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EFFECTS OF TEMPERATURE ON THE NEAR-NOZZLE ACOUSTIC TONES OF HIGH-SPEED JETS

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ABSTRACT

The effects of temperature on the acoustic tones emerging near the nozzle of high-speed round jets are investigated using large-eddy simulations. The jets have acoustic Mach numbers, corresponding to the ratios between the nozzle-exit velocities and the speed of sound in the ambient medium, between 0.30 and 1.30 and nozzle-exit temperatures equal to 1, 1.5 and 2.25 times the ambient temperature. For the hot jets, as for the isothermal jets, peaks emerge in the near-nozzle spectra, more or less strongly depending on the jet velocity. They do not appear to vary much with temperature at a fixed jet flow Mach number. Their frequencies and tonal characters can be explained by the properties of the guided jet waves predicted for a vortex sheet.

Keywords: *jet noise, acoustic tones, guided jet waves, large-eddy simulation, vortex-sheet model.*

1. INTRODUCTION

The presence of acoustic tones of physical nature near the nozzle of high-speed jets has been recently recognized [1, 2]. These tones, first documented in 2006 [3], have been shown to be related to the existence of guided jet waves (GJW), essentially confined inside the jet core, whose properties were described theoretically thirty years ago [4]. These waves have been shown to be involved in the feedback mechanisms establishing in impinging and screeching jets [5–10] but also in the generation of acoustic tones near the nozzle [1, 2, 11, 12] and in the upstream far field [13] of high-speed free jets. In free jets with laminar initial conditions, they have also been revealed to excite the instability waves near the nozzle [14].

Most studies on near-nozzle acoustic tones in free jets have been performed for cold of isothermal jets, and very few dealt with hot jets. However, the theoretical developments of Towne *et al.* [1] suggested that tones should exist in the latter jets, over nearly the same Mach number range as for isothermal jets. The recent experiments of Upadhyay & Zaman [15] also showed that near-nozzle acoustic tones emerge at least up to a jet stagnation temperature of 473 K. For a given jet Mach number, their Strouhal numbers based on jet diameter and velocity were found to decrease with temperature with no notable change in their amplitudes.

In this work, the effects of jet temperature on the acoustic tones near the nozzle of round free jets are investigated by computing isothermal and hot jets using compressible large-eddy simulations (LES). The presence of tonal components will be sought in the near-nozzle pressure spectra. The variations of the tone characteristics with jet temperature will then be discussed and compared with the variations of the properties of the GJW predicted for a vortex sheet.

2. PARAMETERS

In this work, eighteen round jets, represented in figure 1 as a function of their nozzle-exit velocities u_j and static temperatures T_j, are considered. Their acoustic Mach numbers $M_a = u_j/c_a$ are equal to 0.30, 0.45, 0.60, 0.75, 0.90, 1.10 and 1.30, their Reynolds numbers $\mathrm{Re}_D = u_j D/\nu_j$ to 100,000 and their temperatures to T_a, $1.5T_a$ and $2.25T_a$, where D, c_a, c_j and ν_j are the nozzle-exit diameter, the

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speed of sound in the ambient medium and in the jet flow and the kinematic molecular viscosity. In the following, for instance, the three jets at $M_a = 0.90$ are referred to as jetMa090T0 for $T_j = T_a$, jetMa090T1 for $T_j = 1.5T_a$ and jetMa090T2 for $T_j = 2.25T_a$. Due to the increase of the speed of sound with temperature, the Mach numbers $M_j = u_j/c_j$ of the hot jets are lower than their acoustic Mach numbers, as illustrated in figure 1. Thus, for example, the Mach number of jetMa110T1 at $M_a = 1.10$ ($M_j = 0.8981$) is nearly identical to that of jetMa090T0 at $M_a = 0.90$ ($M_j = 0.90$).

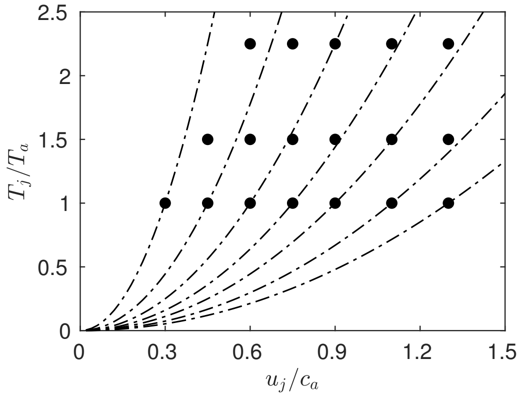

Figure 1. Nozzle-exit velocities u_j and temperatures T_j of ● present jets; $- \cdot - \cdot$ isocontours for M_j = 0.30, 0.45, 0.60, 0.75, 0.90, 1.10 and 1.30, from left to right.

