Analysis of Aerodynamic Sound Source with Measurement of Static-Pressure Fluctuation*

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The objective of this investigation is to develop a method for detecting the aerodynamic sound source in a low-Mach number turbulent wake. We therefore introduced coherent output power (COP) in terms of surface pressure and vorticity fluctuation to evaluate vorticity contribution to aerodynamic sound generation. Moreover, aerodynamic sound source was calculated by using a modified Lighthill-Curle's equation; that is, surface pressure fluctuation was replaced by COP. It was found that the intensity of COP corresponds to the distribution of the aerodynamic sound source caused by unsteady vorticity fluctuation. It therefore more directly reflects the aerodynamic aspects of the sound source. And we measured the distribution of aerodynamic sound source in the wake of a circular cylinder with Reynolds number of 4.0×10^4 . This measurements show that aerodynamic sound is generated near the formation region of Karman vortices. It is therefore concluded that the separated shear layers play an important role in generating aerodynamic sound. Moreover, our identification method by using COP can successfully evaluate aerodynamic properties of a sound source.

Key Words: Aerodynamic Acoustics, Noise, Pressure Distribution, Vortex, Wake, Turbulent Flow, Flow Measurements

1. Introduction

The maximum speed of high speed trains has been in an upward trend for several years⁽¹⁾. Cooling flow rates inside air conditioners and computers are also increasing. Consequently, aerodynamic noise radiated from these products is rapidly increasing, because aerodynamic noise is proportional to the sixth power of flow velocity. Aerodynamic noise must therefore be reduced in these products. Much research has been directed at noise reduction and prediction in product development.

Since Mach number of the flow velocity in these

products is comparatively small (under 0.3 in the case of high-speed trains) and the wavelength of resulting aerodynamic sound is larger than the size of these products, the radiated aerodynamic sound can be formulated by Lighthill-Curle's theory⁽²⁾. Therefore, the aerodynamic sound source is conventionally investigated by using surface pressure fluctuation, which acts as a dipole source, as formulated in Lighthill-Curle's equation. Then this type of aerodynamic sound is called dipole sound. This theory is useful for estimating the aerodynamic sound. The authors⁽³⁾⁻⁽⁵⁾ showed the coherence length of the surface pressure fluctuation is also an important factor in calculating aerodynamic sound. The calculated aerodynamic sound is in good agreement with the measured one, provided that the coherence length is taken into account. The accuracy of the prediction is less than ± 1 dB; therefore, Lighthill-Curle's theory is generally known to be the most convenient theory currently available. And the coherent length revealed that aerodynamic sound depends on the eddy structure of the flow field. Therefore, destruction of the eddy

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structure effectively reduces the aerodynamic sound.

Moreover, as computer technology rapidly improves, computational fluid dynamics can be applied to more complicated problems. And high-performance computers can calculate an unsteady-turbulent flow field. As a result, aerodynamic sound can now be numerically calculated⁽⁶⁾⁻⁽⁹⁾. Kato et al.^{(6),(7)} numerically calculated the aerodynamic sound spectrum by using a 'large eddy simulation' and Lighthill-Curle's theory. And their predicted aerodynamic sound spectra are in good agreement with those from a wind tunnel experiment. Predicting aerodynamic sound by Lighthill-Curle's theory will therefore become popular in industrial fields.

However, Lighthill-Curle's theory gives us no information about the relationship between unsteady vorticity fluctuation and aerodynamic sound. That is, it only shows aerodynamic sound is generated by surface pressure fluctuation or aerodynamic forces. This theory is intuitively easy to understand because it does not include the relationship between 'complicated unsteady vorticity fluctuation' and aerodynamic sound; it requires surface pressure fluctuation only. We therefore cannot obtain the vortex contribution to aerodynamic sound generation by using Lighthill-Curle's theory.

