ON THE LINEARITY OF THE QUIETING OF HIGH SPEED JETS BY HEATING

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Summary High-speed jets are known become quieter when the high-speed stream is heated at constant velocity. The cause of the noise reduction is not known but it is hypothesized that it can be partially explained through modification of the jet's large scale dynamics. It is found through simulations of the linearized dynamics of the initial jet mixing layers that the large-scale entropy fluctuations play an increasing role with increased temperature, as expected, but also that these fluctuations are partially responsible for reducing the radiated sound. Preliminary results from a multiscale linear theory are developed toward explaining this observation and suggest that the entropy fluctuations are less efficient sound radiators.

INTRODUCTION

It is known that the sound emitted by a turbulent jet is a function of both its Mach number and of its temperature. For low speed jets with fixed acoustic Mach number $M_a = U_j/a_\infty < 0.7$, heating increases the radiated sound while, for higher speed jets, heating decreases the sound [1, 2]. Several theoretical explanations for these observations exist but none are universally accepted [3, 4, 2]. In the context of Lighthill's acoustic analogy [5] the heating effects on the noise source are often associated with the so-called 'entropy term,' $[p - p_\infty - a_\infty^2(\rho - \rho_\infty)]\delta_{ij}$. Lilley [6] rearranged this term into an alternative form where the enthalpy fluctuations are more closely tied the source structure. In high-speed heated jets it has been shown [7, 8] that, indeed, the enthalpy source term does increase with heating. However, those investigations also suggest that the effects of heating are not solely tied to the enthalpy fluctuations but, instead, alter the spatial and temporal structure of the source. In this paper it is argued that one affect of heating is to alter the structure of the jet's large scale behavior, as characterized by its 'instability wave' behavior, which, in turn, affects the jet's radiated sound. As such we focus on the changes that occur in a planar mixing layer before addressing axisymmetric mixing layers and turbulent jets. Observations support this claim indirectly by showing a monotonic decrease in the frequency-dependent sound pressure levels, including those frequencies typically associated with the larger scale dynamics [2], when high-speed jets are heated.

To this end we examine carefully the dynamical role played by the entropy field through numerical simulations and a multi-scale linear theory. The geometric simplicity of the jet's initial mixing layer is exploited to simplify the analysis and as a surrogate for future work with axisymmetric shear layers and turbulent jets. Only the numerical simulation results are presented here; the multiscale theory results will be presented at the meeting.

METHOD

We study the development of disturbances on a spatially developing compressible mixing layer at fixed velocity ratio $U_1 = 0$, $U_2 = 1.12a_\infty$ but at varying total temperature ratios $\mathrm{TR} = T_{t2}/T_{t1} = \{1.00, 1.25, 1.50, 2.00, 2.50, 3.00\}$. These conditions span those typically found in cold, isothermal, and heated jets in the laboratory. The Mach number of lower, high-speed stream drops from 1.3 to 0.7 as the temperature is raised. To permit comparison with the linear theory presented in the next section, we assume the disturbances are of sufficiently low amplitude but allow them to grow on a turbulent mixing layer mean profile whose growth rate is a function of M_c. Spatial, inviscid instability waves computed from the compressible Rayleigh equation are used to seed the mixing layer whose dynamics are modeled using the linearized Euler equations solved using a globally third-order accurate summation-by-parts approximation with an explicit norm [9]; the scheme is second order on boundaries and fourth order in the interior. The boundary conditions utilized the simultaneous-approximation-term approach [10] modified for the current linearized equations. The time advancement used a traditional fourth-order Runge-Kutta method with a fixed timestep corresponding to a CFL of approximately 0.4. This approach has been shown to be stable and accurate for a variety of problems in aeroacoustics [11].

