inter noise
2013 | INNSBRUCK | AUSTRIA
15.-18. SEPTEMBER 2013
NOISE CONTROL FOR QUALITY OF LIFE

Measurement of velocity field in flows around a cascade of flat plates with acoustic resonance

Hiroshi Yokoyama[1], Katsuya Kitamiya[2], and Akiyoshi Iida[3]

[1, 2, 3]Department of Mechanical Engineering, Toyohashi University of Technology

1-1, Hibarigaoka, Tenpaku, Toyohashi-shi, Aichi, 441-8550, Japan

ABSTRACT

In order to clarify the effects of acoustic resonance on flows around a cascade of flat plates, aerodynamic noise and velocity field of the wake were measured. Five plates were placed parallel to a uniform flow. Separation-to-thickness ratio, s/b, was 6.0 and chord length-to-thickness ratio, C/b, was 15. Sound pressure level suddenly increases at specific freestream velocity of 44 m/s. At that velocity, the Reynolds number based on the thickness and the freestream velocity was 5.8×10^3. The spanwise and normal direction coherence of the velocity fluctuations in the wake were measured with two hot-wire anemometers. When the acoustic resonance occurs, the coherence between the velocity fluctuations in the wake of a plate and that of a neighboring plate becomes higher. This means that synchronization of the shedding of the vortices occurs in wakes of the neighboring plates. The coherence of normal direction was clarified to be high. When acoustic resonance occurs, the coherence between the velocity fluctuations in the wake of the plate in the spanwise direction also becomes higher. This means the structures of the vortices is two-dimensional. These synchronized structures of the vortices in the vertical and spanwise direction contribute to the reinforcement of the sound pressure level.

Keywords: Aeroacoustics, Measurement, Cascade of flat plates

1. INTRODUCTION

A huge noise often radiates from flows around a cascade of flat plates as shown in Figure 1. These configurations are found in front grille of automobile or louver. The flow field around circular cylinders and square cylinders placed vertical to a uniform flow has been studied by many investigators [1-2].

Bearman and Wadcock [1] measured the coherence of the velocity fluctuations in the wake by shedding of the vortices of two cylinders vertical to the flow with two hot-wire anemometers. The gap between the cylinders, s, was changed. The Reynolds number based on the freestream velocity and cylinder's diameter was 2.5×10^4. In case of $s/d = 4.0$, the velocity fluctuations in the wake of each circular cylinder was not correlated. As s/d approaches 1.33, the coherence becomes higher and the phase of the shedding of the vortices from two cylinders was anti-phase mode. Inoue and Suzuki [2] performed direct simulation based on compressible Navier-Stokes equation for three side-by-side square cylinders. The Reynolds number based on freestream velocity and one side of the square cylinder was 150. As a result, for $1.0 \le s/d \le 1.5$, the frequency of the shedding of the vortices from

---

[1] h-yokoyama@me.tut.ac.jp
[2] kitamiya@aero.me.tut.ac.jp
[3] iida@me.tut.ac.jp

each square cylinder equaled and synchronized. For $s/d \geq 2.0$, such synchronization didn't occur. In the previous study described above, the flow patterns in the wakes were clarified changing s/d. However the effects of acoustic resonance on the flows have not been argued. Parker [3] clarified that the sound from the flow around a cascade of flat plates increases at specific freestream velocity. This phenomenon is due to the coupling between vortex shedding in the wakes and the acoustic resonance between the flat plates. However the effects of the acoustic resonance on the flow field have not been clarified yet. And direct simulation has been performed for flows around a cascade of flat plates [4], but experimental data of coherence for the computational validation are lacking.

In the present paper, in order to clarify effects of acoustic resonance on flows around a cascade of flat plates, wind tunnel experiments were performed. In particular, we measured the coherence function of velocity fluctuations in spanwise and normal directions for resonant and non-resonant conditions with two sets of hot-wire anemometers. The separation-to-thickness is large enough that fluid dynamical interaction does not occur without acoustic resonance ($s/b = 6.0$) [1-2].