If aerodynamic sound is reduced during development of new products, the surface pressure fluctuation is also reduced. However, it is difficult to clarify which part of the flow contributes to the generation of the aerodynamic sound. So we cannot obtain the general criterion for reducing aerodynamic sound. From the aerodynamic point of view, even in a low-Mach-number wake, we have to consider that the relationship between vorticity fluctuation and aerodynamic sound in order to reveal the origin of aerodynamic sound. We therefore attempt to measure the coherence between aerodynamic sound and unsteady vorticity fluctuation. Here we assumed that unsteady vorticity fluctuation generates aerodynamic sound. In order to distinguish an aerodynamically sound source from a conventional sound source of Lighthill-Curle's theory, unsteady vorticity fluctuation is defined as a 'true sound source'. And surface pressure fluctuation is assumed to be an 'apparent sound source'.

We developed a quantitative method for identifying an aerodynamic sound source; it is based on Lighthill-Curle's theory and the correlation analysis between a 'true sound source' and an 'apparent sound source'. This identification method was applied to the aerodynamic sound radiated from a circular cylinder at Reynolds number of 4×10^4 . In this experiment, because static-pressure fluctuation is closely related to

vorticity fluctuation, static-pressure was used to evaluate the unsteady vorticity fluctuation. And it is easier to measure surface pressure fluctuation than vorticity fluctuation. The identification of aerodynamic sound showed that the aerodynamic sound radiated from the circular cylinder is generated near the formation region of Karman vortices. It is therefore concluded that the separated shear layers play an important role in generating aerodynamic sound.

Nomenclature

- D : diameter of the circular cylinder
- f : frequency
- p : sound pressure level
- P_s : surface pressure fluctuation
- P : static-pressure fluctuation
- P_c : coherent output power in terms of surface pressure and vortex motion
- Re : Reynolds number $= UD/\nu$
- U : velocity of uniform flow
- u : instantaneous velocity of streamwise component
- v : instantaneous velocity of vertical component
- ω_z : spanwise vorticity fluctuation
- X : streamwise direction
- Y : vertical direction
- Z : spanwise direction
- ρ : density of air
- θ : angle of pressure tap position from forward stagnation region on the cylinder surface
- ν : kinematic viscosity of air
- ϕ : phase angle of conditional sampling

2. Experimental Apparatus

2.1 Vorticity probe

To estimate the vorticity contribution to aerodynamic sound generation, it is necessary to measure vorticity fluctuation and surface pressure fluctuation, simultaneously. However, measurement of instantaneous vorticity fluctuation in a turbulent flow field is difficult because the turbulent flow field has various size of eddies. High resolution of the vorticity probe is therefore necessary both in time and spatial domains. As a vorticity probe to satisfy such conditions, a probe combining four hot-wire vorticity probe was developed as shown in Fig. 1⁽¹⁰⁾. This probe is composed of a parallel I-type probe and an X-array probe. The parallel array probe measures velocity fluctuation in the streamwise direction. This velocity is then used to calculate cross-section gradient, $\partial u / \partial y$. The X-array probe measures the cross-stream component, which is used in Taylor's hypothesis to transform temporal derivatives into streamwise derivatives, $\partial v / \partial x$. The vorticity hot-wires can therefore

measure instantaneous spanwise vorticity, $\omega_z = (\partial u / \partial y - \partial v / \partial x)$.

In order to evaluate the resolution of the vorticity probe, vorticity fluctuation in a two-dimensional jet (slit width, $2h=1$ cm; slit height 40 cm) was measured. Makita et al.⁽¹¹⁾ showed that the eddy structure of a two-dimensional jet can be controlled by using an acoustic wave from an external loudspeaker. The experimental conditions are thereby stabilized and the vorticity structure can be measured. And the two-dimensional excited jet is therefore suitable for evaluating the performance of the vorticity probe.

