Noise Sources in Heated Coaxial Jets

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Abstract:
The aerodynamic and acoustic fields of hot coaxial jets are analyzed based on a hybrid computational aeroacoustics (CAA) approach. Two hot coaxial jets and one cold coaxial jet are considered to investigate the acoustic changes caused by a non-uniform density field. The Mach numbers of the hot primary jets are 0.6 and 0.88. The numerical method is based on large-eddy simulations (LES) and solutions of the acoustic perturbation equations (APE). The acoustic far-field is strongly influenced by multiple shear layers and density inhomogeneity. One of the fundamental changes due to the temperature gradient is the local sound speed of the mixing layer. Across the shear layer the acoustic waves undergo refraction. The turbulent mixing which determines the unsteady eddy convection and the sound generation requires a systematic analysis to identify the noise sources. The present investigation emphasizes that besides the outer shear layer between the secondary jet and the ambient flow the hot primary flow has a major impact on the noise spectra in at the near far-field. The detailed sound spectra evidence the sideline and the downstream acoustics which are enhanced by the pronounced temperature gradient.

Mots clefs: coaxial jet noise, large-eddy simulation (LES), acoustic perturbation equations (APE), multiple shear layer, density inhomogeneity

1 Introduction
Jet noise is one of the significant phenomena for the design of aircraft engines. Since 1952 a vast number of publications appeared on sound generation due to turbulence interacting with shear layers, Mach wave radiation, and convecting vortex packets [1]. In many investigations on cold jets a noise mechanism is proposed to have similarity spectra for the two components of turbulent mixing. That is, the sound spectrum is dominated by large turbulence structures and fine-scale turbulence [2]. When hot jets are considered, the jet temperature is another significant parameter and the similarity spectra show a good agreement with the experimental data of both subsonic and supersonic jets. Viswanathan [3], however, argues that the acoustic change at high jet temperatures, which is an extra dipole source in the classical theories, is caused by Reynolds number effects. These to a certain extent contradictory interpretations motivate the present numerical analysis on acoustic sources in hot jets. To understand the details of the sound generation process, which is highly intricate in multiple shear layer flows [4, 5, 6], it requires a systematic investigation concerning the acoustic sources due to hot streams and multiple shear layers in coaxial jets.

To compute the acoustic field of hot coaxial jets a hybrid large-eddy simulation/computational aeroacoustics (LES/CAA) approach is applied. That is, a two-step method using large-eddy simulation for the flow field and acoustic perturbation equations (APE) [7] for the acoustic field is used. The source terms in the APE formulation are related to certain noise generation mechanisms and thus, it is possible to analyze the acoustic sources in detail. Using the noise source terms of the acoustic perturbation equations for a compressible fluid the source strength inside hot coaxial jets is analyzed by discrete Fourier transform. The findings will evidence the acoustic radiation to be intensified by the pronounced temperature gradient. Furthermore, the large turbulence structures and the fine-scale turbulence, which are excited by the multiple shear layers, are also shown to describe two independent noise sources in hot coaxial jets.

2 Numerical Method

2.1 Flow Configuration
The Reynolds number of the round coaxial jets is \(Re_D=400,000\), It is based on the mean velocity of the secondary jet \(U_s\), the jet diameter \(D_\text{s}\), the density \(\rho\), and the viscosity \(\mu\) at the nozzle exit. During the large-eddy simulation a mean velocity profile \(\overline{\nu}\) using the hyperbolic tangent function,

\[
\overline{\nu}(r) = \frac{U_s}{2} \left(1 + \tanh \frac{R_s - r}{2\delta_{m,s}}\right) + \frac{U_p - U_s}{2} \left(1 + \tanh \frac{R_p - r}{2\delta_{m,p}}\right),
\]

(1)
2.2 Governing Equations and Computational Scheme

The governing equations of the flow field are the unsteady compressible Navier-Stokes equations being filtered using the Favre-averaging procedure. The system of equations is closed by an implicit eddy diffusivity approach [9].

