Numerical Simulation of the Noise Generation at the Outlet Section of Combustion Chambers

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Introduction

The noise radiation of an aircraft is a compound of several sources. The aero-engine as a major sound source is addressed in several ways in order to reduce the jet and fan noise. However, the understanding of combustion and turbine noise may lead to an noise reduction in the reward section of the aero-engine for future applications. Combustion noise is uasually radiated with high amplitudes at low frequencies.

The main focus of the presented approach is on the propagation of combustion noise. The noise is only in part generated by the unsteady combustion itself. Indirect combustion noise, radiated by convected entropy fluctuations accelerated in the outlet section of the combustion chamber is an important secondary sound source. This sound source is fully described by the Computational Aeroacoustic (CAA) approach presented (see Figure 1).

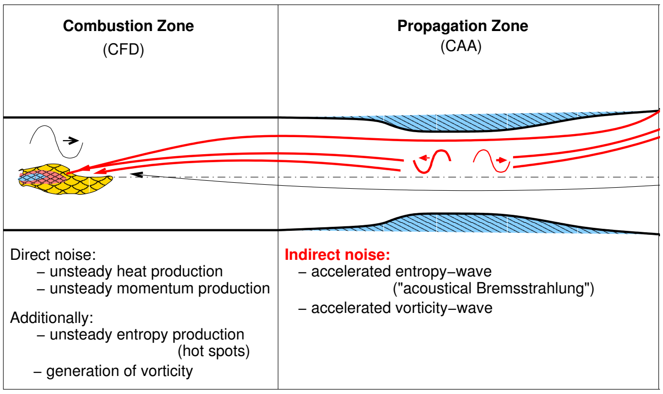

Figure 1: Overview of the sources of sound in a simplified combustion chamber with outlet nozzle

Objective

The objective of this work is to develop a method for the prediction of combustion noise in the design phase. The full Navier–Stokes equations describe the wave propagation in the combustion chamber and the outlet. However, the numerical methods capable of solving these equations produce high computational costs. Even with modern computer power, the resolution required for the convection of density fluctuations in the slow combustion chamber flow is often beyond the scope of problems to be solved in a reasonable time. Therefore a zonal approach, as is established for interior noise propagation [2], was chosen to describe the combustion noise.

The first step in this development is to show that the method, based on the fully non-isentropic linearized Euler equations, is able to reproduce theoretically predicted sound radiation (p'/ϱ'_s), reflection (R) and transmission coefficients (T) in a nozzle flow from a given initial entropy fluctuation (ϱ'_s) or sound wave (p'_{1+}). As a theoretical benchmark we choose the compact nozzle considerations of Marble & Candel [3]. This approach fits the requirement of compressible, subsonic flows for validation with entropy and acoustic wave propagation best. The theory is however limited to cases where all wavelengths are much larger than the nozzle length Δl. The critical condition is given by the density fluctuation convected with the flow speed. The numerical discretization is determined by Δl, which has to be resolved by at least 10 points. The theoretical result for the nozzle drafted in Figure 2, based on the assumption of a one–dimensional compressible mean flow is restated in Table 1 as function of the inlet Mach-number M_1, the outlet Mach-number M_2 and the ratio of the specific heats γ.

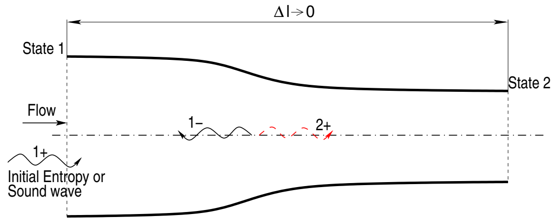

Figure 2: Sketch of the nozzle setup used for the validation experiments

Table 1: Result of the considerations according to [3]

input	transfer function
ϱ'_s	$\frac{p'_{1-}}{\varrho'_s} = -\left(\frac{M_2-M_1}{1-M_1}\right)\left(\frac{\frac{1}{2}M_1}{1+\frac{1}{2}(\gamma-1)\,M_1\,M_2}\right)a_1^2$ $\frac{p'_{2+}}{\varrho'_s} = \left(\frac{M_2-M_1}{1+M_2}\right)\left(\frac{\frac{1}{2}M_2}{1+\frac{1}{2}(\gamma-1)\,M_1\,M_2}\right)a_1^2 \left(\frac{1+\frac{1}{2}(\gamma-1)\,M_1^2}{1+\frac{1}{2}(\gamma-1)\,M_2^2}\right)^{\frac{\gamma}{\gamma-1}}$
p'_{1+}	$R = \left(\frac{1+M_1}{M_1+M_2}\right)\left(\frac{M_2-M_1}{1-M_1}\right)\left(\frac{1-\frac{1}{2}(\gamma-1)\,M_1\,M_2}{1+\frac{1}{2}(\gamma-1)\,M_1\,M_2}\right)$ $T = \left(\frac{1+M_1}{M_1+M_2}\right)\left(\frac{2\,M_2}{1+M_2}\right)\left(\frac{1+\frac{1}{2}(\gamma-1)\,M_2^2}{1+\frac{1}{2}(\gamma-1)\,M_1\,M_2}\right)\left(\frac{1+\frac{1}{2}(\gamma-1)\,M_1^2}{1+\frac{1}{2}(\gamma-1)\,M_2^2}\right)^{\frac{\gamma}{\gamma-1}}$

Numerical Method

The spatial discretization is based on the optimized fourth order Dispersion-Relation-Preserving scheme [5]. The time stepping utilizes alternating optimized fourth order six stage and five stage Runge–Kutta–schemes [1] in 2N storage form [4].