The vorticity distribution was measured by using the vorticity probe and was compared with that measured by the conditional sampling method by Makita et al. Figure 2 compares the vorticity distribution at $X/2h=5$ to 8.5 in the two-dimensional jet. This figure shows that measurement error of the vorticity probe is about 10%. Since the vorticity calculation requires the signal from four hot-wires, the measurement accuracy of the vorticity probe depends on the dispersion of the calibration error of each hot-wire. Moreover, the probe is sensitive to temperature drift. The accuracy of the vorticity probe is thus lower than that of the conventional velocity measurement, and calibration is difficult. And if the sensor is to be used for product development, simple and easy calibration is essential. Methods for more conveniently measuring the flow field of the wake are therefore necessary.

2.2 Static-pressure probe

Shirahama and Toyoda^{(12),(13)} showed that static-pressure fluctuation is closely related to vorticity fluctuation in an axial round jet. We therefore estimated the relationship between aerodynamic sound and static-pressure fluctuation instead of vorticity fluctuation. The static-pressure measurement is superior to vorticity measurement because derivative operation is not necessary. And both static-pressure and aerodynamic sound are physical quantities. Static-pressure can be therefore directly converted to aerodynamic sound.

Professor Toyoda^{(12),(13)} of the Hokkaido Institute of Technology, developed a static-pressure probe

Fig. 1 Vorticity probe

(Fig. 3) for measuring static-pressure fluctuation. This sensor has a static-pressure tube of about 1 mm diameter and about 55 mm length with eight pressure holes of 0.4 mm diameter. The tip of the tube is cut so that the flow is not disturbed. The pressure wave is measured by a condenser microphone (1/4-inch diameter) installed at the other end of the pressure tube.

2.2.1 Frequency responses The microphone used for measuring pressure gives a frequency response that is flat to about 40 kHz; however, a resonance occurs at low frequency when pressure is measured through a long pressure tube such as this static-pressure probe. The half wavelength of the resonance corresponds to the cavity of the pressure tube (40 mm in this probe). This is because the pressure plane of the microphone is bigger than the diameter of the static-pressure tube. So the volume between the pressure-tube and the microphone rapidly increases. As a result, Helmholtz resonance is also generated.

The frequency characteristics of the static-pressure probe must therefore be estimated beforehand. To do this, the random noise is generated in the chamber by a loudspeaker. And the frequency response between the static-pressure probe and the reference microphone is shown in Figs. 4 and 5. The resonant frequency of the organ pipe and that of Helmholtz resonance is about 4 250 Hz and 1 930 Hz, respectively. Since Helmholtz resonant frequency is lower than that of the organ pipe at present study, the upper frequency of the static-pressure probe is limited

Fig. 2 Precision of vorticity measurements, ω_{zc} : Conditional sampling method, ω_{zp} : Present method

Fig. 3 Static-pressure probe

Fig. 4 Gain property of static-pressure probe
—: Calculation, ○: Experiment

Fig. 5 Phase property of static-pressure probe
—: Calculation, ○: Experiment

by Helmholtz resonance. It is thus possible that the Helmholtz resonance can be calculated by a single oscillatory system consisting of a mass and a spring. Theoretical lines are drawn in Figs. 4 and 5 in order to compare measured and calculated. These figures show that the frequency responses of the pressure probe are both a nearly-flat 1.5 kHz.

3. Experimental Measurement and Analytical Calculation

3.1 Experimental method

A low-noise wind tunnel was used in the experiments. It has a square test section of 500 by 500 mm and a length of 2 600 mm as shown in Fig. 6. This wind tunnel has an intensity of turbulence of less than 0.2% and a nonuniformity of the velocity distribution about 1% or less at a flow velocity of 30 m/s. And background noise of this wind tunnel is less than 30 dB at a flow velocity of 15 m/s. Velocity and static pressure are measured by a three-dimensional traversing unit mounted on the test section.