The equations describing the sound propagation are the acoustic perturbation equations (APE). Since a compressible flow problem is tackled the APE-4 system is used [7]. Neglecting the non-linear terms containing entropy fluctuations the perturbation equations can be derived from the continuity and Navier-Stokes equations. These neglected terms occur as additional source terms on the right-hand side of the final formulation. Incorporating the entropy gradient terms and using the first-order formulation of the second law of thermodynamics the APE-4 system reads

\[
\begin{align*}
\frac{\partial \rho'}{\partial t} + \bar{\alpha}^2 \nabla \cdot \left( \bar{\rho} u' + \overline{\rho' u'^2} \right) &= \bar{\alpha}^2 q_c, \\
\frac{\partial u'}{\partial t} + \nabla \left( \overline{u \cdot u'} + \nabla \left( \frac{\rho'}{\overline{\rho}} \right) \right) &= q_m,
\end{align*}
\]

where the original right-hand side terms are

\[
\begin{align*}
q_c &= -\nabla \cdot \left( \rho' u' \right)' + \frac{\bar{p}}{c_p} \frac{\partial s'}{\partial t}, \\
q_m &= - (\omega \times u)' + T' \nabla \sigma - s' \nabla T - \left( \nabla \left( \frac{u'}{2} \right)^2 \right)' + \left( \frac{\nabla \cdot \tau}{\mu} \right)'.
\end{align*}
\]

In this study all source terms but the viscous source are included in the right-hand side of the momentum equation of the APE system. The perturbed density is determined by the perturbation pressure

\[
p' - \bar{\alpha}^2 \rho' = \frac{\gamma \bar{p}}{c_p} s'.
\]

The first step of the hybrid method is based on an LES for the turbulent jet flow to provide the data of the noise source terms. Then, the corresponding acoustic field is computed by solving the acoustic perturbation equations.

<table>
<thead>
<tr>
<th>condition</th>
<th>$\rho_s$</th>
<th>$U_s$</th>
<th>$D/\mu_s$</th>
<th>$R_p/\mu_s$</th>
<th>$U_p/U_s$</th>
<th>$U_p/a_\infty$</th>
<th>$U_s/a_\infty$</th>
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<th>$T_p/T_0s$</th>
<th>$T_s/T_\infty$</th>
<th>$U_p/a_p$</th>
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</thead>
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<tr>
<td>$c_{j_c}$</td>
<td>400,000</td>
<td>220,000</td>
<td>1.1</td>
<td>1.0</td>
<td>0.9</td>
<td>1.0</td>
<td>0.9</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>$c_{j_{h1}}$</td>
<td>400,000</td>
<td>220,000</td>
<td>1.1</td>
<td>1.0</td>
<td>0.9</td>
<td>2.7</td>
<td>1.0</td>
<td>2.4</td>
<td>1.0</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>$c_{j_{h2}}$</td>
<td>400,000</td>
<td>314,000</td>
<td>1.57</td>
<td>1.4</td>
<td>0.9</td>
<td>2.7</td>
<td>2.6</td>
<td>1.0</td>
<td>0.88</td>
<td></td>
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</tr>
</tbody>
</table>
The details of the general set-up of the large-eddy simulation (LES) method, the quality of which has been proven in several analyses [10, 11, 12], are given in Meinke et al. [13]. The LES is based on a finite-volume method, in which the inviscid fluxes are spatially discretized by the AUSM scheme using the MUSCL approach and a centered approximation for the pressure term. The viscous terms are approximated by a centered discretization. For the temporal integration an explicit five-step Runge-Kutta formulation is used. To eliminate spurious wave reflections on the boundaries, a sponge layer is imposed [14].