The simulation methods and parameters are detailed in a paper [11] on the isothermal jets. The jets are computed by LES using low-dispersion and low-dissipation schemes on grids containing slightly more than one billion points. They originate at $z = 0$ from a pipe nozzle of radius $r_0 = D/2$ into a medium at temperature $T_a = 293$ K and pressure $p_a = 10^5$ Pa, with a mean velocity profile similar to a Blasius laminar profile of momentum thickness $\delta_\theta = 0.018r_0$ and a peak root-mean-square value u'_e of velocity fluctuations close to $0.09u_j$. The simulation times t after the transient periods vary between $700r_0/u_j$ and $4,000r_0/u_j$ depending on the jet conditions. During time t, density, velocities and pressure have been recorded at several locations, refer to reference [16].

3. RESULTS

The presence of acoustic tones near the nozzle of the jets has been examined by computing pressure spectra at $z = 0$ and $r = 1.5r_0$. Overall, acoustic peaks can be found in all cases. However, as for the isothermal jets [11], they are more or less tonal depending on the jet velocity. Their variations with jet temperature are illustrated below.

The spectra obtained for the isothermal jet at $M_a = 0.90$ and the two jets at $T_j = 1.5T_a$ at $M_a = 0.90$ and 1.10 are represented in figures 2(a-c) as a function of the Strouhal number $\mathrm{St}_D = fD/u_j$, where f is the frequency. For jetMa090T0, tones emerge in figure 2(a) close to the cut-off Strouhal numbers of the first azimuthal modes of the free-stream upstream-propagating GJW, as reported previously [1, 2, 11]. For jetMa090T1 with same exit velocity as jetMa090T0, peaks are also visible in figure 2(b) but they are less intense, broader and at higher Strouhal numbers than in figure 2(a). Finally, for jetMa110T1 with nearly the same Mach number M_j as jetMa090T0, the results in figure 2(c) strongly resemble those in figure 2(a). There are tones with comparable amplitudes at similar Strouhal numbers. The peak amplitudes are only slightly higher and their Strouhal numbers are slightly lower for the hot jet than for the isothermal one, in agreement with the experiments of Upadhyay & Zaman [15] (e.g. $St_D = 0.397$ vs 0.418 and $SPL = 126.8$ dB vs 124.8 dB for the dominant tones). Therefore, at a fixed exit velocity, rising jet temperature reduces the amplitudes and increases the frequencies of the near-nozzle peaks, whereas at a fixed Mach number M_j the peak properties do not change much. In the two cases, however, the peak frequencies fairly agree with the cut-off Strouhal numbers of the free-stream upstream-propagating GJW modes.

The peak Strouhal numbers in the near-nozzle spectra for mode $n_\theta = 0$ for $T_j = T_a$, $T_j = 1.5T_a$ and $T_j = 2.25T_a$ are represented in figures 3(a-c) as a function of u_j/c_a. The allowable frequency bands of the free-stream upstream-propagating GJW are also shown. The band upper limits are displayed in red or in green, as they correspond, respectively, to stationary GJW with zero group velocity or to the least-dispersed GJW when stationary GJW do not exist [11]. For the hot jets, as for the isothermal jets, at sufficiently high jet velocity, the peak Strouhal numbers are located near the band upper limits. In addition, the peaks are tonal for a stationary GJW limit (e.g. for jetMa110T1) and broadband for a least-dispersed GJW limit (e.g. for jetMa090T1). Therefore, the variations of the peak frequency and degree of emergence mainly result from those of the GJW properties. These properties do not vary much with jet temperature at a fixed M_j, explaining the strong similarities between the results from jetMa09T0 and jetMa110T1 both at $M_j \simeq 0.90$.

