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Jet noise modelling and control/Modélisation et contrôle du bruit de jet

Computational analysis of exit conditions on the sound field of turbulent hot jets

Mehmet Onur Cetin [a,*], Seong Ryong Koh [a], Matthias Meinke [a,b], Wolfgang Schröder [a,b]

[a] Institute of Aerodynamics, RWTH Aachen University, Wüllnerstraße 5a, 52062 Aachen, Germany
[b] Forschungszentrum Jülich, JARA – High-Performance Computing, 52425 Jülich, Germany

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ABSTRACT

A hybrid computational fluid dynamics (CFD) and computational aeroacoustics (CAA) method is used to compute the acoustic field of turbulent hot jets at a Reynolds number $Re = 316,000$ and a Mach number $M = 0.12$. The flow field computations are performed by highly resolved large-eddy simulations (LES), from which sound source terms are extracted to compute the acoustic field by solving the acoustic perturbation equations (APE). Two jets are considered to analyze the impact of exit conditions on the resulting jet sound field. First, a jet emanating from a fully resolved non-generic nozzle is simulated by solving the discrete conservation equations. This computation of the jet flow is denoted free-exit-flow (FEF) formulation. For the second computation, the nozzle geometry is not included in the computational domain. Time averaged exit conditions, i.e. velocity and density profiles of the first formulation, plus a jet forcing in form of vortex rings are imposed at the inlet of the second jet configuration. This formulation is denoted imposed-exit-flow (IEF) formulation. The free-exit-flow case shows up to 50% higher turbulent kinetic energy than the imposed-exit-flow case in the jet near field, which drastically impacts noise generation. The FEF and IEF configurations reveal quite a different qualitative behavior of the sound spectra, especially in the sideline direction where the entropy source term dominates sound generation. This difference occurs since the noise sources generated by density and pressure fluctuations are not perfectly modeled by the vortex ring forcing method in the IEF solution. However, the total overall sound pressure level shows the same qualitative behavior for the FEF and IEF formulations. Towards the downstream direction, the sound spectra of the FEF and IEF solutions converge.

1. Introduction

The understanding of the acoustic field of propulsive jets is one of the most elusive problems in aeroacoustics, although impressive research results have been obtained over the last few decades. The jet near field and the dominant noise sources strongly depend on the flow conditions at the nozzle exit. In other words, the overall reliability of an acoustic prediction is defined by the quality of the jet inlet conditions, and an accurate determination of the acoustic field requires the computa-

* Corresponding author.
E-mail address: o.cetin@aia.rwth-aachen.de (M.O. Cetin).

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tion of the flow inside the nozzle. Zaman [1], for example, experimentally showed that two jets with the same nozzle exit diameter but different interior nozzle details can produce remarkably varying spectra.

However, to reduce the computational costs, it was common in the past to exclude the nozzle geometry from the computational domain. In those studies, usually artificial perturbations are imposed to prevent any spurious noise generation. The transition to a fully turbulent free-shear layer is initiated by synthetic fluctuations to obtain the correct spreading rate of the free-shear layer. Although highly developed inflow formulations exist, which are extremely useful for generic nozzle geometries, it is still questionable whether such inflow forcing methods yield an acceptably accurate sound field in the near field, i.e. sound pressure level distributions, directivity pattern etc., when technically relevant nozzle geometries are considered.

