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IMPACT OF THE NOZZLE EXHAUST TEMPERATURE ON THE NEAR-FIELD NOISE EMITTED BY SUBSONIC JETS

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ABSTRACT

This study provides an analysis of the impact of temperature on the near pressure field of three subsonic jets, using data from well-resolved compressible Large-Eddy Simulations. The jets have nozzle-exit temperatures equal to 1, 1.5, and 2.25 times the ambient temperature, an acoustic Mach number of $M_a = 0.9$ and a Reynolds number of $Re_D = 10^5$. Pressure time series were extracted from several virtual probes distributed in the near field of the jets, covering a region extending up to 20 jet diameters in the streamwise direction and 3 jet diameters radially, repeating this planar distribution across different azimuthal angles. The data were analyzed in both the Fourier and Wavelet domains, facilitating simultaneous representation in the time-frequency domain. The analysis focused on evaluating the influence of nozzle exhaust temperature on pressure fluctuations in the near field of the single-stream jets. In addition, a wavelet-based acoustic decomposition technique was applied to assess the effects of nozzle exit temperature on both the acoustic and hydrodynamic pressure fields. The parameters of a wave-packet model for subsonic jet noise were finally analyzed and systematically optimized.

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1. INTRODUCTION

The noise generated by high-speed turbulent jets remains a critical challenge in the design of modern civil aircraft, particularly during take-off when engine thrust is maximized. Since Lighthill's pioneering formulation of aeroacoustic theory [1], extensive research has sought to unravel the physical mechanisms through which turbulent jet flows produce sound. Seminal contributions by [2, 3], and [4], among others, have established that coherent turbulent structures within the jet shear layer act as primary noise sources. Recent advances in modeling, particularly through wavepacket-based approaches and linear stability analysis, have significantly improved the predictions of jet noise radiation. Studies such as those by [5,6], and [7,8] demonstrate the efficiency of these frameworks in linking hydrodynamic instabilities to far-field acoustics.

Despite these advancements, the existing models often rely on simplifications, such as assuming steady base flows, neglecting temperature variations, or linearizing sound propagation that limit their applicability to idealized configurations. While analytical studies such as those of Kam et al. [9] and the experimental analysis by Vishwanathan [10] have explored heated jets, most numerical and experimental efforts focus on jets at ambient temperatures, leaving a gap in understanding how elevated exhaust temperatures, typical of aeronautical engines, influence noise generation and propagation.

This work addresses these limitations by investigating the generation of acoustic waves in high-speed turbulent jets with temperature ratios ranging from 1 to 2.25 relative to ambient conditions. The jets have an acoustic Mach number of 0.9 and are highly disturbed at the nozzle exit. They have been computed using compressible Large-Eddy Simulations (LES). The LES datasets allow for a comprehensive analysis of both acoustic and hydrodynamic fields through a combination of Fourier and wavelet-based techniques. A wavelet-based acoustic decomposition method [11, 12] is applied to the jet near pressure field to highlight the effects of temperature on jet noise radiation.

Furthermore, this study systematically optimizes the parameters of a wavepacket noise prediction model, based on the methodology of [7,8]. Although earlier work demonstrated strong agreement with experimental data for cold subsonic jets, the extension to heated flows presented here aims to increase the fidelity of the model.

Details on the numerical setup and the wavelet-based processing procedure are given in Sections II and III, respectively. The main results are reported in Section IV while concluding remarks are given in Section V.

2. NUMERICAL SETUP

The LES simulations were performed by solving the three-dimensional compressible Navier-Stokes equations in cylindrical coordinates, using low-dissipation and low-dispersion explicit schemes [13]. The computational grid extends up to $x/D = 20$ in the axial direction and up to $r/D = 7.5$ in the radial direction, where D if the jet nozzle diameter.

For this analysis, we considered three jets with nozzle exhaust temperatures $T = T_a$, $T = 1.5T_a$, and $T = 2.25T_a$, where T_a is the ambient temperature. The jet acoustic Mach number are fixed at $M_a = 0.9$, resulting in jet Mach numbers decreasing with the nozzle-exhaust temperature. The jet Reynolds number is equal to 10^5 in all cases. Finally, the turbulence levels at the nozzle exit has been fixed to $TI = 9\%$ by tripping the boundary layers inside the nozzle.