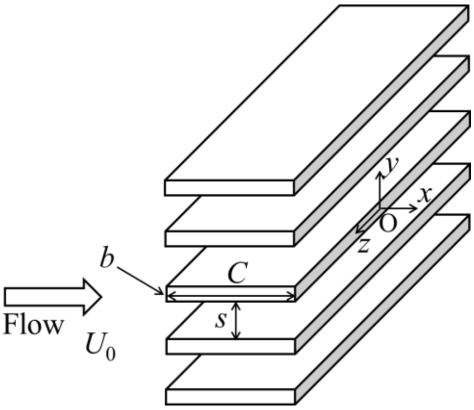


Figure 1 – Configuration of flow around a cascade of flat plates

2. EXPERIMENTAL METHODS

2.1 Flow Configurations

Table 1 shows the experimental parameters. The plate thickness, b, is 2 mm, and aspect ratio C/b is 15.0. The separation-to-thickness ratio, s/b, is 6.0 for the cascade of flat plates. Preliminary experiments have confirmed that acoustic resonance occurs in a half-wavelength mode along the chord length at $U_0 = 44$ m/s. In the experiments, the sound pressure level was measured with the configurations of $N = 1 \sim 6$, $C/b = 10 \sim 25$, and $s/b = 2.5 \sim 20$ ($N \geq 2$) at $U_0 = 10 \sim 50$ m/s, and the resonant frequency of the half-wavelength mode was found to be predicted by the empirical formula

$$f_{res} = 0.5\left(\frac{a_0}{C}\right) \Bigg/ \left(1+\alpha\left(\frac{s}{C}\right)^{\beta}\right), \alpha = 0.7, \beta = 0.84 \tag{1}$$

where a_0 is the speed of sound. At $U_0 = 44$ m/s, the Reynolds number based on the thickness and the freestream velocity is 5.8×10^3, and the freestream Mach number is $M = U_0/a_0 = 0.13$.

The plates are hereinafter referred to as plates A, B, C, D, and E starting from the top, as shown in Figure 2. The x, y, and z axes were set in the flow, normal, and spanwise directions, respectively. The experiments were performed for $N = 1$ and 5. The origin of the coordinate system is located on the spanwise middle x-y plane and at the midpoint between the upper and lower edges of the plate for $N = 1$ or plate C for $N = 5$, as shown in Figure 2. The sound pressure level at the point indicated by $x = 0$ and $y/b = 215$ was measured using a sound level meter with nondirectional 1/2 inch microphone at $U_0 = 20 \sim 60$ m/s for $N = 1$ and 5. The profiles of the mean and RMS values of the velocity in the wake ($x/b = 2.5$) were also measured using a hot-wire anemometer for $N = 5$ at $U_0 = 44$ m/s. Moreover, the normal and spanwise variations of the coherence function values of the velocity fluctuations were measured using two hot-wires at $U_0 = 30$, 44 and 55 m/s.

Table 1 – Experimental parameters

Thickness b [m]	Length C/b	Velocity U_0 [m/s]	Number of plates N	Distance s/b	Re_b (U_0 = 44 m/s)
2.0×10^{-3}	15.0	20 ～ 60	1, 5	6.0	5.8×10^{3}

2.2 Wind Tunnel

The experiments were conducted using the suction-type, low-noise wind tunnel, which was proposed by Rouse and Hassen [5] as shown in Figure 2. At a wind speed of 50 m/s, the freestream turbulence intensity was less than 1.0 %, the non-uniformity of mean flow velocity was less than 0.2 %, and the background noise level was suppressed to less than 73.5 dB.

In order to keep the two-dimensionality of flow, in the spanwise direction, the test section composed of the flat plates was terminated by two end walls. However, the metal end walls cause sound reflection [6]. Hence, the end walls were constructed of porous plates in order to suppress sound reflections. Figure 3 shows the suppressing effect of sound reflections. In the velocity range of this experiment, the peak is predicted to appear only once by formula (1). But using metal end plates, the peak appear twice. It seems to be due to the sound reflection in the spanwise direction to increase sound pressure level. Suppressing sound reflection using porous end plates, we could measure acoustic resonant sound only with a mode along the chord length direction.

