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Flow-induced in-line oscillation of a circular cylinder

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Abstract

Flow-induced in-line oscillation of a circular cylinder either spring-mounted (two-dimensional rigid cylinder) or cantilevered was experimentally studied in free-oscillation tests in a water tunnel. In the free-oscillation tests of a two-dimensional cylinder, two different types of excitations appear at approximately half of the resonance flow velocity. The response amplitudes are sensitive to the reduced mass-damping parameter for the in-line oscillation in the first excitation region with a symmetric vortex street, while the alternate vortices are locked-in with the vibration of the cylinder in the second excitation region. For a cantilevered circular cylinder with a finite span-length, it is found that cylinders with aspect ratios of 5 and 10 have a single excitation region, and cylinders with aspect ratios of 14 and 21 have two excitation regions. The mechanism of vibration was also investigated using a splitter plate in the wake to prevent alternate vortices. It is noted that the amplitude of oscillation with the splitter plate is greater than that without the splitter plate, especially at $Vr = 2.3$ to 3.0, where a cylinder with an end plate shows the second excitation region. In other words, the alternate vortices suppress the excitation amplitude in this range. The results of this study are providing important supporting data for the recent Standard JSME S012-1998, "Guideline for Evaluation of Flow-Induced Vibration of a Cylindrical Structure in a Pipe", by the Japan Society of Mechanical Engineers.

Keywords: Flow-induced vibration; In-line oscillation; Circular cylinder; Cantilevered cylinder; Water tunnel

1. Introduction

Flow-induced vibration of bluff bodies has been of great interest for many decades and frequently occurs in industrial plants such as nuclear power plants, petroleum/chemical plants and in offshore structures. When the working fluid is a liquid, a thermocouple on a sensor probe with extremely small mass ratio inserted in the pipe system may be easily induced to oscillate by the flow. For example, a flow-induced vibration in the streamwise direction caused the damage to a thermocouple in the fast breeder reactor Monju of the Japan Nuclear Cycle Development Institute in 1995.

Vortex shedding from an elastically supported cylinder can cause the cylinder to oscillate in the cross-flow and streamwise (in-line) directions, if the structural damping of the system is small. In addition, the value of the mass ratio M $(= m/\rho d^2;\ m$ is a mass per unit span length, ρ is fluid density and d is a diameter of the cylinder) is small in liquid such as water, oil and metal sodium at high temperature. The in-line oscillation occurs easily at low reduced velocity because the reduced mass-damping parameter Cn $(= 2M\delta;\ \delta$ is the logarithmic decrement of the structural damping) is extremely small.

While most researchers have focused on the cross-flow oscillation due to the vortex-excitation, such as Scruton (1963) [1] and so on, few studies have been conducted on the in-line oscillation of a circular cylinder. King et al. (1973) [2] carried out

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experiments on the in-line oscillation of a flexible cantilevered circular cylinder in an open water channel. The cantilevered cylinder in their experiments, however, had a large value of aspect ratio of 41. They observed that when the *Cn* number is less than 1, the in-line oscillation occurs with large amplitude at low reduced velocities. Two excitation regions of in-line oscillation occur near half of the resonance velocity, that is, the first excitation region appears at the lower velocities than half of the resonance velocity, and the second region appears at the higher velocities. However, it is considered to be fundamental and important to obtain the response characteristics of in-line oscillation and to evaluate the critical values of the mass-damping parameter for the in-line oscillation of a two-dimensional circular cylinder. The mechanical conditions of oscillation are like the free-oscillation tests in the cross-flow carried out by Scruton [1]. Recently, we carried out free oscillation tests in the in-line direction for the circular cylinder elastically supported at both ends in a wind tunnel [3,4]. The structural damping parameter *Cn* was varied over a wide testing range to evaluate the critical value at which the in-line oscillation is suppressed. It is found that two excitation regions of the in-line oscillation are observed at reduced velocity in the range $1.0 < Vr < 4.0$. The cylinder sheds symmetrical vortices in the first region, and alternate vortices in the second region. It is proved that the maximum amplitudes decrease more readily with increasing reduced mass-damping parameter *Cn* in the first region than in the second region. So, JSME Standard S012-1998, "Guideline for Evaluation of Flow-Induced Vibration of a Cylindrical Structure in a Pipe" by the Japan Society of Mechanical Engineers [5] was established based on this data, and states that the criterion $Vr < 1.0$ is effective for avoiding in-line oscillation, while the criteria of $Vr < 3.3$ and $Cn > 2.5$ are effective in suppressing in-line oscillation. In addition, it is also fundamental and important to evaluate the critical values of the mass-damping parameter for a cantilevered cylinder with a finite aspect ratio like a thermocouple and a sensor probe. According to wind tunnel tests of Scruton [1] on the cross-flow oscillation, the response characteristics of an elastical cantilevered cylinder are different from those of a two-dimensional circular cylinder. Thus, it is important to elucidate the influence of the aspect ratio L/d, where L is the length of a cantilevered cylinder on the characteristics of oscillation, and it should be certified that the Standard JSME S012-1998 [3] covers the case of a cantilevered cylinder of a finite aspect ratio.

