Effect of Resonant Environment on Discrete Frequency Noise Generation from a Two-Dimensional Airfoil

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Abstract. It is known that discrete frequency noise with specific peak frequency, which is often called tonal noise, is generated from an airfoil in the flow conditions within certain Reynolds number range. In this study, the tone noise generated from the NACA0012 airfoil inclined at a small angle to the stream is investigated. The test has been conducted in two different configurations to clarify the effect of resonant environment on the noise generation: one is a duct configuration in which wall was installed at both sides across the airfoil, and the other is a wall-free configuration without any wall around the airfoil. The numerical simulation with lattice Boltzmann method (LBM) also has been conducted to investigate detailed generation mechanism of the tone noise. The experimental results show that the tone noise is generated with several peak frequencies in the wall-free configuration, while it has a single peak for the duct configuration. The simulation results are compared with the experiments at two configurations in terms of sound pressure spectrum, and the pressure fluctuation leading to the tone noise and the corresponding unsteady flow phenomenon are discussed to clarify the noise generation mechanism. A feedback loop is formed between the vortex shedding from separated blade surface boundary layer and the resulting aerodynamic sound at the trailing edge, which results in the tone noise.

1. Introduction

Fans are often used close to our living environments, such as air conditioner blowers, ventilation fans, and computer cooling fans. Therefore, the reduction of fan noise is one of the important issue to be addressed in the development of fans, not to mention the improvement in efficiency. It is known that discrete frequency noise (tone noise) with a specific peak frequency is generated from an airfoil at a certain Reynolds number condition. This is related to the generation of the fan noise, and many researches have been conducted to clarify the mechanism of tone noise generation [1-4].

Detailed experiments on the tone noise generated from an airfoil were conducted by Paterson et al. [5], who suggested that the tone noise was related to the laminar boundary layer on the pressure side of the airfoil. They also showed that the frequency of tone had a ladder-like structure. Tam [6] proposed a model of acoustic feedback loop between the trailing edge and the sound source in the wake, and stated that the sound source was induced by boundary layer instability. Arbey et al. [7] experimentally confirmed a feedback loop between the Tollmien-Schlichting (TS) wave, which was generated at the position of maximum velocity on the airfoil, and the out-of-phase acoustic wave due to diffraction at the trailing edge. While there are many studies on the cause of tone noise generation,
few studies have been conducted on the effects of surrounding wall on the aerodynamic noise, although it should be considered in the environment where fans are actually used.

In this study, the tone noise generated from the NACA0012 airfoil inclined at a small angle to the stream is investigated. The test has been conducted in two different configurations to clarify the effect of resonant environment on the noise generation: one is a duct configuration in which side walls were installed across the airfoil, and the other is a wall-free configuration with no obstacles around the airfoil. The numerical simulation with lattice Boltzmann method (LBM) also has been conducted to investigate detailed generation mechanism of the tone noise.

2. Experimental set-up

Figure 1 shows the outline of the wind tunnel used for the preset experiment, and Figure 2 shows the test section and sound measurement positions. The test section is placed in an anechoic room, and the position of the microphones was set at the midspan of the airfoil. The flow enters the test section, exiting from a contracted nozzle with a duct width of 250 mm and a duct height of 160 mm. The NACA0012 airfoil with the chord length $C$ of 80 mm is placed 200 mm downstream in the streamwise direction from the nozzle exit. In order to investigate the effects of sound reflection and resonance, the side wall made of sheet metal, which is detachable from the test section, is attached to the contracted nozzle exit on the both sides across the airfoil. To ensure the two dimensionality of the flow, the endwall made of a sound transmitting material is also provided on the upper and lower sides of the nozzle exit. A PVA sponge (Bell-eater DC(A), Fuji Chemical Industries, Ltd.) was used for the sound transmitting endwall. The length of the duct surrounded by the sound-transmitting endwall and the side walls is 600 mm. In the test, the nozzle exit flow velocity was set at 25 m/s, and the turbulence intensity was approximately 1%. For comparison, the test was also conducted in the wall-free configuration, in which the side wall was detached, as well as in the duct configuration.

![Figure 1. Illustration of test facility.](image1)

![Figure 2. Sound measurement points with microphones.](image2)

Figure 3 shows the tone noise generation conditions [8]. In the figure, open symbols correspond to the conditions in which the tone noise phenomenon has been observed, while filled symbols correspond to the conditions in which it was not observed. The red symbol indicates the flow condition for this study. Since the Reynolds number based on the chord length and the inlet flow velocity is $1.3 \times 10^5$ in the present study, the occurrence of tone noise is expected under the condition
with the angle of attack less than 5 degrees, as shown in the figure. The test was conducted by changing the angle of attack in one degree increments from 0 to 8 degrees. In the paper, we will discuss the result for the angle of attack of 3 degrees.