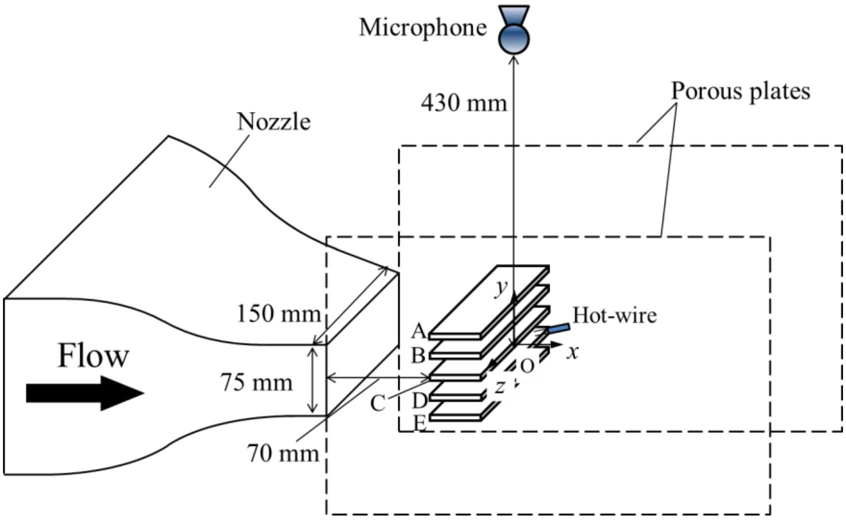


Figure 2 – Schematics of Experimental setup

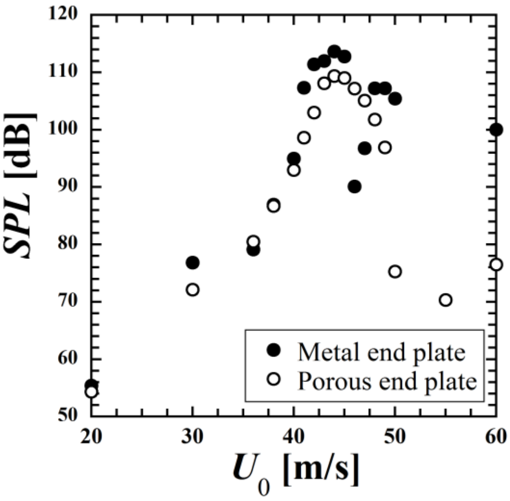


Figure 3 – Effect of the material of end plats on sound pressure level

2.2 Sound Measurement

We used a sound level meter with nondirectional 1/2 inch microphone, which was calibrated using an acoustic calibrator. The calibrator generates sound with 94.0 dB at 1000 Hz.

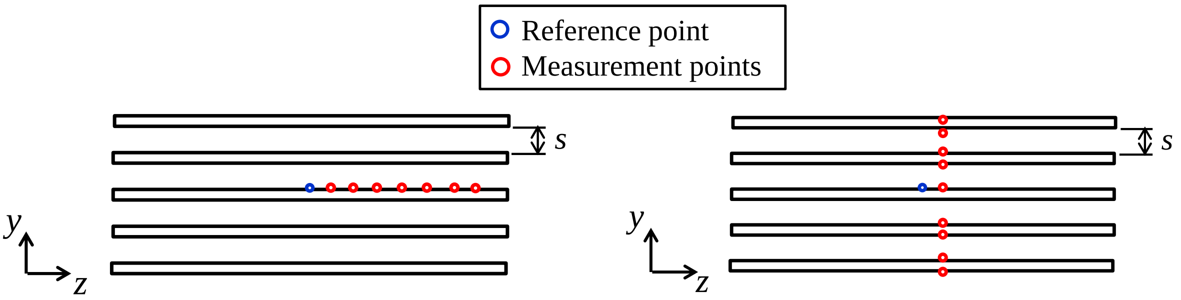
The freestrem velocity, U_0, was changed from 20 to 60 m/s for N = 1 and 5. In order to find velocity which the sound pressure level reaches maximum, the sound pressure level was measured by 1 m/s increments in the velocity range predicted acoustic resonance occurs (U_0 = 40 ~ 50 m/s). And the difference of the levels of tonal sound is compared.

