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Flow Sensitivity Analysis for the Feedback Loop Phenomenon of Subsonic Jet Noise Generation

Shota Morita, Aiko Yakeno, Christophe Bogey and Shigeru Obayashi

Abstract In this study, the feedback loop phenomena caused by upstream propagating waves (guided jet waves) in a Mach 0.9 free jet are investigated. A point source is placed at the edge of the potential core of a three-dimensional free jet as a noise source in the jet and the sensitivity of the flow field is measured. The results show that the case $St_D = 0.47$ has the highest sensitivity, which was consistent with the allowable frequency range of the guided jet wave. This result supports the idea that guided jet waves cause free shear layer instability waves.

1 Introduction

The relationship between jet stream instability waves and the resulting acoustic noise generation is one of the important research questions in science and engineering. Jet engine exhaust noise in commercial aircraft has been a significant problem for over 70 years. This noise is caused by the motion of the vortices generated by the jet, and in this case, it is called "vortex noise". Especially in supersonic jets [1] and impinging jets [2], it has been suggested that jet noise causes flow instability waves, generates

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sound waves of specific frequencies, and repeats this interaction. This is called the acoustic feedback mechanism. According to a recent review paper [3], the process of the feedback loop is divided into four stages: (a) hydrodynamic perturbation is generated and it propagates to the downstream (downstream process), (b) this perturbation is converted and it propagates to the upstream direction typically in the form of an acoustic wave (generation process), (c) the acoustic wave reaches to the sensitivity point of the flow (upstream process), and (d) a new downstream instability hydrodynamic wave is reproduced by the upstream wave (receptivity process).

Recently, it has been suggested that the generation of sound in high-speed subsonic jets is also explained by a feedback loop mechanism [4][5][6]. The story of a subsonic jet feedback loop phenomenon follows: (a) flow instability waves propagate to the downstream direction, (b) this wave forms a vortex and generates the acoustic waves, (c) this wave propagates to the upstream direction, and (d) regenerate the flow instability waves. Particularly, the first stage of vortex coupling caused by Kelvin-Helmholtz instability which propagates to the upstream direction, and causes the repetition of flow instability. Moreover, the upstream propagating wave exists on the jet axis for an $M=0.9$ jet [7]. It is also considered as the cause of the feedback loop. However, there remain questions about how the upstream-guided jet waves occur and if they affect the flow instability waves or not. Therefore, the purpose of the study is to investigate the relationship between the guided jet waves and Mach 0.9 jet flow instability waves. However, although linear stability analysis can look at the amplification rate of the flow field over time, it cannot analyze the effects of local disturbances on the entire flow field. In this study, we measure the flow sensitivity to sound waves in a flow by placing a virtual point source in the flow field and measuring the turbulence in the flow field using flow simulation.

This paper is organized as follows. Section 2 describes the flow sensitivity measurement and the computational method used in this study. section 3 presents the results of the analysis when applied to a three-dimensional jet. Finally, section 4 shows the conclusion of this paper.

2 Method: Flow Sensitivity Measurement

In this study, we measure the sensitivity of flow to acoustic waves by the following method. Specifically, we computed the time-averaged flow of the free jet and introduced a single-frequency acoustic source at the end of the potential core on the jet axis. We computed the time evolution of the turbulent kinetic energy k near the jet exit as the sensitivity criteria, which formulation is shown in Eq.(1). This allows us to consider the relationship between sound waves and flow more directly. In this study, a point source emitting acoustic waves at a single frequency at the end of the potential core of the jet is reproduced by representing a small object that appears and disappears in the flow by the Volume Penalization method (VP method) [8][9]. Here, the end of the potential core is considered the origin of the jet noise [10].

$$k = \frac{1}{2}\rho(u'^2 + v'^2 + w'^2) \quad (1)$$

We describe the governing equations used in flow analysis and the VP method used to reproduce point sources in the flow sensitivity measurement. The VP method is a type of virtual boundary method that represents an object in a flow. Specifically, an object is represented by adding an external force term called a Penalization term, which acts only in the object region, to the governing equations of the fluid. When the object does not have any porosity and movement speed, the governing equations of a VP method for compressible flow are expressed by the following Eqs. (2)-(4).

