise of air taxis equipped with electric motors.

At present, most auralizations used in aircraft design are realized using well-proven semi-empirical models (chapter 2). However, when it comes to the prediction of acoustic emissions of disruptive innovations on noise reduction of the primary partial sound sources on aircraft they are not suitable, since these innovations are usually based on changes in the fundamental geometry of the engine.

Aiming at the single sound sources (chapter 3) improvements in noise reduction can be especially expected in the primary reduction of unshielded jet noise. These are supplemented by approaches to shielded fan noise by engine-over-the-wing concepts that are not covered in this paper. In order to provide an adequate auralization possibility for these latest approaches, in this paper firstly the method for numerical source modelling of jet noise is established and its implementation presented (chapter 4). Finally, results are shown and their relevance on auralization are discussed (chapter 5).

2 Auralization Approaches

In the field of aircraft noise auralizations basically two different types of auralizations can be distinguished (fig.1): The *deterministic* methods are the most frequently used approach for application purposes offering simple and fast recording-based realizations. The microphone recordings of flyovers are re-synthesized for dynamic source signal generation using methods such as granular synthesis of quasi-stationary operating conditions extracted from short time signal snippets of the recording [1]. Thereby, instantaneously the angles between source and receiver as well as the height of the source during the flyover have to be tracked which is done usually using GPS data. For imitation of acoustic propagation effects time-varying filters [2] are employed that, on the one hand, enable real-time computation but on the other hand are limited in their generalizability for scientific purposes since the recorded events are inherently determined by their preconditions (such as weather conditions).

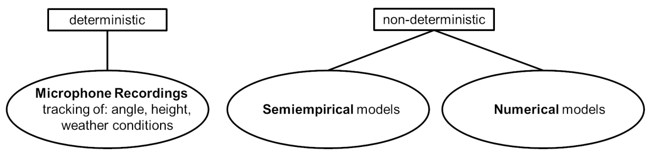

Figure 1: Common approaches for the auralization of aircraft noise.

In contrast, *non-deterministic* approaches such as analytical and numerical calculations can form the basis of the modelling of partial sound sources. Where

- **semi-empirical** models are either based on extensively validated databases [3][4],
- **numerical** models are based on numerical computations (CFD, FEM, BEM) and thereby fully parametrically variable

and are more suitable for scientific purpose.

It is useful to subdivide the transmission path between source and receiver at certain interfaces and to reduce the complexity of the mathematical description accordingly with increasing distance from the source (fig.2) since the sound fields in different source volumes of the partial sound sources cannot be calculated in a joint simulation due to the considerable computing effort.

Analogously to the above mentioned semi-empirical databases of the near field also exist databses on the interface to the far-field - that include the scattering influences of the wings, the fuselage and the background flow [5][6].

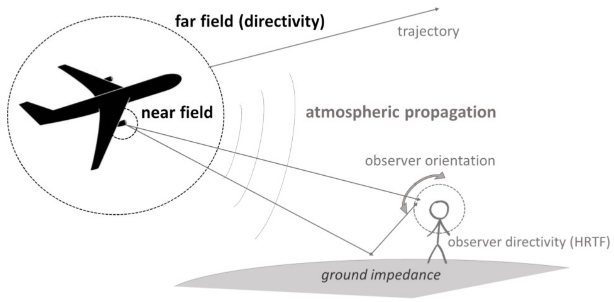

Figure 2: Interfaces definitions for the physically-based auralization of aircraft noise.

However, due to their nature to rely on already existing geometries, semi-empirical models are inherently disadvantageous for the acoustic a-priori evaluation of disruptive technologies. This is the main reason where the numerically based auralization approach comes into play.

3 Partial Sound Sources of Aircraft Noise

In order to give a feeling for which partial sound sources are usually considered in the auralization of aircraft noise, an overview is given in fig.3.

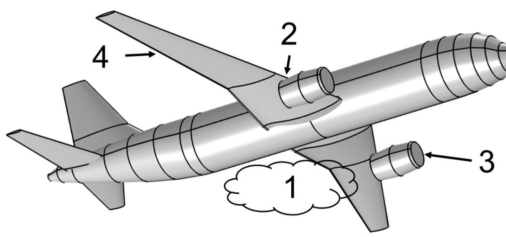

Figure 3: Partial sources of aircraft noise. The simulations of chapter 4 were performed on the CeRAS model shown (CSR-01 from [7]).