2.3 Measurement of Velocity Field

A hot-wire anemometer [7] has been used for the measurement of velocity in turbulent flow fields. In our experiments, a hot-wire anemometer with I typed single wire with the diameter is 5μm and 1 mm length tungsten wire was used. The hot-wire anemometer was calibrated by formula (2) refer to King's law [8]. U is the velocity measured by a Pitot tube anemometer and E is the output voltage of hot-wire. We drew a calibration curve and determined the coefficients, a, b, and c, and the error was as to be within 1%.

$$U = \left(a + bE^2 + cE^4\right)^{2.22} \tag{2}$$

The measurement range of profiles of mean and RMS values of the velocity in the wake (x/b = 2.5) is -3.5 ≤ y/b≤ 3.5. Figure 4 shows measurement points of coherence function values. The diameter of the hot-wire probe is 4 mm. To avoid the interaction of hot-wire probes, the minimum distance between hot-wires were set at 5 mm.



(a) Spanwise direction (b) Normal direction

Figure 4 – Measurement points of coherence function values

2.4 Data Analysis

For the sound measurements, the measurement time was 30 s and the sampling frequency was 40 kHz. The frequency resolution was ΔSt = $\Delta fb/U_0$ = 0.00044 for U_0 = 44 m/s. The sound pressure spectrum was averaged 584 times.

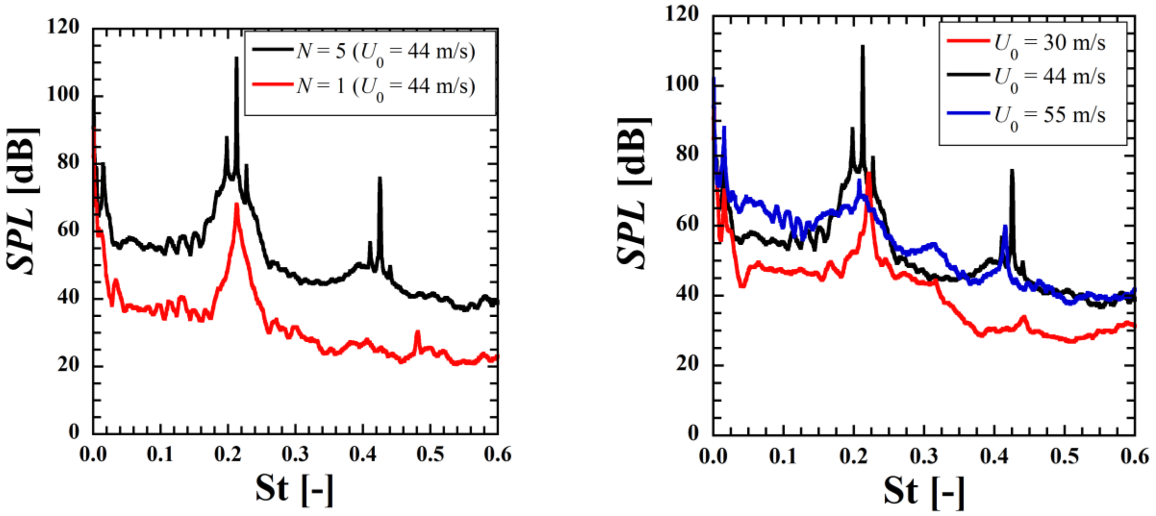
For the measurement of velocity fields, the measurement time was 60 s and the sampling frequency was 40 kHz. The frequency resolution was ΔSt = $\Delta fb/U_0$ = 0.00044 for U_0 = 44 m/s. The average number with reference to time for the calculation of the power spectra and the coherence function values is 1170 times.