More information on the LES and properties of the jet flow and acoustic fields can be found in previous papers [13, 14]

3. POST-PROCESSING PROCEDURE

3.1 Wavelet-based analysis

The data processing relies on separating the acoustic component of the pressure signals from the hydrodynamic counterpart. This goal is achieved by applying the procedure proposed by [15] and [11, 12, 16] that is briefly worked out in what follows.

The method is based on the wavelet transform of pressure signals and an appropriate filtering of the resulting wavelet coefficients. It is known that the wavelet transform performs well in identifying and isolating intermittent or time-dependent features. For a pressure time series $p(t)$, the wavelet transform can be formally represented by the following expression [17–21]:

$$w(s,t) = C_\psi^{-\frac{1}{2}} s^{-\frac{1}{2}} \int_{-\infty}^{\infty} p(\tau)\psi^*\left(\frac{t-\tau}{s}\right) d\tau, \quad (1)$$

where s is the wavelet scale, τ is a time shift, $C_\psi^{-\frac{1}{2}}$ is a constant that takes into account the mean value of $\psi(t)$ and $\psi^*\left(\frac{t-\tau}{s}\right)$ is the complex conjugate of the dilated and translated mother wavelet $\psi(t)$.

To perform the acoustic/hydrodynamic separation, the wavelet coefficients can be separated by assuming that the hydrodynamic contribution, being related to localized eddy structures, compresses well onto the wavelet basis so that it originates, in the transformed domain, few but with large amplitude wavelet coefficients [11,12]. Thus, the so-called pseudo-sound (i.e., the hydrodynamic component of pressure fluctuations) can be extracted by selecting the wavelet coefficients exceeding a proper threshold. In the present approach, the threshold is identified through the so-called WT3 technique. The procedure is based on an iterative process originally developed for signal denoising [22] and then applied to the analysis of coherent structures in turbulence [23]. Details about the procedure have been reported in [11]

Specifically, the chosen method is based on single-point statistics. Thus it does not require any additional signals taken from other virtual probes. Furthermore it has been applied successfully also to configurations out of jet noise (e.g. [24–26]). In the present approach, the application of the decomposition procedure provides the reconstruction in the physical domain both of the hydrodynamic and acoustic pressure in the near field of the jet.

The two time series are then processed separately and the statistical properties are eventually computed.

3.2 Wave-packet modeling

The wavepacket approach considered in this work follows the method described in [7, 8]. Specifically, the wave-packet noise source introduces some parameters whose value can be adjusted to match the pressure fluctuations from the reference jet using LES. A wave-packet describing the pressure fluctuations for a free jet is obtained by optimizing its parameters with near-field data on co-axial lines at two radial distances from the jet axis, namely $r/D = 2$ and 2.5. The radial distance of the near field probes has been chosen considering that the wavepacket model is valid for lines that are outside of the jet stream, and at the same time sufficiently close to the jet to sense and provide information about the hydrodynamic component of the pressure fluctuation. In the following, the data at the mentioned lines are referred to as *training* set, meaning that the model is informed by these data, while a *test* set is composed of the pressure field at other monitoring points.

4. RESULTS

A frequency-domain analysis of the wavelet-decomposed near-pressure field is first presented. The frequency dependence of the near-field acoustic component is evaluated through the spectra of both hydrodynamic and acoustic pressure, expressed in terms of the Sound Pressure Level (SPL) using the following equation:

$$SPL = 10\log_{10}\left(\frac{\mathrm{PSD}\Delta f_{\mathrm{ref}}}{p_{\mathrm{ref}}^2}\right), \qquad (2)$$

where PSD denotes the power spectral density evaluated using Welch's method setting Nyquist frequency at St = 12.8, with 256 samples per bin, and applying a Hanning window.

The SPL of the acoustic pressure field obtained at a radial distance of $r/D = 2$ in the jet near pressure field are shown in Figure 1 . It reveals a reduction in the acoustic component across all frequencies with increasing temperature, with the attenuation being more pronounced at higher axial distances.

The SPL frequency peak is also significantly reduced with the increase in nozzle exhaust temperature. This can be attributed to the more rapid development of the Kelvin-Helmholtz shear-layer wave instabilities in the hot jets.