The partial sound sources are:

- 1: Jet Noise (distributed source)
- 2: Fan Outlet Noise
- 3: Fan Inlet Noise
- 4: Airframe Noise (e.g. flap, slat, trailing edge)

Even marked here only one-sided, all types of noise occur symmetrically on both sides of the fuselage. Since in a parallel research study possible concepts for the reduction of jet noise are investigated, this paper also concentrates on this.
The output of the jet flow simulation is an acoustic near field description of a jet engine flow field and was obtained by computational fluid dynamics (CFD) simulations using Reynolds-averaged Navier-Stokes equations (RANS).

4 Far Field Simulation of Jet Noise

With reference to fig.2, the near field data are transferred on spherical grids and transferred to both source regions of the far-field simulation to take advantage of the complexity reduction for larger source volumes, fig.4 emphasizes graphically the arrangement.

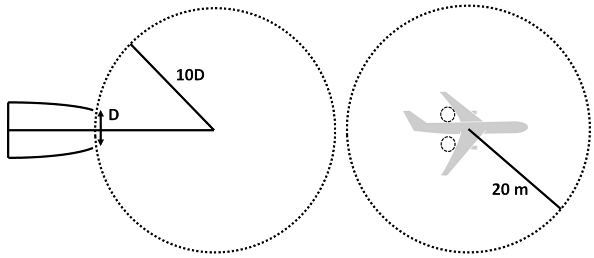

Figure 4: Visualization of the simulation setup. Left: near field, right: far field with positions of near fields shown

The radii of the near-field grid were chosen with ten times the nozzle diameter D to ensure that all acoustic source terms of the jet noise are confined in the source volume. The radius of the far-field directivity was chosen to 20 m so that the reference aircraft is completely within it.
Mathematically, the complexity of the RANS simulation in the near field is reduced to the far field where *linearized Navier-Stokes equations* (LNSE) are employed (eqs.(1)-(3)). These equations take into account the complex interactions between an acoustic pressure field and a stationary background flow that also includes the influences of non-isothermal, viscous and compressible flow conditions as well as turbulence.
As the name indicates, a *linearization* is applied to the full set of *Navier-Stokes equations* used for near-field simulation in frequency-domain ending up in first-order perturbations around the steady-state background flow:

$$j\omega\rho + \nabla \cdot (\rho_0 \mathbf{u} + \rho \mathbf{u}_0) = M \tag{1}$$

$$\rho_0 \left[j\omega \mathbf{u} + (\mathbf{u} \cdot \nabla)\mathbf{u}_0 + (\mathbf{u}_0 \cdot \nabla)\mathbf{u} \right] + \rho(\mathbf{u}_0 \cdot \nabla)\mathbf{u}_0 = \nabla \cdot \tau - \mathbf{u}_0 M \tag{2}$$

$$\begin{aligned} &\rho_0 c_p \left[j\omega T_{gas} + \mathbf{u} \cdot \nabla T_{sur} + \mathbf{u}_0 \cdot \nabla T_{gas} \right] + (\rho c_p)\mathbf{u}_0 \cdot \nabla T_{sur} \\ &- \alpha_p T_{sur} \left[j\omega p + \mathbf{u} \cdot \nabla p_0 + \mathbf{u}_0 \cdot \nabla p \right] - (\alpha_p T_{gas})\mathbf{u}_0 \cdot \nabla p_0 \\ &= \nabla \cdot (\kappa \nabla T_{gas}) + q \end{aligned} \tag{3}$$

where M is a mass source and q heat source respectively, that are external excitations from the jet engine (the derivation of the parameter values is presented below). $\mathbf{u}$ is the fluid velocity, ρ denotes the fluid density, p is the fluid pressure, T_{gas} the exhaust and T_{sur} the ambient temperature respectively. Subscripts 0 denote the mentioned steady-state background, whereas the subscript-free variables denote the first-order perturbations. Coefficients are c_p for heat capacity, α_p for isobaric thermal expansion, τ is the linearized viscous stress tensor and κ the thermal conductivity. Despite its complex foundation, we sum up laxly:

> "The background flow changes the stimuli without making noise itself."

