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The effects of temperature on vortex-pairing noise in axisymmetric subsonic jets

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Abstract

Thermal effects on the sound generation by vortex pairing are investigated in axisymmetric subsonic jets. Direct numerical simulation of compressible Navier-Stokes equations is performed for an accurate description of near-field flow dynamics and far-field sound. As the core temperature increasing, the positions of vortex roll-up and pairing move upstream, and the noise intensity is enhanced. In addition, sound predicted by Lilley-Goldstein acoustic analogy is consistent with the result of simulation in all cases. A further analysis of sound sources of the Lilley-Goldstein equation shows that the thermodynamic component has remarkable influence in non-isothermal jets, especially in the cold one. Moreover, sound generation in the isothermal jet is specifically studied by a simple nonlinear interaction model based on instability waves which are obtained by solving linear parabolized stability equations. The major radiation pattern given by the model is found to be in good agreement with the directly computed data, suggesting the great importance of nonlinear interaction in subsonic jet noise.

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Keywords: DNS; Noise; LPSE.

1. Introduction

Jet noise has been widely studied over past sixty years, however, it is still quite a challenging problem in aeroacoustics because of lacking enough understanding of noise generation mechanisms. Now, it is well known that vortex plays a significant role in processes of sound generation. The relationship between near-field complicated vortex dynamics, such as vortex roll-up and vortex pairing, and far-field noise has been extensively investigated [1–3]. By imposing the most unstable instability wave and its harmonics, Mitchell et al. [1] and Colonius et al. [2] found that the process of vortex pairing contributes to far-field noise dominantly. However, the influence of temperature on the processes of vortex pairing and sound radiation has been less studied.

Large scale vortex structures are found to be existed in both turbulent and laminar flow, which are believed to be associated with hydrodynamic instability, namely, Kelvin-Helmholtz instability, of shear layers. The instability waves have been detected both in supersonic jets [4] and subsonic jets [5]. However, the precise relationship between

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far-field noise and instability waves is still an open question. Based on instability modes, Sandham et al. [6,7] build a simple nonlinear model considering their quadratic interaction and then attempt to reveal some prominent processes of sound generation in a subsonic jet. They found that the difference mode interaction model is successful in predicting some aspects of far-field noise. In this paper, the difference mode interaction model is introduced to investigate the role of nonlinear interaction in sound generation by vortex pairing.

The goal of present work is to investigate the influence of temperature on vortex pairing and sound radiation in axisymmetric subsonic jets. With the aid of the difference mode interaction model, the role of nonlinear interactions of spatially evolving instability waves in sound generation is also studied for the isothermal jet. Furthermore, combined with Lilley-Goldstein acoustic analogy, we predicted the far-field noise reasonably, and compared them with directly computed data.

2. Methods and Parameters

The Navier-Stokes equations in cylindrical coordinates are solved without any modeling approximation. A fourth-order Runge-Kutta scheme is used for long time integration. The spatial derivatives are discretized by 7-point dispersion-relation-preserving scheme. The non-reflective boundary and buffer zones are used in the inflow, top and outflow boundaries. The initial inlet velocity profile is the solution to the steady axisymmetric compressible boundary layer equations. The governing equations and detailed numerical approaches have been elucidated in our previous work [8].

The axisymmetric subsonic jets with three different temperature ratios are simulated, the detailed parameters are listed in table 1. U_j and a denote the jet velocity and sound speed. R is the jet radius. Ma and Re indicate the Mach number and Reynolds number respectively. In order to trigger the roll-up and pairing of vortex rings, The flow is harmonically forced in the inlet buffer zone with small disturbances, namely, instability waves, at the fundamental and the first subharmonic frequencies as performed by [3]. The fundamental frequency is corresponding to the frequency of the most unstable mode predicted by linear stability theory. The acoustic analogy introduced by [9] is used to compute the far-field noise.

Table 1. Parameters of computation. The subscript $()_j$ denotes the quantities in the center line,and $()_\infty$ denotes far field quantities.

Case	$Ma_\infty = U_j/a_\infty$	$Ma_j = U_j/a_j$	T_j/T_∞	$Re = \rho_j U_j R/\mu_j$
JetM09TR150	0.9	0.735	1.5	1 800
JetM09TR100	0.9	0.9	1.0	1 800
JetM09TR085	0.9	0.97	0.85	1 800

3. Results and Discussions

In this section, we will discuss the influence of temperature on the near-field vortex dynamics and far-field sound. Fig.1 presents a comparison between the vorticity field of hot(top), isothermal(middle) and cold(bottom) cases. In this figure, it can be observed that the gross features of near-field dynamics are almost unchanged. In all cases, the jet undergos the same evolution procedures of vortex including linear growth of the disturbance energy, vortex rolling-up and merging, and then viscous dissipation, the same as the observation in [1]. However, the positions of roll-up and pairing move downstream as the core temperature is decreased. This is in correspondence with the predictions of linear stability which shows that the growth rate decreases as the core temperature is decreased [10]. Additionally, it is found that counter-rotating vorticity appears in the hot jet, and this feature is also found in globally unstable round jet [11].