Conversely, in Figure 2, the SPL of the hydrodynamic pressure field appear to weakly depend on the jet temperature. Notably, a significant difference between Figures 2(a) and (c) is only observed at low x/D.

The variation in acoustic pressure field intensity indicates a change in directivity. To illustrate this, the OASPL maps obtained for the acoustic field, evaluated using the following equation:

$$\mathrm{OASPL} = 20\log_{10}\left(\frac{\sigma}{p_{\mathrm{ref}}}\right), \qquad (3)$$

are presented in figure 3, where σ is the standard deviation of the pressure signal and p_{ref} is a reference pressure whose value is $20\mu Pa$.

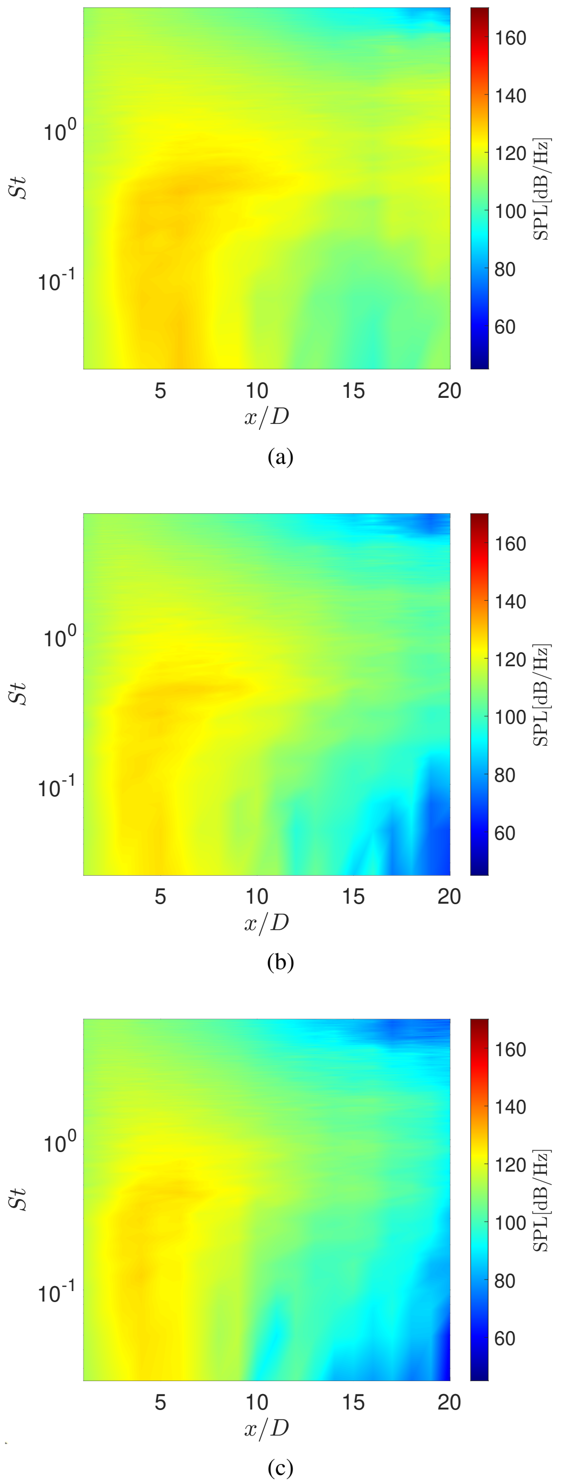


Figure 1: SPL of the acoustic pressure field at $r/D = 2 :$: (a) $T = T_a$; (b) $T = 1.5T_a$; (c) $T = 2.25T_a$.