A metallic circular cylinder with a diameter D of 40 mm and a length L of 500 mm was fixed horizontally in the test section and positioned 0.25 m from the end of the contraction nozzle. The origin of the coordinate system was located at the center of the test

Fig. 6 Schematic diagram of experimental apparatus

cylinder. And the flow direction and vertical direction correspond to the X and Y axes, respectively; therefore, the spanwise direction of the cylinder is the Z axis (as shown in Fig. 6). All the distances were normalized with the diameter of the test cylinder. The experiment was done at a mean flow velocity of 15 m/s and a Reynolds number of 4.0×10^4 . And the fundamental frequency of a Karman vortex was 75 Hz.

In order to decrease blockage of the traversing unit in the test section, the upper floor of the test section moves horizontally with the traversing mechanism. The vertical support is the only part of the traverse inserted in the test section. The blockage of the traverse unit is therefore less than 3%. The vorticity probe and static-pressure probe were installed horizontally (separated by 6 mm) on the traverse unit. The vorticity fluctuation ω_z and static-pressure fluctuation P were simultaneously measured at $X/D=1.25-7.00$ and $Y/D=-1.4-1.4$ in the wake of the circular cylinder. All data were digitized by a data-acquisition system (Masscomp MC6500 computer) with a 12-bit A/D converter at a sampling frequency of 5 kHz. There are 21 measuring points in the X direction and 29 points in the Y -direction. And the total number of the measuring points for the wake measurement is 609 points. At each measurement point, data was collected for 20 sec.

The test cylinder had twelve pressure taps (an array of eleven taps and one reference tap) fabricated on the cylinder surface. Condenser microphones with a diameter of half an inch were embedded in the cylinder. And surface pressure fluctuation was measured through pressure taps of 1 mm diameter and about 1 mm length. Since the Helmholtz resonance frequency of the pressure tap is about 1 380 Hz, gain and phase errors are respectively less than 3 dB and 5 degrees at frequencies lower than 800 Hz. Since under

our experimental conditions, the dominant frequency of the pressure fluctuation lies between 50 and 300 Hz, the measurement does not influence the Helmholtz resonance.

The eleven pressure taps are separated by $0.375 D$ in the spanwise direction, and spanwise distribution of surface pressure was measured at θ of 0 to 180 degrees from the forward stagnation point. The surface pressure was also recorded by the data-acquisition system simultaneously. Then, the correlation between static-pressure fluctuation (or vorticity fluctuation) and surface pressure fluctuation was calculated.

If the modulation of low frequency is removed, surface pressure fluctuation at θ of 60 degrees from the forward stagnation point can be considered a sinusoidal wave with a fundamental frequency of Karman vorticity. The trigger signal for conditional sampling was therefore obtained at θ of 60 degrees. The measured data in the wake are averaged at the same phase-angle of the trigger signal.

The scale of the turbulence eddy in the streamwise direction can be evaluated by using the reciprocal of the wave number k of $U/(2\pi f)$. The streamwise scale of Karman vorticity in this study can therefore be considered to be about 30 mm. According to the upper limit of the measurable frequency of the vorticity and static-pressure probes, the smallest scale is 2.5 and 2 mm, respectively. The spatial resolution of the probes is therefore sufficiently smaller than the streamwise scale of the fundamental vorticity.

The time required for the conditional sampling is generally long. Therefore, it is necessary to keep the conditions of the sensors. Moreover, the flow field also be constant during the experiment. In this study, measuring time was set to two hours, and the sensors were calibrated every two hours. And the averaged velocity and pressure were checked at a reference position. It takes about eight hours to measure the whole wake. The experiment was conducted two times, and was confirmed that the average velocity and intensity of turbulence did not change during the experiments.