Figure 3. Tone noise generation conditions [8]. The red circle indicates the flow configuration for the present study.

3. Numerical method
In order to clarify the mechanism of sound generation from the airfoil, the numerical simulation was conducted. In this study, the lattice Boltzmann method (LBM) was chosen. Since discrete frequency sound is generated, it is considered that an acoustic feedback loop would be created. Therefore, to consider the acoustic feedback in the simulation, the acoustic field must be calculated coupling with the flow field calculation. The in-house simulation code was used in this study, which has been well validated [9, 10].

3.1. Lattice Boltzmann method
The lattice BGK (Bhatnager-Gross-Krook) equation is written as

\[ f_i(x + c_i \Delta t, t + \Delta t) = f_i(x, t) - \frac{1}{\tau} \left[ f_i(x, t) - f_{eq}^{i}(x, t) \right] \]  

where \( f \) is the particle distribution function, \( c \) is the particle velocity, \( f_{eq}^{i} \) is the local equilibrium velocity distribution function, \( \tau \) is the single relaxation time, and the subscript \( i \) represents the direction of particles’ motion. Fluid density and momentum are defined as follows:

\[ \rho = \sum_i f_i \]  

\[ \rho u = \sum_i f_i c_i \]  

The single relaxation time \( \tau \) has a relation with the kinematic viscosity \( \nu \), which can be written as the following equation.

\[ \nu = \frac{1}{3} \left( \frac{\tau}{2} - \frac{1}{2} \right) c^2 \Delta t \]  

As a discrete velocity model, the D3Q15 model was used in the present simulation [9]. Actually, the simulation was conducted in two dimensions by applying the periodical condition to the spanwise direction. As demonstrated by the fact that the tone noise does not occur when the boundary layer is in a turbulent state, it is reasonable to think that the inherent mechanism of the tone noise would be two dimensional and thereby could be captured by such two dimensional simulations [8]. However, it should be noted that actual flow, especially the boundary layer after the laminar separation, is not rigorously two dimensional.

The local equilibrium velocity distribution function for the D3Q15 model is given as follows:
where \( w_i \) is the weighting factor, which is defined as \( w_0 = 2/9 \), \( w_{1,6} = 1/9 \), \( w_{7,14} = 1/72 \).

### 3.2. Computational mesh

The computational mesh was generated by the Building-Cube Method (BCM) [11]. The BCM divides a computational domain into multiple cubes of various sizes, and each of which has a regular uniform spacing lattice with equal number of mesh points. By allocating small cubes to the vicinity of a body, the BCM generates locally refined grids. Each cube has a regular lattice with uniform spacing. Therefore, the mesh generated by the BCM is available for LBM computations, provided that the distribution functions are appropriately scaled in their exchange at the interface between the cubes with different mesh size [9, 10]. In addition, the BCM is suitable for parallel computations. Since all cubes have the same number of mesh points, it is easy to distribute computational tasks across multiple processors. In the present simulation, the computation was parallelized with the domain decomposition method using MPI.

Figure 4 shows the computational mesh. In the figure, the cubes generated by BCM are shown. The computational domain has the area of \( 60C \times 60C \) (4,800 mm \( \times \) 4,800 mm). The cube was subdivided into 15 stages and the grid points of 41 \( \times \) 41 are allotted to each cube, so that the minimum mesh spacing normalized by the chord length is \( 9.16 \times 10^{-5} \). This minimum mesh spacing was determined so as to satisfy the condition of \( y^+ < 1 \), assuming the flow is turbulent at the trailing-edge of the airfoil. Actually, however, turbulence cannot be captured since the simulation in this study is two-dimensional.

As shown in Figure 4 (c), the smallest cubes are placed around the blade suction surface near the trailing edge to accurately capture the vortex shedding. The total number of grid points for the wall-free configuration is 33.6M. In the duct configuration, the total number of grid points increases due to the presence of the side wall and it amounts to 85.4M.