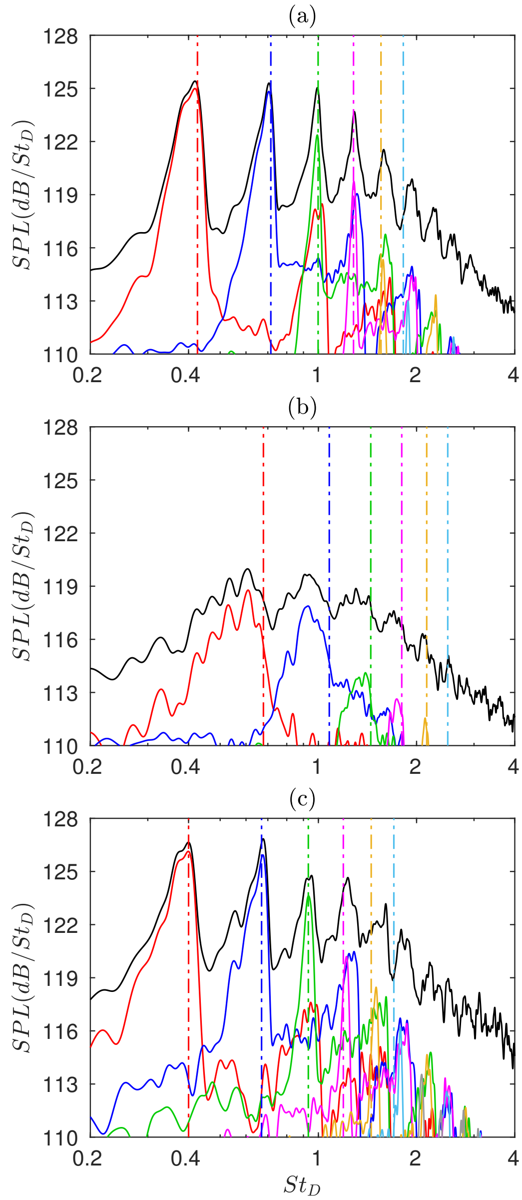

Figure 2. Sound pressure levels obtained at $z = 0$ and $r = 1.5r_0$ for (a) jetMa090T0, (b) jetMa090T1, (c) jetMa110T1 as a function of St$_D$: — total and $n_\theta =$ — 0, — 1, — 2, — 3, — 4 and — 5; (dash-dotted lines) cut-off Strouhal numbers of the modes (n_θ, $n_r = 1$) of the free-stream upstream-propagating GJW using the same colours as for the solid lines, where n_θ and n_r are the azimuthal and radial numbers of the GJW modes.

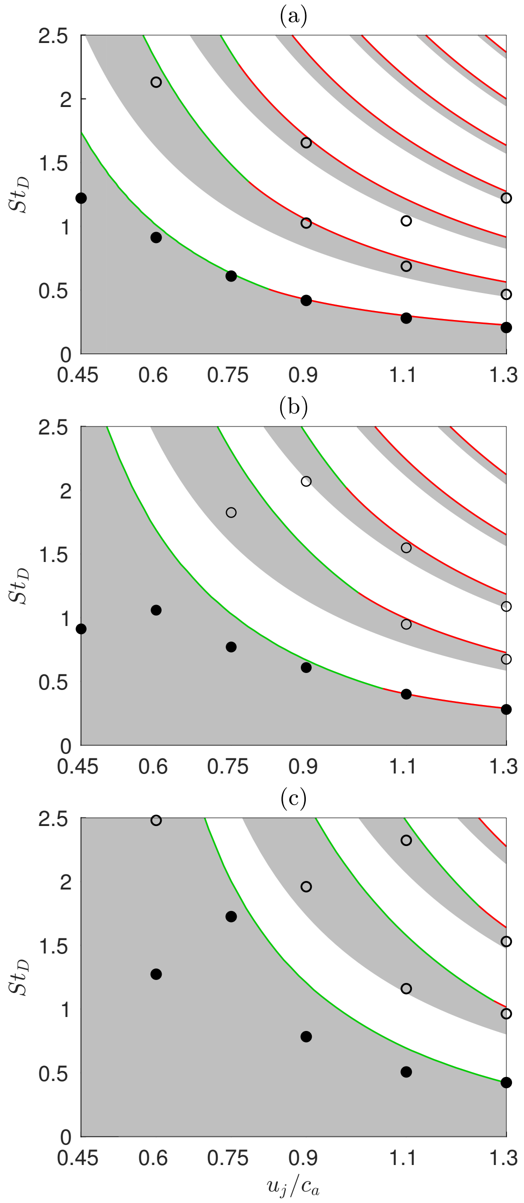

Figure 3. Variations with u_j/c_a of the peak Strouhal numbers in the pressure spectra at $z = 0$ and $r = 1.5r_0$ for $n_\theta = 0$ for (a) $T_j = T_a$, (b) $T_j = 1.5T_a$ and (c) $T_j = 2.25T_a$: ● dominant and ○ secondary peaks; (grey) frequency bands of the free-stream upstream-propagating GJW, upper band limits corresponding to — stationary and — the least-dispersed GJW.

4. CONCLUSION

In this work, it is found that, as for isothermal jets, acoustic peaks emerge in the pressure spectra obtained near the nozzle of high-speed hot jets, With rising jet temperature, the peaks are weaker and at higher Strouhal numbers at a fixed nozzle-exit velocity, whereas they do not change much at a fixed jet Mach number. These results, as well as the characteristics of the peaks, in terms of frequency, intensity, degree of emergence and width, in the hot jets can be explained by the properties of the GJW predicted for a vortex sheet.

5. ACKNOWLEDGMENTS

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