3.2 Identification of aerodynamic sound source

A microphone array⁽¹⁴⁾ and a parabola microphone⁽¹⁵⁾ are usually used to measure sound source distribution. In such an acoustic method, the element size of the measurement equipment is proportional to the wavelength of the sound source. To measure the fundamental frequency (about 75 Hz), the size of the array must be over 3 m long. The length of the array is therefore longer than the length of the test section. In addition, space resolution of the acoustic measure-

ments is limited by the wavelength. That is, the space resolution is about 1.5 m at a frequency of 100 Hz. However, the largest scale of the flow field is about 40 mm in the present investigation, which corresponds the diameter of the test cylinder. In general, the scale of the acoustic field is sufficiently larger than the scale of the flow field. This is clear because the ratio of representative scale of the sound and representative scale of the flow field is proportional to the reciprocal of Mach number in a low-Mach-number flow field.

And the ratio of the dipole sound and vortex sound (quadrupole) is proportional to the square of Mach number. The dipole source thus dominates aerodynamic sound field in a low-Mach-number flow. Thus, acoustic measurement shows that only the surface pressure corresponds to aerodynamic sound source. Therefore, we cannot examine the relation between unsteady vorticity fluctuation and aerodynamic sound.

From the aerodynamic point of view, we have to consider that the relationship between vorticity fluctuation and aerodynamic sound in order to reveal the origin of aerodynamic sound.

We attempt to estimate aerodynamic sound source by using a correlation measurement of unsteady-vorticity and surface-pressure fluctuation. Since the vorticity (or static-pressure) probe generates aerodynamic sound, we have to measure the surface pressure fluctuation instead of the aerodynamic sound radiated from the circular cylinder. This is because it is difficult to remove the influence of the aerodynamic sound radiated from the vorticity probe. In this work, we therefore use the surface pressure fluctuation to estimate the aerodynamic sound source.

First, we measured the coherent output power (COP), P_c , between the vorticity fluctuation in the wake and the surface pressure distribution. That is,

$$P_c(f)^2 = \frac{|G_{wp}(f)|^2}{|G_w(f)||G_p(f)|} P(f)^2, \quad (1)$$

where G_{wp} is a cross-spectrum of vorticity and surface pressure fluctuation, and G_w is a Fourier transform of vorticity and G_p is surface pressure fluctuation.

According to Lighthill-Curle's theory, aerodynamic sound can be calculated by using surface pressure fluctuation. So we replace surface pressure fluctuation with COP in order to estimate the vorticity contribution to aerodynamic sound as follows,

$$\overline{p^2(x)} = \frac{1}{16 \pi^2 a^2 x^4} L L_c \left(x_i \frac{\partial f_i}{\partial t} \right)^2, \quad (2)$$

$$f_i = \int_0^{2\pi} n_i P_c \frac{D}{2} d\theta, \quad (3)$$

where a denotes the speed of sound, L denotes the

cylinder length, and L_c denotes coherence length of surface pressure fluctuation. Coherence length L_c is equivalent to a spanwise length along which pressure fluctuations are significantly correlated and indicates a three-dimensional structure in the wake of the circular cylinder.

The intensity of COP corresponds to a dipole sound source produced by the unsteady vorticity fluctuation. Therefore, Eqs. (2) and (3) show the vorticity contribution to the aerodynamic sound generation at each measurement point in the wake. Moreover, we estimated the position of the aerodynamic sound source by using Eqs. (2) and (3). In this experiment, aerodynamic sound was calculated from vorticity fluctuation at the center cross section of XY plane ($Z/D=0$). The aerodynamic sound depends on three dimensionality of the flow field. It is therefore necessary to measure vorticity fluctuation in the spanwise direction in the wake of the circular cylinder. It takes a long time to measure the three-dimensional structure of the wake because the number of measuring points drastically increases. And it is difficult to maintain the experimental conditions for such a long period. In this study, we estimated the three-dimensional vorticity distribution by using the spanwise coherence length previously defined by authors⁽⁵⁾. That is, the coherence length of a fundamental frequency is given by Eq. (4),

$$\frac{L_c}{D} = \frac{511}{\sqrt{Re}}. \quad (4)$$

Moreover, the coherence length of another kind of vortex is (such as turbulent eddies) about 0.5 times the cylinder diameter. In other words, the effect of three dimensionality can be evaluated by using the spanwise coherence length.