3. RESULTS AND DISCUSSION

3.1 Sound Pressure

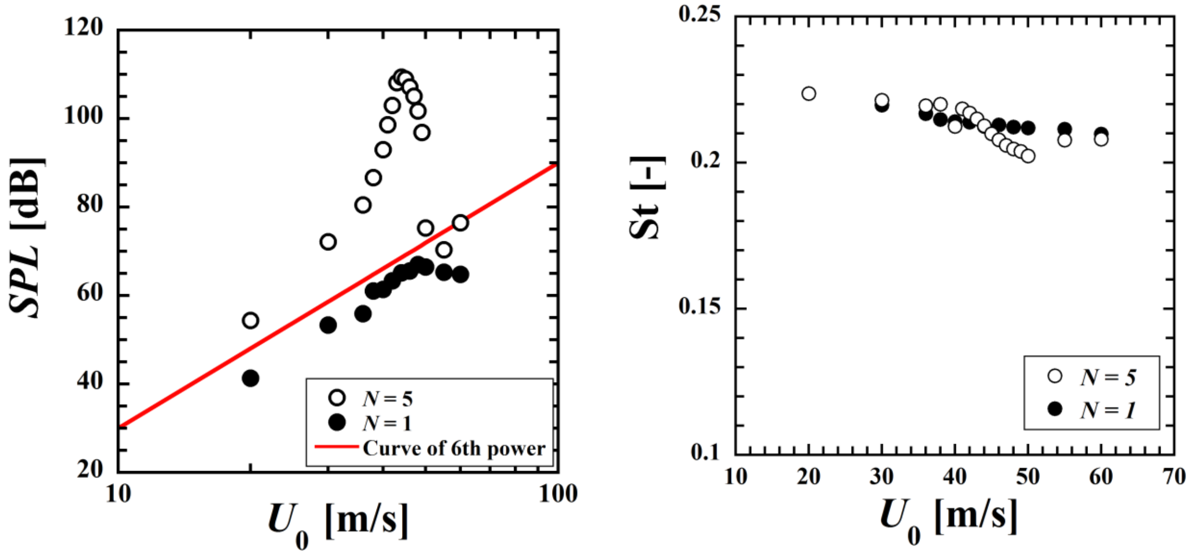
Figure 5(a) shows the sound pressure spectra for N = 1 and 5 at U_0 = 44 m/s. Although both spectra have peak at St = fb/U_0 = 0.21, the peak level for N = 5 is much higher than N = 1 because the acoustic resonance does not occur for N = 1. Figure 5(b) shows the sound pressure spectra at U_0 = 30, 44, and 55 m/s for N = 5. The peak level at U_0 = 44 m/s is much higher compared to U_0 = 30 and 55 m/s due to the coupling between the shedding of the vortices from the flat plates and acoustic resonance between the flat plates.

Figure 6(a) shows the influence of the freestream velocity on the level of the tonal sound for N = 1 and 5. In the result, there is a peak at U_0 = 44 m/s for N = 5, whereas the level of proportional to the sixth power of the velocity for $N = 1$. Acoustic resonance occurs at this velocity for $N = 5$. The resonant frequency predicted by formula (1) is 4323 Hz and the measured frequency at $U_0 = 44$ m/s is 4677 Hz. The difference is considered the number of plates. Preliminary experiment performed mainly for $N = 3$, whereas this experiment performed for $N = 5$. And so, the resonant frequency predicted by formula (1) becomes low. These frequencies approximately agree, and so the mode of the occurring acoustic resonance is considered to be measured. The freestream velocity $U_0 = 30$ and 55 m/s are determined as a non-resonant condition because the levels of tonal sounds are much lower than that at $U_0 = 44$ m/s. Figure 6(b) shows the influence of freestresm velocity on the Strouhal number. For $N = 1$, the Strouhal number is almost 0.21 for all the velocities. This indicates that the shedding of the vortices does not depend on freestrem velocity. For $N = 5$, the Strouhal number is almost 0.22 except velocity range for the occurrence of the acoustic resonance ($U_0 = 40 \sim 50$ m/s). When acoustic resonance occurs, it is considered that the acoustic resonance locks the frequency of the shedding of the vortices.



(a) (b)

Figure 5 – Sound pressure spectra (a) Effect of plate number at $U_0 = 44$ m/s (b) Effect of freestream velocity for $N = 5$ ($U_0 = 30$, 44 and 55 m/s)