### 3.3. Boundary conditions

The section indicated as “nozzle” in Figure 4 represents the nozzle discharge port, which corresponds to the inlet boundary. At the inlet, the velocity \( U_{in} \) was imposed and the local equilibrium distribution function calculated from that macroscopic quantity was given. Assuming that the inlet flow is uniform, \( U_{in} \) was set to 25 m/s, based on the nozzle exit flow velocity in the experiment. The bounce back scheme was used to specify the non-slip condition at wall. The wall section is indicated as “wall” in the figure. At the other outer boundary, the pressure was fixed and the velocity was extrapolated from the inner nodes next to the boundary. The local equilibrium distribution function was also used for the outer boundary condition. As previously mentioned, the periodic condition was applied to the spanwise direction for the two dimensional simulation.

![Figure 4. Computational mesh (only cubes are shown).](image-url)
4. Results and discussions

4.1. Effect of Resonant Environment

Figure 5 shows frequency spectra of the sound in the wall-free configuration. The pressure data used for the sound spectrum calculation are the ones obtained by Mic.1 through Mic.3 shown in Figure 2. The sound spectra of the simulation results were directly computed from the pressure data at the microphone positions, without using the acoustic analogy. In order to develop the flow into a quasi-steady flow, the simulations were conducted for more than 120 non-dimensional time before acquiring the unsteady pressure data. The non-dimensional time is defined based on the chord length and the mainstream velocity. The pressure data were acquired with the sampling frequency of 78.6 kHz. For the FFT analysis, data with 8,192 sampling points were used and ensemble averaging was performed for 10 sets of FFT analysis result. The result shows that the tone noise is a discrete frequency noise which has multiple peaks. In the experimental result, those peaks are observed at 1,716 Hz, 1,923 Hz, 2,127 Hz and 2,340 Hz, while they are found at 1,677 Hz, 1,840 Hz, 2,051 Hz and 2,387 Hz in the simulation result. The frequency and SPL values of the peaks in the simulation are a little different from those in the experiment. Although the quantitative difference remains between the experimental result and simulation result, the fact that the similar multiple peaks were reproduced means that the simulation succeeded in capturing the flow physics behind the tone noise generation. Therefore, the flow mechanism of the tone noise generation can be discussed based on the present simulation result.

![Figure 5. Sound spectra in the wall-free configuration. Red: Mic.1, Blue: Mic.2, Green: Mic.3.](image)

Figure 6 shows frequency spectra of the sound in the duct configuration. As is the case in Figure 5, the pressure data at Mic.1 through Mic.3 are analyzed. In the duct configuration, only a single peak is observed as the dominant sound. The peak frequency is 1,993 Hz in the experiment, while in the simulation it is 1,879 Hz, which is slightly lower and its SPL value is decreased. It should be considered that the switch of the number of peak in the sound spectrum is related to the acoustic effects due to the side wall. In fact, the change in the discrete frequency noise is attributed to

![Figure 6. Sound spectra in the duct configuration. Red: Mic.1, Blue: Mic.2, Green: Mic.3.](image)
resonance produced inside the duct, as mentioned later. The acoustic effect was well reproduced by the simulation.

4.2. Generation mechanism of the discrete frequency noise
In the previous section, it turned out that there was a difference in the sound spectrum between the two configurations. However, it is unclear what caused the difference. Therefore, in this section, the generation mechanism of tone noise is discussed based on the numerical simulation results.

Figure 7 shows a snapshot of vorticity distribution in two configuration cases. The figure shows that the boundary layer on the blade suction surface is separated to roll up at around the mid-chord, and the resultant vortices are shedding from the trailing edge. In the duct configuration, the vortices rolling up on the blade suction surface are arranged at regular intervals, whereas in the wall-free configuration, the vortices are found to be unequally spaced. Figure 8 shows pressure fluctuation distributions. In the wall-free configuration, the sound pressure waves are generated near the trailing edge and spreading in a concentric fashion. On the other hand, such sound waves are not clearly identified in the duct configuration, and instead antiphase pressure fluctuations are observed on the upper and lower sides of the airfoil.

Figure 9 shows frequency spectra of the time variation of lift. The dipole sound is dominant in a low Mach number flow such as the present case, so the fluctuation of fluid force acting on the airfoil is responsible for the sound generation. The lift variation is caused by the vortex shedding at the trailing edge. It follows that the vortex shedding from the trailing edge generates the discrete frequency sound of the tone noise. In fact, these peaks correspond with the frequency peaks of the tone noise shown in Figures 5 and 6. Compared to those figures, the peaks corresponding to the discrete frequency sound can be clearly confirmed in Figure 9.
Assuming that the sound generated by the vortex shedding from the trailing edge gives a feedback to the roll-up of shear layer, that is the boundary layer separation, the frequency of tone noise can be calculated as follows.