4. Results and Discussion

4.1 Flow field around the circular cylinder

The near wake of the circular cylinder measured by a conditional sampling method. Figures 7 and 8 show the velocity vector at a constant phase, ψ of 0 and 90 degrees, respectively. These figures, visualized as an observer moving downstream at $0.75U$, show the separated shear layer rolls up at the formation region of Karman vortices; that is $X/D=1.5$ to 2.0 and $Y/D=0.4$. And the large-scale structure of Karman vortex is clearly observed by conditional sampling. The general tendency of these figures is similar to the precise measurement of a flying hot-wire by Cantwell et al.⁽¹⁶⁾. However, the velocity distribution just behind the circular cylinder, $X/D=1.25$, is influenced by the counterflow.

Vorticity distribution at a phase angle, ψ of 0 is shown in Fig. 9. The vorticity distribution in the wake

is not clear in this figure. In general, operation of spatial derivatives causes increasing error. This is because the vorticity measurement requires the spatial derivatives of the velocity field. Therefore, measurement error is large. The positions of the large-scale vortex estimated from the velocity vector are shown in Fig. 9 as positive and negative symbols. At $X/D < 3.5$, the vorticities correspond to the eddy structure. However, the small scale eddies (at $X/D > 5$) were not observed because dispersion of vorticity is large in this region.

Figures 10 and 11 show the contours of static-pressure fluctuation at constant phases, ψ of 0 and 90 degrees, respectively. A large-scale structure in the wake of the cylinder is clearly observed. We can therefore conclude that static-pressure fluctuation is

Fig. 7 Velocity field at constant phase $\psi=0$ as an observer moving downstream at $0.75U$

Fig. 8 Velocity field at constant phase $\psi=90$ as an observer moving downstream at $0.75U$

Fig. 9 Contours of vorticity at constant phase $\psi=0$

Fig. 10 Contours of static-pressure coefficient at constant phase, $\psi=0$

Fig. 11 Contours of static-pressure coefficient at constant phase, $\psi=90$

closely related to vorticity fluctuation.

Convection velocity is calculated from the migration length of the negative peak of the static-pressure at every 30 degree phase angle. The calculated convection velocity is 0.73 times the uniform velocity. This velocity is also equivalent to that ($0.755U_0$) measured by Cantwell et al.

4.2 Aerodynamic sound source

Since the static-pressure probe has a long pressure-tube, it is difficult to measure the static-pressure fluctuation just behind the cylinder. This is because the static-pressure is influenced by the counterflow as well as the large angle of attack of velocity field and sensor. It is therefore difficult to accurately measure just behind the circular cylinder at $X/D < 1.0$. Our analysis is thus limited at $X/D > 1.25$. So we cannot estimate vorticity contribution to the aerodynamic sound generation at $X/D < 1.0$.

The distribution of the aerodynamic sound source was calculated by a modified Lighthill-Curle's equation (3) (including intensity of COP) as shown in Figs. 12 and 13. These figures represent distribution of aerodynamic sound source calculated from vorticity and static-pressure fluctuation, respectively. Comparing the figures shows that the sound source calculated from the vorticity is close to the circular cylinder. Thus, the sound source distribution is not in perfect agreement in these figures. However, the general