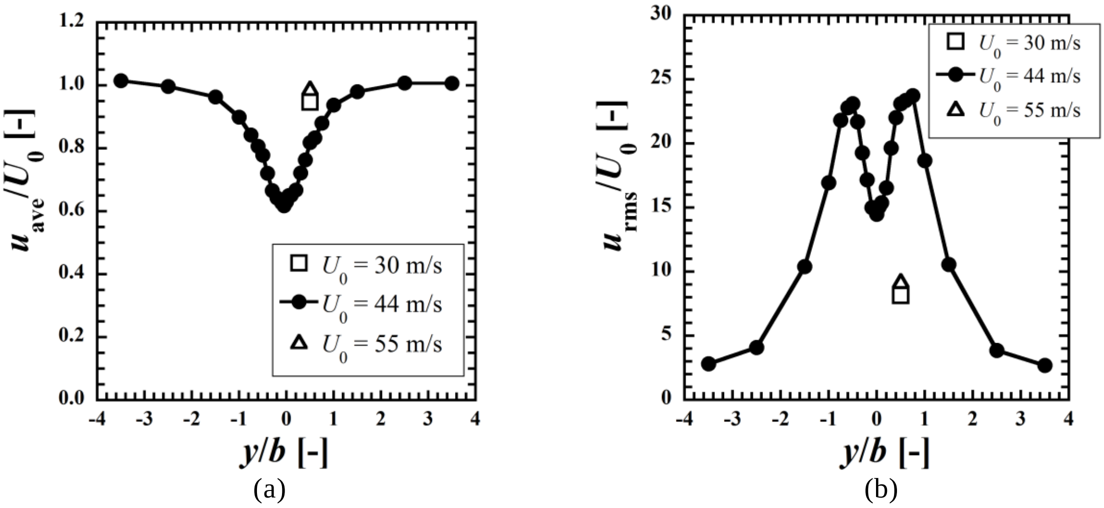
(a) (b)

Figure 6 – Influence of freestream velocity (a) Tonal sound levels at $x = 0$ and $y/b = 215$ (b) Strouhal number

3.2 Intensity of Vortices

Figure 7 shows profiles of the measured velocity, u, in the wake (x/b = 2.5) for N = 5 at U_0 = 44 m/s. The mean velocity profile is almost symmetry and reach a minimum at y/b = 0. The half-value breadth is about y/b = ±0.5. In the wake between the plates, the measured velocity to freestream velocity ratio, u_{ave}/U_0, becomes almost 1.0 and the RMS values is small. These profiles are nearly equal to the results of flows around a circular cylinder [9-10]. From those results, fluid dynamical interaction between neighboring plates is considered to do not occur. The RMS values profile is also almost symmetry and reach a maximum at y/b = ±0.5 due to vortices shed from upper and lower edge of the plate. In order to clarify vortical structures, coherence functions of the velocity fluctuations were measured along this line because the two-dimensionality of the vortices shed from the plates affects the sound pressure level.

Figure 8 shows the power spectra of u for N = 5 at y/b = 0.5, where is non-dimensionalized by the freestream velocity, U_0. The non-dimensional peak level at U_0 = 44 m/s is much higher than those at U_0 = 30 and 55 m/s. This result indicates that the acoustic resonance intensifies the power of the velocity fluctuations of the shed vortices.



(a) (b)

Figure 7 – Measured velocity, u, profiles (x/b = 0.25, N = 5, U_0 = 44 m/s) (a) Mean values (b)RMS values

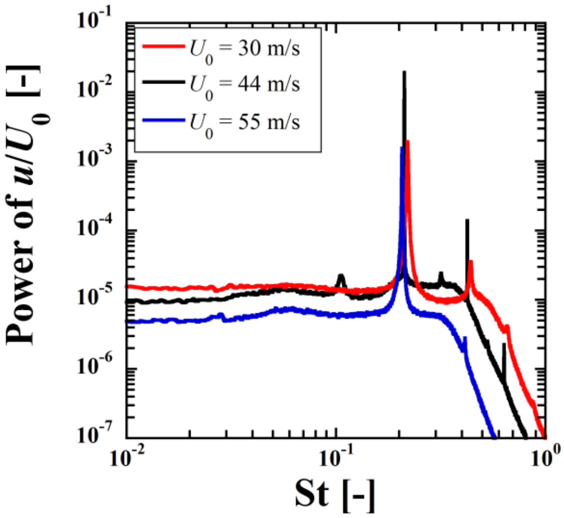


Figure 8 – Power spectra of u/U_0 for N = 5 at y/b = 0.5 (U_0 = 30, 44 and 55 m/s)