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_j}{\partial x_j} = 0, \quad (2)$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} - \frac{\chi}{\eta} u_i, \quad (3)$$

$$\frac{\partial e}{\partial t} + \frac{\partial (e + p) u_j}{\partial x_j} = \frac{\partial u_i \tau_{ij}}{\partial x_i} + \frac{\partial}{\partial x_j} \left(\kappa \frac{\partial T}{\partial x_j} \right), \quad (4)$$

Here, ρ is the density, u_j is the flow velocity, p is the pressure, τ_{ij} is the viscous stress tensor, e is the internal energy, T is the temperature, and κ is the specific heat ratio. In addition, χ is the mask function that takes 1 in the object region and 0 in the fluid region and η is the permeability that simulates the permeability of the object.

In this study, three-dimensional jet simulations were performed using an in-house solver. This is developed for simulating the three-dimensional compressible flow. For spatial discretization, the 6th-order accurate compact scheme and the 10th-order accurate compact filter [11] were used. The free parameter α_f is set to 0.495, referring to Kawai et al. (2010) [12]. For the time integration, we used the third-order accurate TVD Runge-Kutta method [13]. The Reynolds number $Re = u_0 D / \nu$ is set to 3125 and the jet Mach number $M = u_0 / c_0$ is set to 0.9. Here, D is the jet diameter, u_0 is the initial velocity of the jet and c_0 is the sonic speed of ambient pressure. The computation region used in this study is described in Fig.1. The sponge region and low-pass filter were applied far from the boundaries to prevent acoustic reflection of the wall.

3 Results and Discussion

3.1 Simulation results

We obtained the time-averaged field of the 3D free jet flow using the computational conditions described in Section 2 to obtain the base flow of the jet for use in the sensitivity computations. The cross-section of the time-averaged field on visualization result is shown in Fig.2(a). From the contour line of this figure, it is observed that the end of the potential core is located at $x/D = 11$, which is shown in the white circle

at Fig.2(a). Since jet noise is generated at the end of the potential core as mentioned in section 2, we set the point source at the end of the potential core.

To estimate the frequency of the upstream propagating guided jet wave, we applied Fourier analysis near the jet exit to the time-series data of pressure fluctuation. The spectrum from the pressure at $(x/D, y/D, z/D)=(1.0, 0.0, 0.0)$ is shown in Fig.2(b). Here, $St_D = fD/u_0$ is the Strouhal number. For verification of our simulation result, the spectrum from the DNS result for $M = 0.9$ and $Re = 3125$ by Bogey [10] is also shown. Three frequency peaks appear at $St_D = 0.47$, $St_D = 1.17$, and $St_D = 1.9$. These are the frequencies of the guided jet waves. However, Our result only corresponds to a $St_D = 0.47$ peak. Therefore, in this study, we focused on the frequency peak of $St_D = 0.47$, which is the first tone of the guided jet wave. From these results, sensitivity measurements were performed for 20 cases from $St_D = 0.1$ to $St_D = 2.0$ and 5 cases of $St_D = 0.42, 0.44, 0.46, 0.47, 0.48$.

3.2 Flow sensitivity measurement result

The results of the flow sensitivity measurement are shown in Fig.3(a) and 3(b). Fig.3(a) plots the time variation of the fluctuation kinetic energy k of each 25 frequency cases. In this study, the computation region of k is set to $0 < x/D < 3.0, -2.0 < y/D < 2.0$ and $-2.0 < z/D < 2.0$. Here, T is nondimensionalized by c_0 and D . The colored lines represent the case around the guided jet wave frequency $St = 0.4$ to $St = 0.5$, a black line shows the case that no point source is introduced, and gray lines show other cases. Fig.3(b) plots the maximum sensitivity values between $T = 0$ and $T = 400$ for each frequency case. From Fig.3(b), the highest sensitivity is found at $St_D = 0.47$, which is consistent with the frequency of the guided-jet wave, and no other results with large sensitivity are found. Moreover, from Fig.3(a), k in the case of $St_D = 0.47$ maximizes and decays around $T = 90$. If the acoustic wave generated at the point source at the end of the potential core is considered to travel in the jet core as a sound wave, it should propagate in the jet at $u/c_0 = -0.1$ due to the relative speed between the advection velocity of the jet flow $u/c_0 = 0.9$ and the

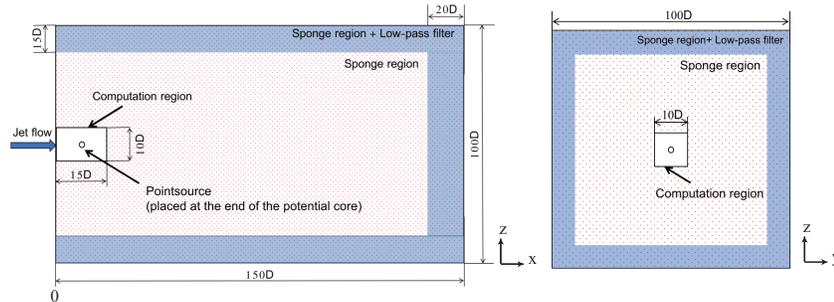


Fig. 1 Computation region in this study.