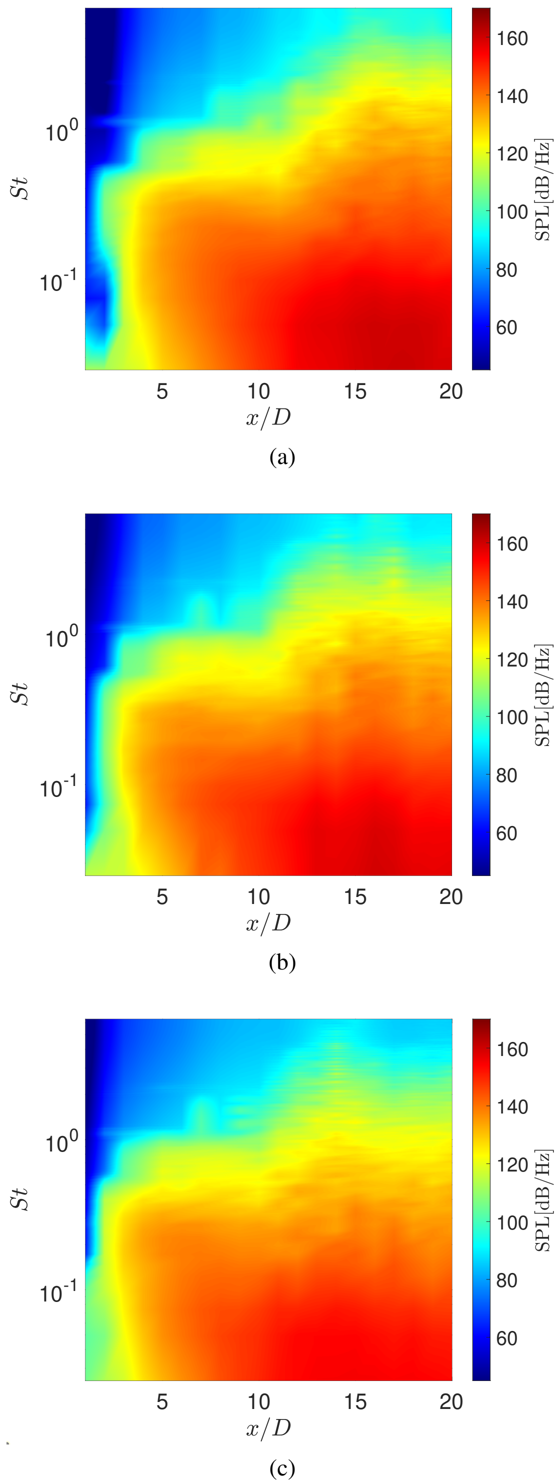


Figure 2: SPL of the hydrodynamic pressure field $r/D = 2$: (a) $T = T_a$; (b) $T = 1.5T_a$; (c) $T = 2.25T_a$.

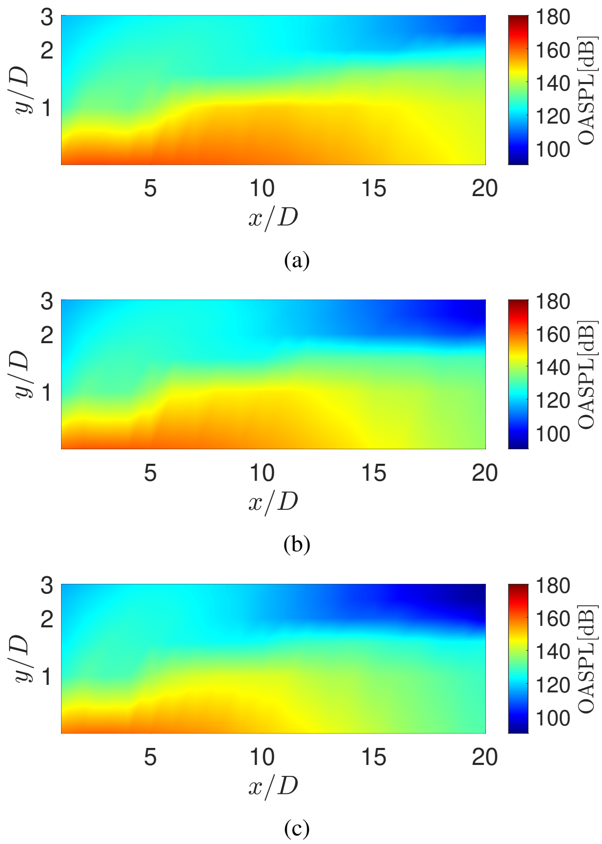


Figure 3: OASPL of the acoustic pressure field: (a) $T = T_a$; (b) $T = 1.5T_a$; (c) $T = 2.25T_a$.