\[ f_n = \frac{n}{l_s} V \]  

(6)

where \( l_s \) is the distance between the separation point and the trailing edge, \( V \) is the convection velocity of separation vortex, and \( n \) corresponds to the number of separation vortices. Figure 10 shows the time variations of the separation point. The separation point is defined as the point where the wall shear stress takes zero. The abscissa denotes the axial distance \( x \) from the leading edge, which is normalized by the axial chord length \( C_x \). In the wall-free configuration, the separation point greatly varies with time compared to the duct configuration in response to the irregular vortex shedding. The time-average separation point is 0.48 \( C_x \) from the leading edge in the wall-free configuration and 0.43 \( C_x \) from the leading edge in the duct configuration. Figure 11 shows the convection velocity of shedding vortex. In the figure, the velocity is normalized by \( U_{in} \). By regarding the vortex center as a local minimum point in the pressure distribution on the blade surface, the convection velocity of the separation vortex passing through a certain observation point was measured. The convection velocity is shown only for the duct configuration in the figure. The estimation of the convection velocity failed in the wall-free configuration, because vortex coalescence sometimes occurred due to the irregular vortex shedding. Assuming that the vortex convection velocity is the same in both configurations, the figure shows that the vortex convection velocity is about 0.57 \( U_{in} \). Substituting \( l_s \) and \( V \) estimated from Figures 10 and 11 into Eq. (6), we obtain tone noise frequencies \( f_5 = 1,712 \) Hz, \( f_6 = 2,055 \) Hz, \( f_7 = 2,398 \) Hz for the wall-free configuration and \( f_6 = 1,875 \) Hz for the duct configuration. These frequency values agree very well with the results shown in Figure 9.

The vortex shedding can be considered to originate from the Kelvin-Helmholtz instability. Assuming that the actual acceptance point of perturbation due to the acoustic wave from the vortex shedding at the trailing edge is not the separation point but the blade leading edge, the equation is modified as follows.

\[ f_m = \frac{m}{C} V \]  

(7)

where \( C \) is the chord length and \( m \) represents the mode. Substituting \( m = 10, 11, 12, 13 \) into the above equation, we obtain the frequencies \( f_{10} = 1,781 \) Hz, \( f_{11} = 1,959 \) Hz, \( f_{12} = 2,138 \) Hz, \( f_{13} = 2,316 \) Hz, which correspond with the tone noise of the experiment shown in Figure 5. In the simulation, the suction surface boundary layer was separated and rolled up near the mid-cord, since the simulation was two dimensional. Actually, however, the growth of the disturbance would be slow and the rolling up of suction surface boundary layer would be near the trailing edge.
The frequency peak in the duct configuration is explained by the air column resonance, which is caused by a standing wave formed between the duct side wall and the airfoil. Figure 12 shows an illustration of the resonance model. The natural frequency of the standing wave formed between the side wall and airfoil is calculated as follows.

\[ f_n = \frac{n}{2l} c_0 \quad (n = 1, 2, 3, \ldots) \]  

(8)

where \( c_0 \) is the speed of sound and \( l \) is half-wavelength of the standing wave. Assuming that \( l \) corresponds with the chord length, we obtain the resonance frequency \( f_1 = 2,146 \) Hz with the speed of sound \( c_0 = 340.0 \) m/s. In practice, it is necessary to slightly correct \( l \) in consideration of the open-end correction. When calculating with \( l = 85 \) mm and 90 mm, the frequencies are \( f = 2,000 \) Hz and 1,889 Hz, respectively. These two frequencies correspond with the peak frequencies of the experimental result and numerical result, respectively. The vortex shedding from the trailing edge is thought to have locked in at this resonance frequency.

5. Conclusion
In this study, the discrete frequency noise (tone noise) generated from the NACA0012 airfoil inclined at a small angle to the stream was investigated. The test was conducted in two different configurations to clarify the effect of resonant environment on the noise generation: a duct configuration and a wall-free configuration. The findings are as follows.

(1) The simulation with the lattice Boltzmann method qualitatively agreed with the experimental result. The simulation results show that vortex shedding at the trailing edge due to laminar boundary layer separation on the blade suction surface is the cause of the tone noise.

(2) In the wall-free configuration, multiple peaks were observed as the tone noise, while it had a single peak in the duct configuration. In the duct configuration, a standing wave was formed between the duct side wall and the airfoil and the air column resonance is caused. The vortex shedding from the trailing edge was locked in at the resonance frequency, so that the noise had a single frequency.

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