During the simulation, the equations are solved in two steps by first performing an incompressible flow simulation and then solving the LNSE around the resulting mean flow field.
In the present study, the full set of LNSE was solved which is not common for aeroacoustic purpose where usually reactive terms are simplified in order to suppress Kelvin-Helmholtz instabilities. These assumptions are well-suited for regions of uniform or no present flow but would neglect the important coupling between acoustic modes and the vortical or entropy disturbances.
Keeping the Kelvin-Helmholtz instabilities as part of the solution can lead to numerical difficulties as undamped growth in time leads to strong local gradients of variables. Solving the LNSE in frequency domain can overcome this drawback. Furthermore, by calculation by the LNSE, the interface condition of the infinitesimally small flow velocity on the hull surface can be considered (fig.5).

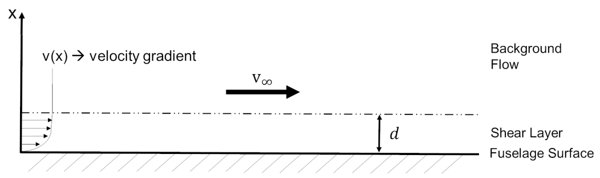

Figure 5: Velocity gradient on fuselage as flow boundary condition.

Aeroacoustic Source Modelling

Finding exact values for the modelling of source variables q and M (in eqs.(1) and (2)) is practically impossible and therefore must be based on estimations. The mass source term M was chosen to reflect the throughput of a typical jet engine in cruise operation, which is around $500\frac{\text{kg}}{\text{s}}$.
In principle, three dominant heat transport mechanisms (radiation, convection, conduction) can be considered for determining the heat flux q in eq.(3):

$$\begin{aligned}\dot{Q}_{total} &= \dot{Q}_{rad} + \dot{Q}_{conv} + \dot{Q}_{cond} \\ &\approx hA(T_{gas} - T_{sur})\end{aligned} \tag{4}$$

where the heat flux q must be passively derived from the according heat transfer rate using $q = \frac{d\dot{Q}}{dA}$. Whereas the surface area of the near field A is a known constant, the temperatures of the exhaust gas T_{gas} and the temperature of the surrounding T_{sur}. More complex is the derivation of the heat transfer coefficient h: due to the negligible factor of the Stefan-Boltzmann constant in the heat radiation term $\dot{Q}_{rad}$ and the very small thermal conductivity of air in the heat conduction term $\dot{Q}_{cond}$, the convection term $\dot{Q}_{conv}$ remains the dominant term in the present scenario.
Since experimentally determined values of forced convection heat transfer coefficients are in the range $500\frac{\text{W}}{m^2\text{K}} < h < 5000\frac{\text{W}}{m^2\text{K}}$ this estimation is still not sufficiently accurate. In order to include more detailed information, the fuel consumption of the jet engine in cruise condition is considered:

$$\begin{aligned}\dot{Q}_{conv} &= \Delta H_c^\circ \cdot TSFC \cdot CT \cdot (1-\eta) \\ &= 48\frac{\text{MJ}}{\text{kg}} \cdot 0,04\frac{\text{kg}}{\text{Nh}} \cdot 29360\text{N} \cdot (1-0,41) \\ &= 9,24\text{MW}\end{aligned} \tag{5}$$

where ΔH_c° is the heat of combustion of kerosene, TSFC is the thrust-specific fuel consumption, CT is the cruise thrust and η is the thermal efficiency of the engine.
Calculated back using the relationship from eq.(4), this would result in a heat transport coefficient of $h = 4160\frac{\text{W}}{m^2\text{K}}$ for the given simulation parameters with $A = 4 \cdot \pi \cdot 10\text{D}^2$ and thus corresponds to the literature values. In addition, the simulation parameters must take into account the atmospheric properties for the respective operating condition, i.e. especially temperature, air pressure and humidity.