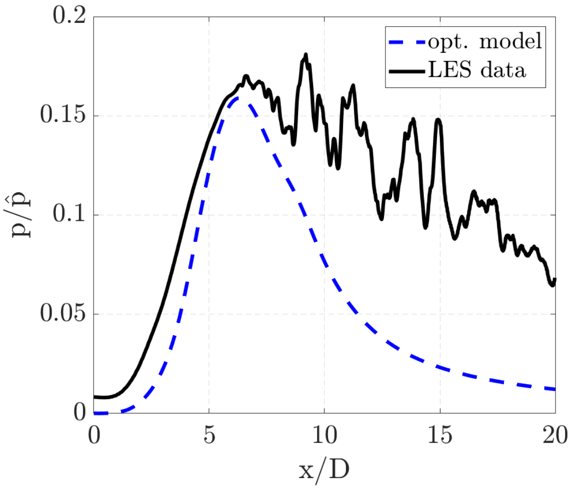
It clearly appears that the amplitude and the directivity of the acoustic pressure field are both significantly affected by the jet temperature, especially further downstream of the jet. Specifically, a reduction in OASPL is observed at high x/D values. Additionally, the OASPL distribution indicates a progressive sideline spread of the noise field as the temperature increases. This can be ascribed to the faster breakdown of large-scale structures as they develop more rapidly.

It is interesting to note that the high-intensity region near the jet axis (represented by the dark red areas in Figure 3) extends from the nozzle exit to a distance between 10 and 15 diameters, depending on the temperature. More specifically, as the nozzle exhaust temperature increases, the axial extent of this high-intensity region contracts, reaching approximately $x/D = 10$ for the highest temperature. This is due to the faster breakdown of large-scale structures.

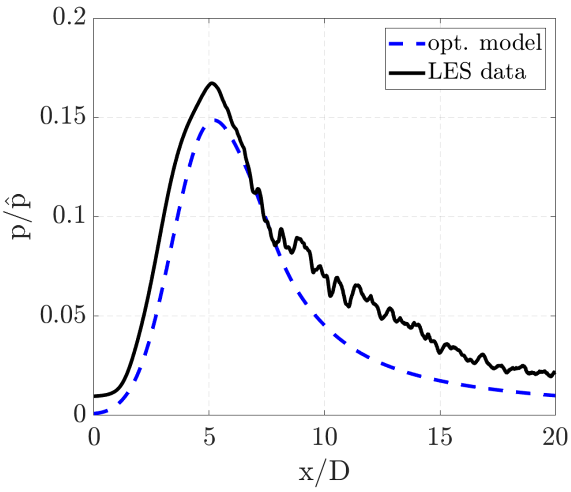
Comparisons of the LES pressure field and that predicted by the optimal wave-packets (see [8] for the approach used) for $T = T_a$ and (b) $T = 2.25T_a$, at a Strouhal number of $St = 0.25$, are finally provided in Figure fig:enter-label. The predictions closely match the shape of the reference data along the near-field lines, but only up to the axial position where the lines begin to interact with the jet flow for the considered Strouhal number. The modification in jet structure due to the higher temperature enhances the effectiveness of wavepacket optimization.

5. CONCLUSIONS

This paper presented an analysis of the effect of nozzle-exit temperature on the near-field acoustic pressure of compressible subsonic jets. The study is based on a high-fidelity, well-resolved large-eddy simulation (LES) database, conducted at fixed acoustic Mach and Reynolds numbers, and turbulence intensity. The acoustic and hydrodynamic pressure components were separated using an established wavelet-based procedure, enabling the reconstruction of both pressure time series with high accuracy. The OASPL maps show a shortening of the high-intensity region observed which suggests a faster breakdown of large-scale coherent structures, shifting the dominant noise sources upstream. A key finding is the shift in noise directivity with increasing temperature. While lower-temperature jets predominantly radiate noise in the aft direction, higher-temperature jets exhibit a more pronounced sideline directivity. The SPL frequency peak is also significantly reduced with increasing nozzle exhaust temperature, likely due to the more rapid development of the Kelvin-Helmholtz instabilities. Finally, the optimized wavepacket approach better predicts the jet pressure field for higher temperature.



(a)



(b)

Figure 4: Comparison between reference and optimized wave-packet normalized pressure at $r/D = 1.5$: (a) $T = T_a$ and (b) $T = 2.25T_a$.

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