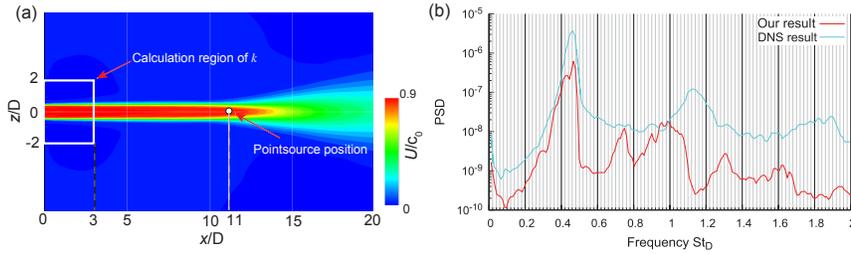


Fig. 2 Configuration of the flow-field of the jet. (a): Time-averaged velocity field of axial velocity. The contour ranges 0 to 0.9, from blue to red. The point source is placed at the end of the potential core, where the white circle is put in this figure. (b): Frequency spectra near the jet exit at $(x/D, y/D, z/D) = (1.0, 0.0, 0.0)$.

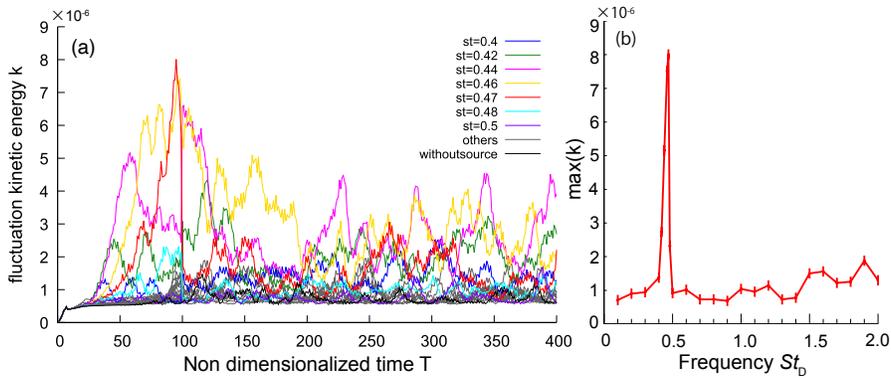


Fig. 3 Flow sensitivity measurement result. (a): Time variation result of the fluctuation kinetic energy k . (b): Relationship between $\max(k)$ for 3d jet and frequency of the pointsource.

speed of sound $u/c_0 = 1$. Since the point source position in this study is $x/D = 11$, the acoustic waves reach $x/D = 2.0$ at $T = 90$. Therefore, it is suggested that the acoustic waves in a jet core that have the guided jet wave frequency affect the flow instability near the jet exit from the relation between the arrival time and kinetic energy profile. From these results, the guided jet waves induce flow instability near the jet exit, which is considered a feedback loop phenomenon.

4 Conclusion

In order to investigate the relationship between the guided jet waves propagating upstream on the jet axis and the shear layer instability waves, which play a role in the feedback loop phenomena, flow sensitivity was measured three-dimensional free jet to the acoustic waves. As the flow sensitivity measurement method, a point

source oscillating at a single frequency is placed in the jet and the kinetic energy is measured near the jet exit. In this study, a point source placed in the jet is realized by the volume penalization method. 25 cases of point sources oscillating at $St_D = 0.1$ to $St_D = 2.0$ were measured. The results show that the point source with $St_D = 0.47$ has the highest sensitivity. The time variation of the sensitivity when a point source was placed corresponded to the time when the acoustic waves inside the jet reached the jet exit. This indicates that the acoustic waves generated at the end of the potential core affect the jet instability of the axisymmetric shear layer that occurs near the jet exit. This supports a feedback loop mechanism in subsonic-free jets.

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