RESULTS

Results from the linearized simulations are presented here for a single frequency case of $\omega = 0.1a_\infty/\delta_{\omega,0}$; multi-frequency results will be presented elsewhere. After the instability waves are introduced, a transient period follows after which a steady, sinusoidal temporal response of all points in space is observed. At the steady state root-mean-square velocity, pressure, and entropy fluctuations are recorded. The varying growth rates of the instability waves with temperature imply that the peak fluctuation levels will be different for a fixed given initial disturbance amplitude. Thus, to put the simulations on an equal footing, the linear results are scaled such that the peak level of u' root-mean-square along $y = 0$ is unity. Justification for this scaling comes from the experimental observation that in heated jets the mixing layer fluctuation levels are approximately constant for fixed velocity [12]. The scaling factors, relative to the cold mixing layer, where $A \in \{1.00, 1.99, 4.41, 22.10, 77.47, 189.53\}$, in a trend consistent with the increase in $-\alpha_i$ with increasing TR. All fields are scaled accordingly.

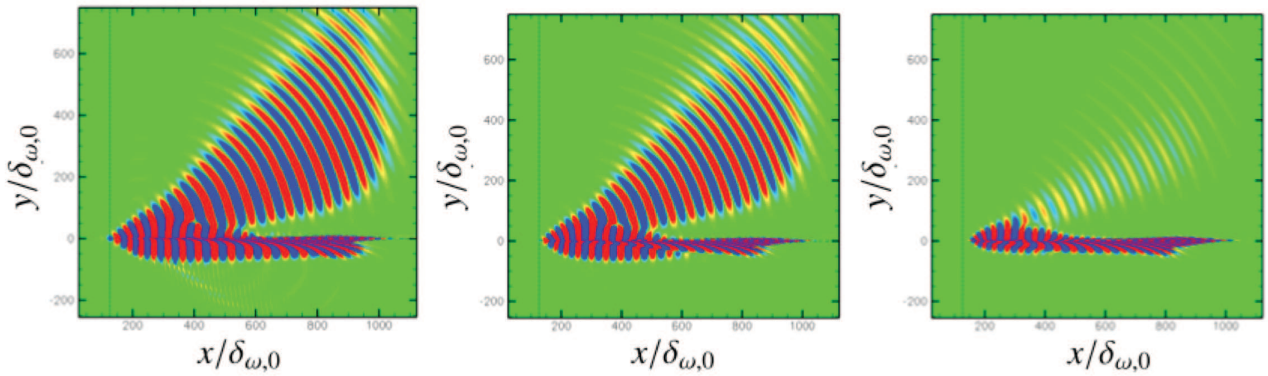

Figure 1. Instantaneous density perturbation $A^{-1}\rho'$ for the cold (TR = 1.0, left), isothermal (TR = 1.25, middle), and heated (TR = 2.00, right) mixing layers. Vertical dashed line corresponds to end of sponge region.

A visualization of the scaled ρ' and the mean streamwise velocity is given in Fig. 1 for a mixing layer at three different temperature ratios corresponding to cold, isothermal, and heated. It is observed that above the mixing layer the density field diminishes in amplitude with increasing temperature, consistent with experimental data on high-speed jets. It appears from the data (not shown) that the velocity and entropy fields become tightly coupled downstream in the mixing layer whereas the pressure field is initially coupled to the velocity but then is not continuously generated, resulting in a single-peaked profile. This latter observation is also found in the far-field directivity where the pressure fluctuations as a function of angle from the downstream mixing layer axis diminish monotonically with increasing temperature.

CONCLUDING REMARKS

Preliminary results from the analysis of a planar, two-dimensional high-speed mixing layer at non-isothermal conditions show consistency with observations from experiments and non-linear large-eddy simulations of high-speed turbulent jets where the radiated sound decreases with increasing temperature ratio. The cause of the reduction is believed to be related to the emergence of significant entropy fluctuations within the mixing layer created by the spatially varying mean velocity and mean entropy gradients. A multiscale linear theory (to be presented at the meeting) suggests a path for explaining the observations by coupling a multiscale expansion near the mixing layer to a globally valid outer problem through the method of matched asymptotic expansions.

CONCLUSIONS

References

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