We carried out experimental studies in a water tunnel, instead of a wind tunnel. Circular cylinders elastically supported are restricted to oscillate in the in-line direction, and the value of the mass ratio M is small, i.e., when the working fluid is water. The structural damping parameter *Cn* was varied over a wide range in order to evaluate the critical value at which the in-line oscillation is suppressed for a cylinder model elastically supported at both ends and a cantilevered model with aspect ratios from 5 to 21. Furthermore, a splitter plate was inserted behind a cylinder to investigate effects of alternate vortex-streets, as done in Aguirre's experiment [6]. The relationship between movement of a cylinder and flow of a near field during an in-line oscillation was investigated.

2. Experimental arrangements

2.1. Water tunnel

The present experiments used the water tunnel shown in Fig. 1. The water tunnel has a rectangular test section of 400 mm × 167 mm. The test section consists of a flow channel and two sections on both sides for installing a test model.

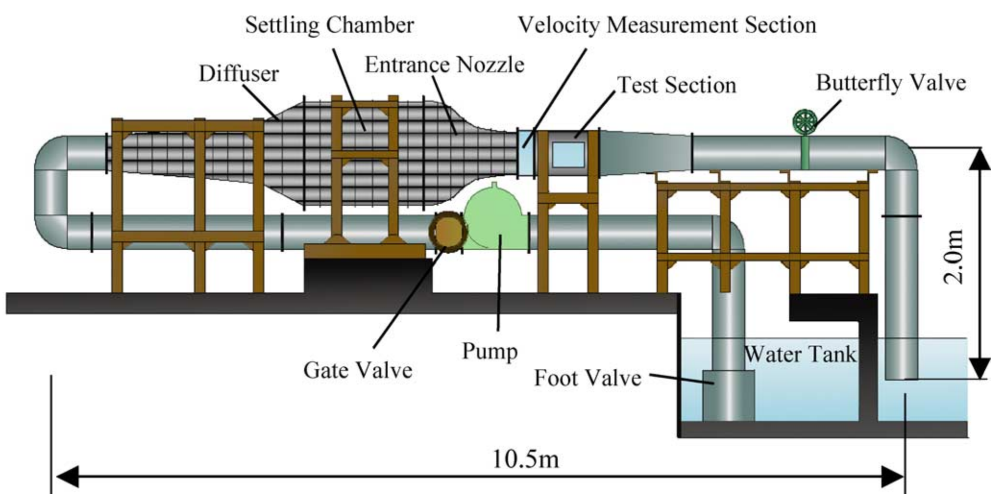

Fig. 1. A water tunnel.