Fig. 12 Contribution of vorticity to aerodynamic sound

Fig. 13 Contribution of static-pressure to aerodynamic sound

tendency is the same. These figures show the aerodynamic sound source concentrates at $X/D=1.5$ and $Y/D=\pm 0.4$. It is remarkable that the aerodynamic sound source is concentrated in a small area at $Y/D=\pm 0.4$. This area does not correspond to the vorticity concentration region; that is $Y/D=0.6$. The aerodynamic sound source lies near the center of the cylinder but the vorticity fluctuation in near to the side of the cylinder. In this region, the alternating vortices come from both sides of the cylinder, and the separated shear layer is stretched by this vortex motion. The separated shear layer therefore rolls up at the formation region of the Karman vortices (Fig. 10). As a result, the stretched shear layer at the formation region makes up about 80% of the dipole sound. So it is concluded that the separated shear layers play an important role in generating

aerodynamic sound, and that the scale and intensity of the separated shear layer is the most important factor in controlling aerodynamic sound generation. Controlling the separated shear layer is therefore effective for reducing aerodynamic sound.

These results from Eq. (3) show the COP method can identify the distribution of an aerodynamic sound source. Especially, it is possible to identify the vortex region, which contributes to the generation of the aerodynamic sound, by measuring static-pressure fluctuation. Moreover, the static-pressure probe is easier to handle and calibrate than the vorticity probe. So the measurement technique can be applied in product development. The static-pressure probe is therefore useful for identifying the aerodynamic sound sources in industrial fields.

4.3 Discussion

In this study, not aerodynamic sound, which arises from a vortex itself, called the vortex sound (the quadrupole sound) generally, but dipole sound, which arises from the body surface, was made the object of research. However, vorticity fluctuation is an important factor to understand the generation mechanism of aerodynamic sound in a low-Mach-number wake. This is because the surface pressure fluctuation is originated from the vorticity fluctuation. Therefore, from the aerodynamic point of view, it is generally considered that aerodynamic sound is generated by unsteady vorticity fluctuation.

Nishioka et al.⁽¹⁷⁾ showed the intensity of vorticity fluctuation is large at $X/D < 0.5$ and $Y/D = 0.6$. However, we have no data representing this region. We thus cannot explain directly the contribution of vorticity fluctuation to the dipole sound just behind the cylinder.

Lighthill-Curle's theory shows that unsteady aerodynamic force generates aerodynamic sound. Therefore, aerodynamic sound depends on the temporary change in the circulation of the circular cylinder. The velocity distribution in the wake thus seems to be the controlling factor of aerodynamic sound. Phillips⁽¹⁸⁾ calculated aerodynamic sound by using the velocity distribution of a cylinder wake, (which was measured by Kovaszny⁽¹⁹⁾) and this calculation agreed with his measured result. The authors therefore consider that the formation region of a Karman vortex becomes a sound source. And in the future, we plan to calculate the contribution of the vorticity to generating aerodynamic sound near the cylinder with numerical simulation.

5. Summary

We developed an identification method for quantitatively estimating the contribution of vorticity

fluctuation to aerodynamic sound generation. We experimentally measured aerodynamic sound, and we also measured correlation of the surface pressure and unsteady vorticity fluctuation. This method uses coherent output power (COP) calculated from vorticity fluctuation and surface pressure fluctuation

Distribution of the aerodynamic sound source was calculated by using COP instead of surface pressure fluctuation (the conventional sources of aerodynamic sound). The intensity of COP corresponds to the distribution of the aerodynamic sound source caused by unsteady vortex motion, which is the most important factor in controlling aerodynamic sound. Aerodynamic sound is generated near the formation region of Karman vortices; that is, at $X/D = 1.5$ to 2.0 and $Y/D = \pm 0.4$ at Reynolds number of 4.0×10^4 . It indicates that aerodynamic sound can be reduced by thickening the separated shear layers and lowering the shear stress. So it is concluded that the separated shear layers play an important role in generating aerodynamic sound.

The static-pressure probe is an effective technique for measuring the properties of aerodynamic sound. In particular, its handling is more convenient than the vorticity probe. So this probe can be applied in industrial fields. Our method, using COP and the static-pressure probe, is therefore suitable for evaluating aerodynamic properties of a sound source.

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