3.3 Coherence of Vortices

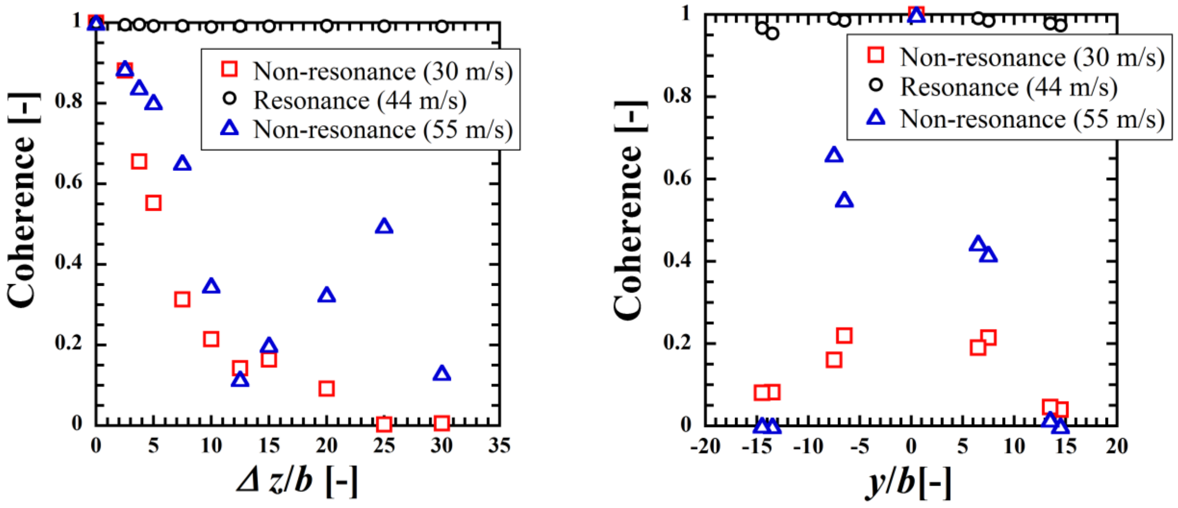
In order to clarify the effects of acoustic resonance on vortices structure, the spanwise and normal directions coherence function of the velocity fluctuations in the wake of the cascade of flat plates were measured with two sets of hot-wire anemometers. Figure 9(a) shows measured coherence function values of the velocity, u, at two points with the distance Δz in the spanwise direction in the wake of plate C ($x/b = 2.5$, $y/b = 0.5$) for $U_0 = 30$, 44 and 55 m/s.

The results indicate that the coherence function values becomes almost 1.0 for all distances for resonant condition of $U_0 = 44$ m/s, whereas the values decrease as Δz becomes lager for the non-resonant condition both of $U_0 = 30$ and 50 m/s. These results indicate that vortex shedding becomes more synchronized in the spanwise direction for the resonant condition. As a result, when very strong tonal noise is radiated, vortex structure is seems to be intensified furthermore.

In the cases of both of non-resonance condition, the coherence functions were decreased with increasing Δz such as the velocity correlation of a homogeneous turbulence. In the case of $U_0 = 30$ m/s, the coherence function is similar to random motion. However, in the case of $U_0 = 55$ m/s, the values become higher for $15 \leq \Delta z/b \leq 25$. In general the coherence function of the high-Reynolds number flow rapidly decreases. It is therefore difficult to describe to the reason that the coherence increased again in this area. In order to eliminate the vibration of the equipment, the effects of resonance between the side plate, error of the hot-wire anemometer and so on, we conducted experiments under various conditions. Moreover, to confirm the reproducibility of the error factors, similar results were always obtained. We believe this is not the result specific to our experimental apparatus, but a reasonable explanation of the increasing of the coherence function at high Reynolds number flow now cannot be. We could like to consider it for our future work.

Figure 9(b) shows the coherence function value between the velocity, u, at $x/b = 2.5$, $y/b = 0.5$, $\Delta z/b = 0$ and those at points along $x/b = 2.5$, $\Delta z/b = 2.5$ for $U_0 = 30$, 44 and 55 m/s. At the reference position of $x/b = 2.5$, $y/b = 0.5$, $\Delta z/b = 0$, the vortices shed from plate C. We focus on the coherence function value at $y/b = \pm 6.5$ and ± 7.5, where the vortices shed from the neighboring plate (plates B and D). The results indicate that the value at $y/b = \pm 6.5$ and ± 7.5 for the resonant condition are obviously higher those for the non-resonance conditions. This indicates that the vortex shedding of one plate and that of the neighboring plates become more synchronized for the resonant condition.