The numerical method for the acoustic simulations requires a high spatial resolution in the wave number space and a high temporal accuracy in the frequency domain. To accurately resolve the acoustic wave propagation, the seven-point stencil dispersion-relation preserving (DRP) scheme [15] is used for the spatial discretization and an alternating 5-6 stage low-dispersion and low-dissipation Runge-Kutta method for the temporal integration [16]. On the inner boundaries between the inhomogeneous and the homogeneous acoustic domain an artificial damping zone has been implemented to suppress spurious sound generated on the embedded boundaries of the LES and the acoustic domain [17]. A detailed description of the two-step method and the discretization of the Navier-Stokes equations and the acoustic perturbation equations is given in Schröder et al. [18] in a general context.

In Fig. 1 the computational domain is presented. The LES domain $X_{\text{LES}}$ extends $12.5D$ in the radial direction and $25D$ in the streamwise direction. The noise source region $X_{\text{SRC}}$, in which the acoustic source terms of the APE-4 equations are calculated, extends $17.5D$ in the axial direction and $3D$ in the radial direction. At the end of this inner domain, which is depicted by a dashed line, an artificial damping zone is defined to suppress spurious noise generated on the embedded boundaries of the acoustic source domain [17]. Using the source terms determined by the LES data the acoustic perturbation equations are solved on a domain $X_{\text{APE}}$ which is five times larger than the LES source region, i.e., it comprises a spatial size of $27.5D$ in the axial and radial direction.

3 Results

Based on the numerical setup described above the turbulent flow fields are determined. Using the unsteady flow data over a time interval $T = 1500R_{s}/U_{s}$ the turbulent statistics are achieved. For the acoustic computations the time step $\Delta t = 0.011R_{s}/U_{\infty}$ is chosen to obtain stable numerical solutions. The acoustic analyses include the sound waves whose maximum length scale $\lambda_{\text{max}}$ is approximately $20D$.

Since the flow configurations consider a clean inflow condition without any nozzle effect an inflow forcing technique is used to generate an artificial turbulent transition. That is, at each time step an artificial vortex ring is imposed on both shear layers. The inflow forcing generates an appropriate turbulent field via the random azimuthal modes for the vortex ring [19]. Figure 2 shows instantaneous vorticity contours of the hot coaxial jet ($c_{\text{h1}}$). The comparison of Figs. 2(a) and (b) illustrates the effect of the artificial inflow forcing.

The turbulence distributions on the jet centerline are presented in Fig. 3(a) with the axial velocity component and in Fig. 3(b) with the radial velocity component. Due to the heat excited flow the hot coaxial jet ($c_{\text{h1}}$) begins turbulent mixing earlier than the cold coaxial jet ($c_{\text{c}}$). Besides, the high speed hot coaxial jet ($c_{\text{h2}}$) shows the much rapid growth and decay of turbulence. This non-linear turbulence saturation is caused by the multiple shear layers which alter the eddy transport inside the coaxial jets.

In Fig. 4 the acoustic field generated by the hot coaxial jet ($c_{\text{h1}}$) is shown. The dominant wave radiation possesses an angular range of $\theta \approx 30-40$ deg. To substantiate the numerically determined acoustic fields experimental results are also considered. The experimental data of the CoJeN project [20] are illustrated for the overall sound pressure level in Fig. 5. The comparison in Fig. 5(a) shows a good agreement between the APE results and the experimental data. In Fig. 5(b) the acoustic directivities at $r_{p} = 40R_{s}$ show a unique pattern for the hot coaxial jet acoustics. The maximum OASPL occurs at $\theta \approx 35$ deg from the jet axis. Compared with the findings of the cold coaxial jet the axial profile of the hot coaxial jet shows an approximately $5-10$dB higher acoustic pressure.