The acoustic field represented by the dilatation rates is showed in Fig.2 for all cases at the fundamental and subharmonic frequency, respectively. For all cases, Fig.2 shows that the far-field noise of the subharmonic frequency is stronger than that of the fundamental frequency. The comparison of dilatation rates for different core temperature shows that heating increases acoustic intensity, while the acoustic intensity of the cold jet is weaker than that of the

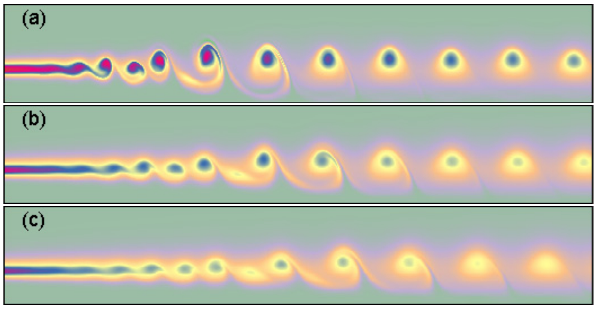

Fig. 1. Instantaneous vorticity field (a) Hot jet; (b) Isothermal jet; (c) Cold jet. Vorticity iso-contour levels:[-0.2,2.5].

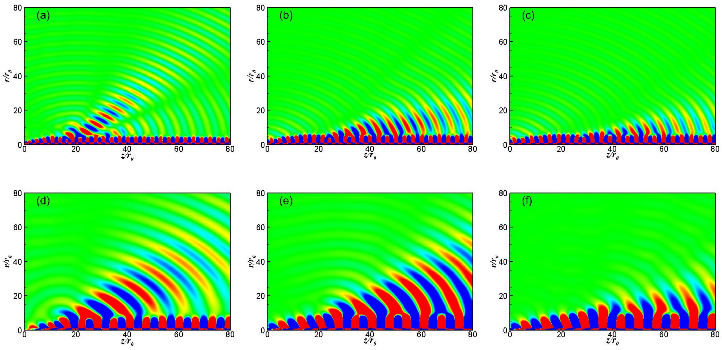

Fig. 2. Directly computed dilatation rates of fundamental(a,b,c) and subharmonic(d,e,f). Hot jet(a,d); Isothermal jet(b,e); Cold jet(c,f). Iso-contour levels: Hot$[-4\times10^{-5}, 4\times10^{-5}]$; Isothermal$[-10^{-5}, 10^{-5}]$; Cold$[-10^{-5}, 10^{-5}]$.

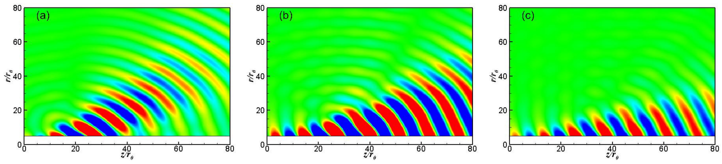

Fig. 3. Dilatation rates of subharmonic frequency obtained using Lilley-Goldstein equation. (a) Hot jet; (b) Isothermal jet; (c) Cold jet. Iso-contour levels: (a) $[-4\times10^{-5}, 4\times10^{-5}]$; (b) $[-10^{-5}, 10^{-5}]$; (c) $[-10^{-5}, 10^{-5}]$.

isothermal one. Furthermore, the radiation pattern varies greatly for different core temperature, as shown in Fig.2. For the hot jet, there are three waves at the fundamental frequency, one of which propagates upstream, while the other two propagate downstream. However, only one wave exists and propagates downstream in other cases of the fundamental frequency. Moreover, the sound radiation moves toward the upstream direction with increased core temperature. Especially, peak value presents at near 42 degree for the heated jet. However, nearly no clear peaks have been found for the isothermal and cold jets.

As previously mentioned, the far-field noise shows a dominant frequency, namely, subharmonic frequency. In the rest of this paper, the solution of Lilley-Goldstein equation is limited to the subharmonic frequency. Fig.3 shows the dilatation rates computed by solving Lilley-Goldstein equation at subharmonic frequency. Compared with the second row of the Fig.2, it is found that the predictions given by the acoustic analogy are in good agreement with the directly computed data. Quantitative comparison is presented in Fig.4. With the exception of some high polar angles, the predictions are in good agreement with the directly computed data. The angles of extinction observed in Ref.[1] are captured by direct computation, as well as the acoustic analogy.