The results showed that not only strong coherent structures in the spanwise direction in the wake of the flat plates, coherent structures are also aligned in the normal direction. Bearman and Wadcock [1] showed the velocity fluctuations in the wake of circular cylinder array were not correlated at $s/b > 4.0$. In the case of non-resonant condition, there is no correlation to flow between the plates as well as the result of Bearman and Wadcock [1]. However, when the acoustic resonance occurs, a strong correlation is observed in spite of the $s/b > 4.0$ conditions. According to Figure 8, the velocity fluctuations are intensified when acoustic resonance occurs. It reveals the acoustic resonance between plates make strong vortical structure. Moreover, the phase of the vortex shedding from the upper and lower plates seems to be anti-phase mode such as the results of Bearman and Wadcock [1].



(a) (b)

Figure 9 – Variation of coherence function value of u (x/b =2.5) (a) Coherent function values of the velocities u at two points with spanwise distance Δz along the line $x/b = 2.5$, $y/b = 0.5$ (b) Coherent function values between the velocity u at $x/b = 2.5$, $y/b = 0.5$, $z/b = 0$ and those at points along the line $x/b = 2.5$, $\Delta z/b = 2.5$

4. CONCLUSIONS

In order to clarify the effects of acoustic resonance on flows around a cascade of flat plates, aerodynamic noise and velocity field of the wake were measured. The sound reflection in the spanwise direction is suppressed using porous end plates. From this result, acoustic resonant sound generated between the flat plates is measured accurately.

For $N = 5$, the sound pressure level increases suddenly at specific freestream velocity of 44 m/s. The level of tonal sound for $N = 5$ at $U_0 = 44$ m/s is much higher than those at other velocity. This means that acoustic resonance occurs at this velocity. And the velocity fluctuations are intensified by the acoustic resonance. The Strouhal number for $N = 5$ decreases in the velocity range for the occurrence of the acoustic resonance. This means that it is considered that the acoustic resonance locks the frequency of the shedding of the vortices.

The measured coherent function value of u indicated that the shedding of the vortices from neighboring plates is synchronized for the resonant condition. Moreover, the shedding of the vortices in the spanwise direction is also synchronized for the resonant condition. These synchronized structures of the vortices in the normal and spanwise direction contribute to the reinforcement of the sound pressure level.

ACKNOWLEDGEMENTS

The present study was supported by a Grant-in-Aid for Scientific Research 24760134 and through the Next-generation Supercomputer Strategy Program by the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT).

REFERENCES

[1] P. W. Bearman and A. J. Wadcock, “The interaction between a pair of circular cylinders normal to a stream,” J. Fluid Mech., 61, 499-511 (1973)

[2] O. Inoue and Y. Suzuki, “Beat of sound generated by flow past three side-by-side square cylinders,” Phys. Fluids 19 , 048102 (2007)

[3] R. Parker, “Resonance effects in wake shedding from parallel plates: Some experimental observations,” J.Sound Vib., 4(1), 62-72 (1966)

[4] H. Yokoyama, K. Kitamiya, and A. Iida, “Direct simulation of acoustic radiation with resonance in flows around a cascade of flat plates,” Proc. INTER-NOISE 2013, No.1084 (2013)

[5] H. Rouse and M. M. Hassen, “Cavitation-free inlets and contractions (Electrical analogy facilitates design problem),” Mech. Engng., 71, 213-416 (1949)

[6] W. K. Blake and D. A. Lynch III, “Source characterization by correlation techniques,” in Aeroacoustic measurements, T. J. Mueller, Ed., Springer-Verlag: Berlin, Heidelberg & New York (2002)

[7] S. C. Morris and J. F. Foss, “Transient thermal response of a hot-wire anemometer,” Meas. Sci. Technol., 14, 251–259 (2003)

[8] L. V. King, “On the Convection of heat from small cylinders in a stream of fluid: Determination of the convection constants of small platinum wires with applications to hot-wire anemometry,” Phil. Trans. R. Soc. Lond. A214, 373-432 (1914)

[9] L. S. G. Kovasznay, “Hot-wire investigation of the wake behind cylinders at low Reynolds numbers,” Proc. R. Soc. Lond., A15, 198, 174-190 (1949)

[10] L. Ong and J. Wallace, “The velocity field of the turbulent very near wake of a circular cylinder,” Exp. in Fluids, 20 441-453 (1996)