In Fig. 6 the acoustic spectra of the cold and the hot coaxial jets are compared. The sound pressure is determined at the radial distance $r_{p} = 40R_{s}$. The downstream acoustics of the cold coaxial jet in Fig. 6(a) shows the pronounced low frequency radiation at $St \approx 0.3$ which moves to $St \approx 0.4$ for the hot coaxial jets. As indicated by the spectrum of $c_{\text{h2}}$ the increase of the acoustic power becomes more prominent when the primary jet speed is higher. The sound generation in the coaxial jets is characterized by two features. The first feature is the downstream acoustics due to the large scale turbulence in the shear layers and the second one is the sideline acoustics enhanced by the temperature gradient. Figure 6(b) illustrates the differences of the sideline acoustics of the coaxial jets. The acoustic radiation almost perpendicular to the jet axis is clearly intensified for the hot coaxial jet more than that of the cold coaxial jet. Besides, in the low frequency band the acoustic level of the hot coaxial jets is higher than that of the cold coaxial jet. Note, however, the present coaxial jet configurations have a mean inlet velocity distribution plus an artificial inflow forcing. This artificial excitation has to be kept in mind when the quantitative findings are considered.
4 Conclusion

The flow field and the acoustic field of one cold and two hot coaxial jets have been analyzed. The Reynolds number have been $Re_D=400,000$ based on the velocity of the secondary jet and the diameter of the nozzle exit. The primary jet temperature of the cold coaxial configuration have been the ambient temperature $T_p = T_\infty$, whereas that of the hot coaxial jets have been defined by $T_p = 2.7T_\infty$. The main objective of the analysis has been the understanding of the differences of the cold and hot coaxial jets and the impact of the temperature gradient on the acoustic field. The numerical method has been based on a hybrid LES/APE method. The acoustic source terms have been the Lamb vector fluctuations, the entropy source terms, and the nonlinear source terms. The overall acoustics and the corresponding sound spectra based on the hybrid LES/APE approach have been in convincing agreement with the experimental measurement. The findings of the hot coaxial jets have shown that the low frequency acoustics increases in the sideline direction, i.e., the sound field perpendicular to the jet axis is enhanced by the pronounced temperature gradient.

Références

[19] Bogey C. and Bailly C. Direct computation of the sound radiated by a high reynolds number, subsonic round jet. In CEAS Workshop from CFD to CAA, Athens, Greece, 7–8 November 2002.
Fig. 1 – Computational domain, (a) meshes at the nozzle exit, (b) schematic of the computational domain in the r-z plane where \( r = \sqrt{x^2 + y^2} \); ----- (APE domain, \( X_{APE} \)), · · · · (LES domain, \( X_{LES} \)), -- (acoustic source region for APE, \( X_{SRC} \)). \( \theta \) is the angle between the position vector \( r_p \) and the streamwise direction (z-coordinate), the jet diameter is denoted by \( D(=2R) \), \( R_p \) and \( R_s \) are the primary and secondary jet radii of the coaxial jets.

Fig. 2 – Instantaneous contours of the vorticity magnitude, \( |\omega| \leq 5a_0/R \), (a) inflow forcing at \( z \simeq R \), (b) no inflow forcing.

Fig. 3 – Axial profiles of turbulence intensity on the jet centerline, (a) axial velocity component, (b) radial velocity component, --- \( \langle cj_c \rangle \), -- \( \langle cj_{h1} \rangle \), - - \( \langle cj_{h2} \rangle \).
Fig. 4 – Instantaneous acoustic pressure contours, $|p'/\rho_\infty a_\infty^2| \leq 10^{-3}$.

Fig. 5 – Overall acoustic directivity based on the APE-4 system: (a) comparison with experimental data from [20], (b) $--$ $(c_j)$, $- - - (c_{jh1})$, $\cdot - - (c_{jh2})$.

Fig. 6 – Sound spectra of acoustic radiation at the angles of (a) $\theta = 25^\circ$ and (b) $\theta = 85^\circ$ at a distance $r_p = 40R_a$, $--$ $(c_j)$, $- - - (c_{jh1})$, $\cdot - - (c_{jh2})$. 