



**HAL**  
open science

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

Christophe Bogey

► **To cite this version:**

Christophe Bogey. EFFECTS OF TEMPERATURE ON THE NEAR-NOZZLE ACOUSTIC TONES OF HIGH-SPEED JETS. Forum Acusticum 2023, 2023, Torino, Italy. 10.61782/fa.2023.0198 . hal-04402186

**HAL Id: hal-04402186**

**<https://hal.science/hal-04402186>**

Submitted on 18 Jan 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



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

**Christophe Bogey**

Univ Lyon, CNRS, Ecole Centrale de Lyon, INSA Lyon, Univ Claude Bernard Lyon I,  
Laboratoire de Mécanique des Fluides et d'Acoustique, UMR 5509, 69130 Ecully, France

## 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

screaming 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 or 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.

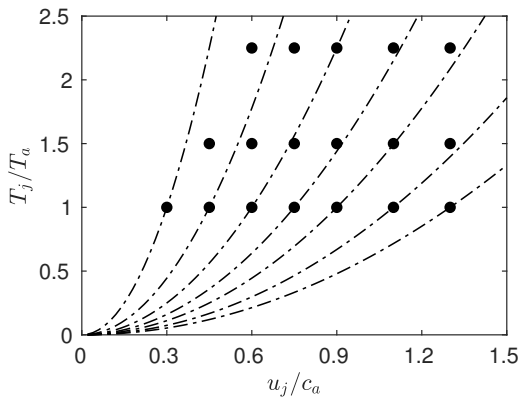
## 2. PARAMETERS

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  $Re_D = u_j D/\nu_j$  to 100, 000 and their temperatures to  $T_a$ ,  $1.5T_a$  and  $2.25T_a$ , where  $D$ ,  $c_a$ ,  $c_j$  and  $\nu_j$  are the nozzle-exit diameter, the

\*Corresponding author: christophe.bogey@ec-lyon.fr.

**Copyright:** ©2023 Christophe Bogey This is an open-access article distributed under the terms of the Creative Commons Attribution 3.0 Unported License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

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; - - - 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].

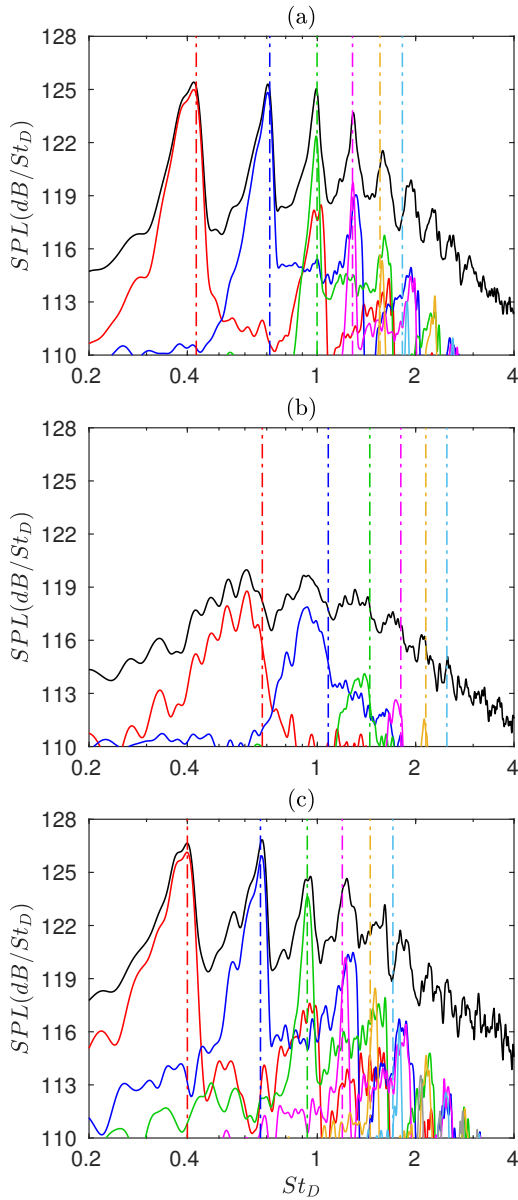
### 3. RESULTS

The presence of acoustic tones near the nozzle of the jets has been examined by computing pressure spectra at  $z =$

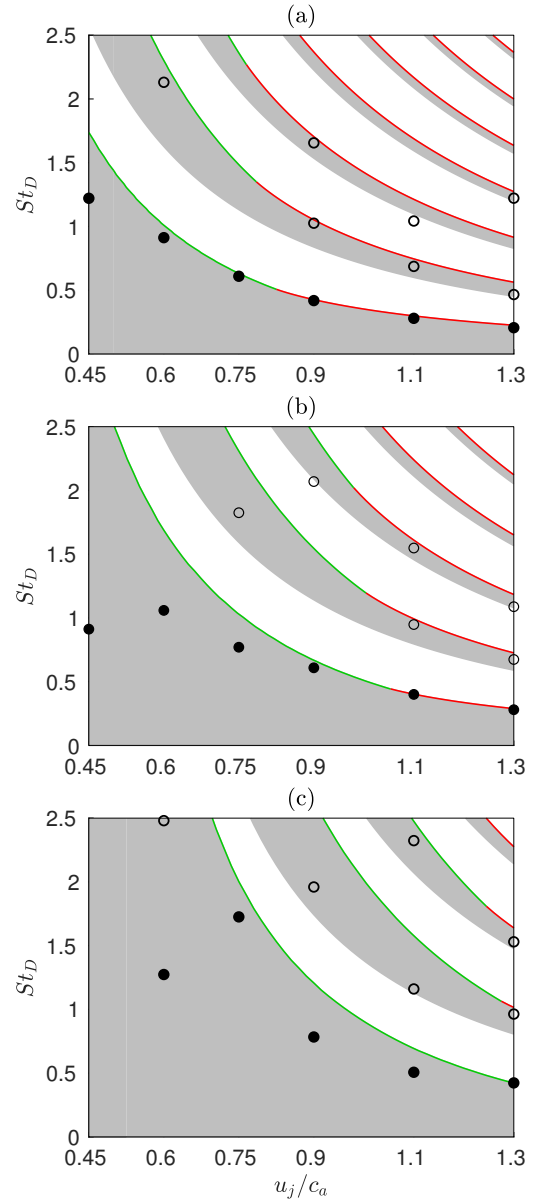
$0$  and  $r = 1.5r_0$ . Overall, acoustic peaks can be found in all cases. However, as for the isothermal jets [11], they are more or less tonal depending on the jet velocity. Their variations with jet temperature are illustrated below.