Results of the Validation

For the comparison with the theory, a set of axisymmetric nozzle and diffuser configurations is considered. The compressible flow speed ratio between inlet and outlet is varied by the inlet Mach-number and the contraction ratio of the nozzle. For the diffuser flows the outlet Mach-number is chosen as the parameter to order the results, while the inlet diameter is varied.

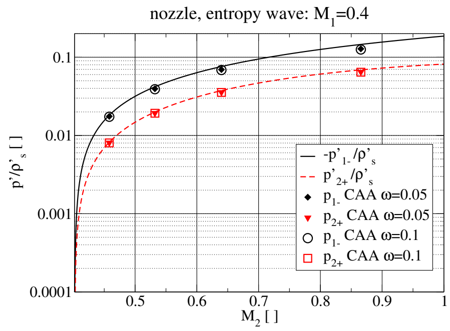

Figure 3: Theoretical comparison of results for an initial entropy wave propagating into different nozzles at inlet Mach number $Ma = 0.4$. The lines represent the theoretical upstream (full) and downstream (dotted) traveling waves, each point the numerical result for a different nozzle.

The results given in Figure 3 show the relative non-dimensional pressure amplitudes of the downstream and upstream running sound waves. The reference used is the initial non-isentropic density perturbation ϱ'_s multiplied by the inlet speed of sound squared c^2. As given theoretically, the secondary sound radiation of the accelerated entropy perturbation increases with the difference in Ma between inlet and outlet. The deviation reaches up to 12 % for the highest contraction ratio.

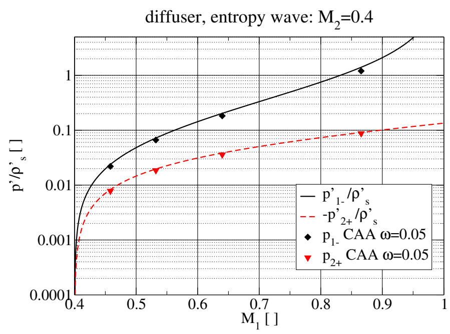

Figure 4: Theoretical comparison of results for an entropy wave propagating into different diffusers at outlet $Ma = 0.4$.

Figure 4 shows how the backward radiated sound pressure approaches infinity, as Ma_1 approaches one. However, in this case the theory ceases to apply. The maximum error is about 10 % for the expansion ratio of 1.56.

One example for the comparison of the acoustic wave propagation in a one-dimensional potential flow is given in Figure 5. The transmitted pressure is close to the initial pressure value, while the reflected pressure amplitude approaches unity with increasing contraction of the nozzle. This result is recognized against the background of the theory considering only the reflection due to a change of flow state and not from the nozzle walls.

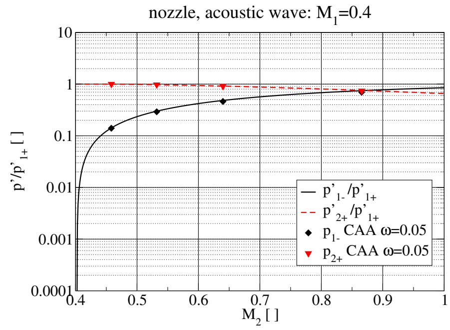

Figure 5: Theoretical comparison of results for an acoustic wave propagating into different nozzles at inlet $Ma = 0.4$.

Discussion

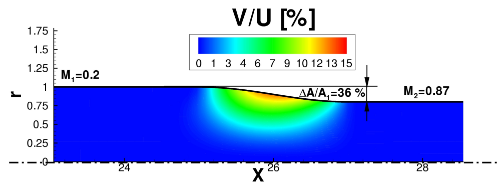

Figure 6: Relative mean flow velocity in radial direction for a nozzle with inflow $Ma = 0.4$ and a contraction ratio of 64 %.

The results of the axisymmetric simulation show a good agreement with the 1D theory of Marble & Candel [3]. The deviation from the theory is explained by reflections at the nozzle walls and the mean flow speed in radial direction, not accounted in the cited theory. One example for a high contraction ratio is given in Figure 6.

Acknowledgment

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References

[1] F. Q. Hu, M. Y. Hussani, and J. L. Manthey. Low-dissipation and Low-dispersion Runge-Kutta Schemes for Computational Acoustics. *J. Comput. Phys.*, 124(1):177–191, 1996.

[2] X.D. Li, C. Schemel, U. Michel, and F. Thiele. On the Azimuthal Mode Propagation in Axisymmetric Duct Flows. *AIAA Paper*, (2002-2521), 2002.

[3] F.E. Marble and S.M. Candel. Acoustic disturbances from gas non-uniformities convected through a nozzle. *J. Sound Vib.*, 55(2):225–243, 1977.

[4] D. Stanescu and W.G. Habashi. 2N-storage Low-dissipation and Low-dispersion Runge-Kutta Schemes for Computational Aeroacoustics. *J. Comput. Phys.*, 143(2):674–681, 1998.

[5] C. K. W. Tam and C. Webb. Dispersion-Relation-Preserving Finite Difference Schemes for Computational Aeroacoustics. *J. Comp Phys.*, 107(2):262–281, August 1993.