In a vast number of large-eddy simulation or direct numerical simulation studies, the effect of artificially forced inflow conditions on the development of cold jets was analyzed. Andersson et al. [2], for instance, exploited numerical data to determine the influence of the inflow conditions on the acoustic field. At a fixed Reynolds number, a jet with synthesized turbulence showed only a small change in the overall sound pressure level (OASPL) distribution compared to a jet without synthesized turbulence. Keiderling et al. [3] numerically studied the influence of inflow forcing on the flow and sound field of isothermal high subsonic jets. They introduced several instability modes to excite the jet turbulence. The amplitude of the inflow disturbances was changed in the range 1.5%, 3%, and 4.5% of the exit velocity. They reported that by increasing the forcing amplitude the low-frequency noise reduces. Moreover, they observed that, in the 3% and 4.5% amplitude cases, a tonal component at $St = 0.9$ occurs, which reduces the frequency where the decay of the SPL spectra occurs. Bogey and Bailly [4] numerically examined the effect of the flow state at the nozzle exit of initially laminar jets on the flow and the resulting acoustic field. They showed that the pairing noise was shifted to higher frequencies as the momentum thickness decreases. They also found a noticeable noise level reduction when random perturbations at the inlet section of the jet are imposed. Furthermore, Bogey and Marsden [5] numerically analyzed the impact of nozzle exit boundary layer thickness on the sound field of subsonic isothermal jets. The inflow distribution was excited by random vortical disturbances. They observed that for an increased boundary layer thickness, the noise level decreases due to the reduction of the turbulence intensities in the near sound field. Bodony and Lele [6] reviewed numerous jet studies being performed at various flow conditions. They concluded that the inflow forcing has a remarkable impact on the turbulence level and the sound field of the jet.

Other jet studies focused on hot flow conditions. Bodony and Lele [7] explored jets at heated and unheated flow conditions. Their results exhibited a lower noise level in the unheated jet at a low Mach number $M = 0.51$. It is known that heated transonic jets, i.e. $M > 0.7$, reduce the noise level, while the noise level is increased for high subsonic jets, $M < 0.7$, compared to the unheated jets at the same jet velocity [8]. Koh et al. [9] numerically investigated single and coaxial jets for hot and cold stream conditions. They showed that the low-frequency noise is enhanced by the pronounced temperature gradients that intensify the turbulent structures. The experimental results in [10] evidenced the dependence of the spectral shape of the acoustic field on the jet temperature, showing an extra hump in the frequency band. Furthermore, subsonic heated jets showed an enlargement of the maxima of the acoustic spectra at acute angles. Gloor et al. [11] numerically investigated the sound field of coaxial hot jets at various temperature ratios between the primary core and the secondary core. They reported, for a higher temperature of the primary core of the jet, an increase of the overall sound pressure level. Far-field measurements of high subsonic jets at varying fluid temperatures were analyzed in [12]. It was found that, at a constant Mach number, an increasing jet temperature decreases the high-frequency content of the noise spectra at shallow radiation angles.

Nozzles with built-in components create an internally mixed multi-shear-layer flow that increases the complexity of the flow state at the exit. The studies [13–17] showed the importance of the internal nozzle geometry upstream of the nozzle exit on the flow field, and thus on the jet noise. Recent efforts focused on the impact of the inner nozzle geometry on the exhaust plume and the resulting acoustic field. Fan flow deflectors, i.e. wedges, vanes etc., for example, are analyzed in [18–21]. Overall, it was found that nozzle built-in components can yield an acoustic shielding effect, i.e. the noise level is mitigated by an increased turbulent mixing in the jet near field. However, it has to be stated that, in the majority of the studies, in which large-eddy simulations or direct numerical simulations were performed, the influence of the nozzle geometry has not been discussed to avoid the enormous computational costs.

The investigation of the impact of the various nozzle exit formulations on the sound field is the purpose of this study. As stated above, previous studies mostly focused on single and coaxial jet flows by prescribing steady inflow distributions plus some perturbations to excite the nonlinear growth of the shear layer instabilities. A study in which the influence of the exit conditions from a realistic multiple shear layer generating nozzle flow on the acoustic field is analyzed is still missing. To investigate such a problem, a slightly simplified helicopter nozzle geometry, which generates an inner shear layer created by flow structures shedding from a centerbody and an outer shear layer from the nozzle lip, is considered.

Highly resolved numerical analyses for low Mach number turbulent hot jets are performed to determine the effect of exit conditions on the resulting acoustic field. The Reynolds number is $Re = 316,000$ and the Mach number is $M = 0.12$. Two jet setups are considered by large-eddy simulations (LES) that determine the sound source terms of the acoustic field, which is simulated by solving the acoustic perturbation equations (APE). In the first setup, the internal nozzle flow is computed so that the nozzle exit flow is determined by the LES solution of the conservation equations. This case is denoted free-exit-flow (FEF) formulation. In the second setup, the details of the flow inside the nozzle are not considered. This formulation is comparable to the standard approach in the literature. The time averaged flow distribution of the nozzle-jet

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