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  $St_D = fD/u_j$ , 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 jetMa090T0 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 ( $n_\theta, n_r = 1$ ) of the free-stream upstream-propagating GJW using the same colours as for the solid lines, where  $n_\theta$  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

This work was granted access to the HPC resources of PMCS2I of Ecole Centrale de Lyon and P2CHPD of Université Lyon I, and to the resources of IDRIS-CNRS under the allocation 2022-2a0204 made by GENCI. It was performed within the framework of the LABEX CeLyA (ANR-10-LABX-0060) of Université de Lyon, within the program *Investissements d'Avenir* (ANR-16-IDEX-0005).

#### 6. REFERENCES

- [1] A. Towne, A. V. G. Cavalieri, P. Jordan, T. Colonius, O. Schmidt, V. Jaunet, and G. A. Brès, "Acoustic resonance in the potential core of subsonic jets," *J. Fluid Mech.*, vol. 825, pp. 1113–1152, 2017.
- [2] G. A. Brès, P. Jordan, V. Jaunet, M. Le Rallic, A. V. G. Cavalieri, A. Towne, S. K. Lele, T. Colonius, and O. T. Schmidt, "Importance of the nozzle-exit boundary-layer state in subsonic turbulent jets," *J. Fluid Mech.*, vol. 851, pp. 83–124, 2018.
- [3] T. Suzuki and T. Colonius, "Instability waves in a subsonic round jet detected using a near-field phased microphone array," *J. Fluid Mech.*, vol. 565, pp. 197–226, 2006.
- [4] C. K. W. Tam and F. Q. Hu, "On the three families of instability waves of high-speed jets," *J. Fluid Mech.*, vol. 201, pp. 447–483, 1989.
- [5] C. K. W. Tam and K. K. Ahuja, "Theoretical model of discrete tone generation by impinging jets," *J. Fluid Mech.*, vol. 214, pp. 67–87, 1990.
- [6] C. Bogey and R. Gojon, "Feedback loop and upwind-propagating waves in ideally-expanded supersonic impinging round jets," *J. Fluid Mech.*, vol. 823, pp. 562–591, 2017.
- [7] P. Jordan, V. Jaunet, A. Towne, A. V. G. Cavalieri, T. Colonius, O. Schmidt, and A. Agarwal, "Jet-flap interaction tones," *J. Fluid Mech.*, vol. 853, pp. 333–358, 2018.
- [8] R. Gojon, C. Bogey, and M. Mihaescu, "Oscillation modes in screeching jets," *AIAA J.*, vol. 56, no. 7, pp. 2918–2924, 2018.
- [9] D. Edgington-Mitchell, "Aeroacoustic resonance and self-excitation in screeching and impinging supersonic jets - A review," *Int. J. Aeroacoust.*, vol. 18, no. 2-3, pp. 118–188, 2019.
- [10] M. Mancinelli, V. Jaunet, P. Jordan, and A. Towne, "Screech-tone prediction using upstream-travelling jet modes," *Exp Fluids*, vol. 60, no. 1, p. 22, 2019.
- [11] C. Bogey, "Acoustic tones in the near-nozzle region of jets: characteristics and variations between Mach numbers 0.5 and 2," *J. Fluid Mech.*, vol. 921, p. A3, 2021.
- [12] K. B. M. Q. Zaman, A. F. Fagan, and P. Upadhyay, "Pressure fluctuations due to 'trapped waves' in the initial region of compressible jets," *J. Fluid Mech.*, vol. 931, p. A30, 2022.
- [13] C. Bogey, "Tones in the acoustic far field of jets in the upstream direction," *AIAA J.*, vol. 60, no. 4, pp. 2397–2406, 2022.
- [14] C. Bogey, "Interactions between upstream-propagating guided jet waves and shear-layer instability waves near the nozzle of subsonic and nearly ideally expanded supersonic free jets with laminar boundary layers," *J. Fluid Mech.*, vol. 949, p. A41, 2022.
- [15] P. Upadhyay and K. B. M. Q. Zaman, "Pressure fluctuations due to 'trapped waves' in heated jets," Tech. Rep. 2022-2829, AIAA Paper, 2022.
- [16] C. Bogey, "A database of flow and near pressure field signals obtained for subsonic and nearly ideally expanded supersonic free jets using large-eddy simulations." <https://hal.archives-ouvertes.fr/hal-03626787>, 2022.