In Lilley-Goldstein equation, the source terms can be divided into momentum and thermodynamic components. The far-field noise generated by each component can be determined independently. Thus, it enables us to estimate the relative contributions of each component. Fig.4 shows the far-field sound radiation computed by using separat-

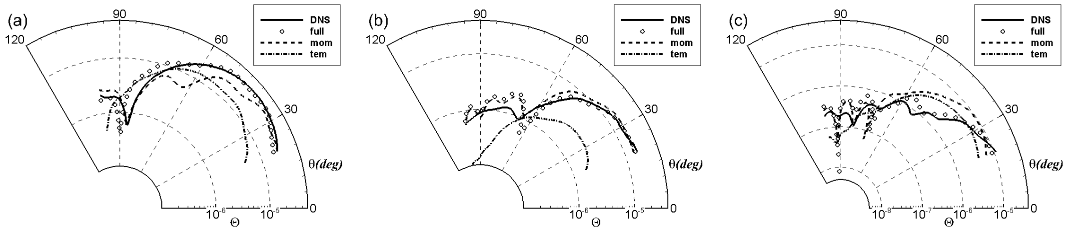

Fig. 4. Comparison of the directly computed dilatation rates to predictions obtained using Lilley-Goldstein equation. The plots are for the jets:(a)hot jet; (b)isothermal jet; and (c) cold jet. The magnitude of the dilatation rate at subharmonic frequency at a distance 50 radii from the apparent source location is shown. — DNS; ∘ full source; − − − momentum component ; − · − thermodynamic component.

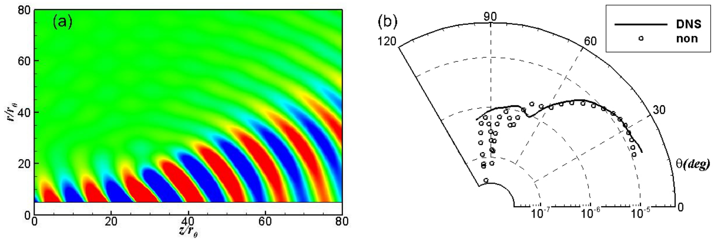

Fig. 5. (a) Dilatation rate obtained by the difference mode interaction model at the subharmonic frequency for the isothermal jet; (b) Comparison of the directly computed dilatation rates(—) to the predictions(∘).

ed terms and full terms, respectively. For the isothermal jet, the radiation from the thermodynamic component is much weaker than that from momentum terms, which can even be neglected. However, for non-isothermal cases, the thermodynamic component is much more important. Interestingly, the sound generated by thermodynamic and momentum component has almost equal amplitude near the angles of extinction. Both of them are larger than the amplitude of sound computed using full source terms. This suggests that canceling between momentum component and thermodynamic component should exist.

Finally, the difference mode interaction model used by Sandham [6,7] is introduced here to investigate the role of nonlinear interaction in sound generation by vortex pairing. The results are shown in Fig.5. Compared with Fig.2(e), the dilatation contours computed by the model is quite similar to the directly computed data. Fig.5(b) plots the magnitude of dilatation along a arc at a distance of 50 radii from the saturation point of the disturbance energy. Here, the amplitude of the simple model is arbitrary and has been adjusted to match the directly computed data. As we can see, a fairly good agreement is achieved between the radiation patterns computed by the simple model and directly computed data, especially at shallow angles. This results suggest that the nonlinear interaction between instability waves paly an important role in sound generation by vortex pairing.

4. Conclusion

The sound generated by vortex pairing in axisymmetric subsonic jets with different core temperature has been investigated. Direct numerical simulation of compressible Navier-Stokes equations is performed for an accurate description of both near-field flow dynamics and far-field sound radiation. Heating makes the positions of vortex roll-up and pairing moving upstream. With the core temperature increasing, the acoustic intensity increases, and the radiation directivity moves toward upstream for both fundamental and subharmonic frequencies. In addition, sound predicted by Lilley-Goldstein acoustic analogy is in good agreement with the result of simulation in all cases. A further analysis of sound sources of the Lilley-Goldstein equation shows that the thermodynamic component has remarkable influence in non-isothermal jets, especially in the cold one. The main radiation pattern has been reproduced reasonably by the difference mode interaction model, indicating that the nonlinear interaction between instability waves plays a substantial role in vortex pairing noise.

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