5 Results

Based on the simulation results, it is possible to analyze the impact of the aeroacoustic sound field properties and the geometrical surrounding of the near field jet flow. For this analysis, a suitable measure is the evaluation of the 3-D directivity on a sphere with radius of 20 meters around the aircraft center, which was defined to half the fuselage length.
It can be seen that the level differences between the strongest and weakest radiation direction are *on average* 68 dB for each single frequency in the considered bandwidth between 1 Hz to 200 Hz.
Particularly noticeable is a frequency-dependent influence of the background flow on the sound field, which is with rising frequency increasingly compressed so that the sound wave in front of the aircraft is piled up as a "wall" in flight direction (fig.6).

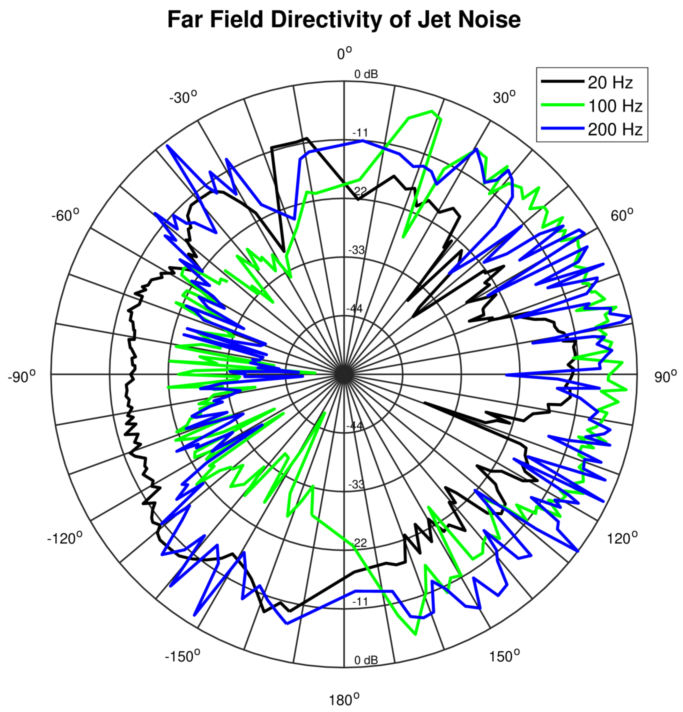

Figure 6: Normalized far field directivity of the jet engine radiation in vertical plane at three frequencies. To the left is the flight direction ($\phi = 0$).

Since this non-symmetric behaviour can also be observed in the horizontal plane, the assumption of rotational symmetry in directivities from semi-empirical source models appears questionable in view of the partly considerable frequency- and angle-dependent notches. The presented high-resolution three-dimensional source model, however, makes it possible to create auralizations that allow all viewing angles from a listener to the aircraft. This raises the question to what extent these spatial differences of the scattering at fuselage and wings must be added (to obtain the effective directivity) and finally are audible at all. For such a consideration, the consideration of the sound propagation through the atmosphere is mandatory since these atmospheric transfer functions also show notches itself. However, due to its difficult and huge computational effort it can only be used on a prototype scale. The numerical far-field simulation suffers from the big disadvantage of the immense computational costs. Even with state-of-the-art solvers using high-performance computing (HPC) clusters, the achievable frequency range is limited to 200 Hz when all degrees of freedom of the LNSE are solved. Approximately, the frequency of 200 Hz corresponds to the upper frequency limit (-3dB) of the acoustic transfer function of the ISA standard atmosphere between a sound source at 2500 m altitude and the earth ground. This means that the presented method is limited to flight altitudes of 2500 m and higher. Above that frequency, a far field calculation is also possible. For this purpose, simplifications of the mathematical complexity must increasingly be made in order to obtain converging solutions. In particular, the reactive terms of eqs. (2) and (3) - which are responsible for the acoustic-flow coupling process - would have to be neglected. This would lead to questionable assumptions as discussed in chapter 4 and should be carefully considered. Furthermore, the use of the latest developments such as multigrid solvers and advanced preconditioners offer further potential.

The present study opens up research fields for improved aircraft auralizations: For enabling *controllable omission* of details that do not affect the audibility, the presented high-fidelity source description can be postprocessed with decomposition for real-time auralizations.

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