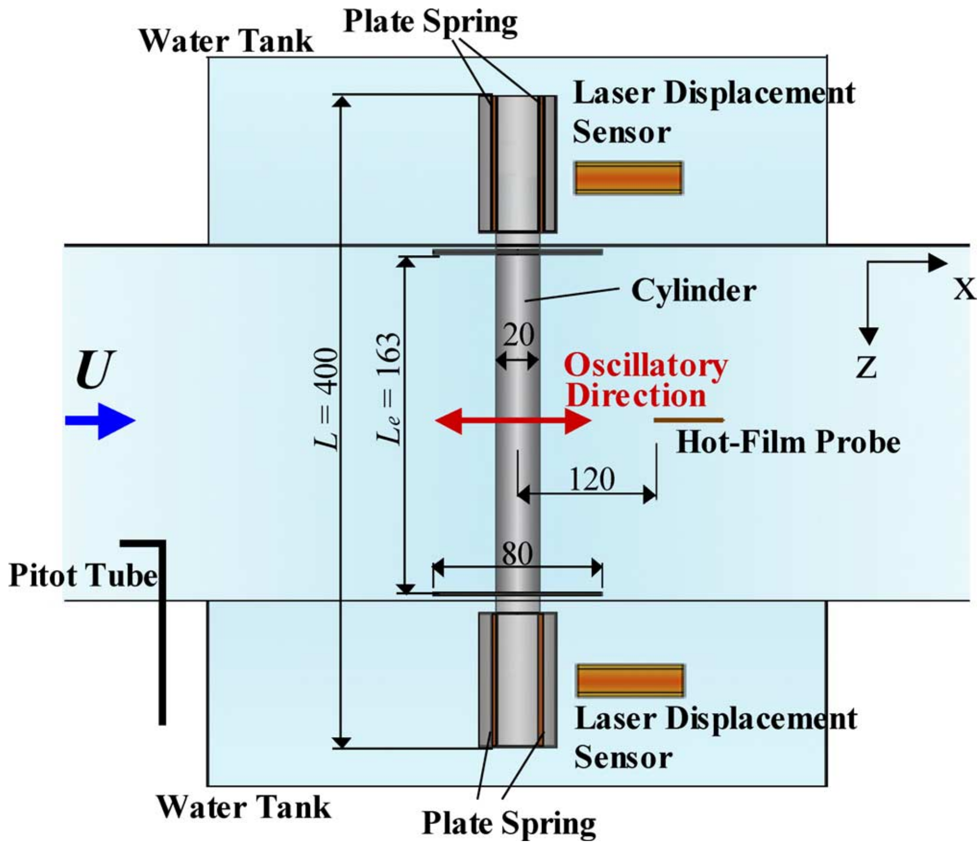

Fig. 2. Experimental set-up of a circular cylinder.

In the experiment, the water velocity U ranged from 0.2 m/s to 1.8 m/s, under the condition that the intensity of turbulence was less than 2.0%. The Reynolds number $Re = Ud/\nu$, where ν is the kinematic viscosity of water, was in the range of 8×10^3 to 4×10^4.

2.2. Circular cylinder models supported elastically at both ends

The present experiments used a cylinder made of stainless steel or duralumin with smooth surfaces. The cylinder had a diameter $d = 20$ mm with effective span length $L_e = 163$ mm subjected to flow. Two circular end plates of 80 mm diameter (about $4d$) and 0.5 mm thick were fitted at both ends of the cylinder. Fig. 2 shows the details of the experimental set-up. Since the model was supported elastically at both ends by four plate springs in each still water sides, the cylinder was allowed to oscillate only in the in-line direction. The amplitudes of the oscillating cylinders were measured by a Laser displacement sensor located in the still water side sections. A hot-film probe located along the outer edge of the wake was used to measure the fluctuating water velocity. Then, the non-dimensional vortex shedding frequencies, Strouhal number $St_w = f_w d/U$ (f_w is the frequency of a wake-vortex), was obtained.

2.3. Cantilevered circular cylinder models

Fig. 3 shows in detail the set-up of the cantilevered circular cylinders with aspect ratios of 5 to 21. The cylinders, made of stainless steel, were elastically supported by a plate-spring and a rubber sheet attached to the ceiling wall of the test section. The natural frequency f_c of the cylinder was adjusted to be a constant value between 20 Hz to 30 Hz by using different plate-springs, and the reduced velocity $Vr = U/f_c d$ was varied from 0.9 to 4.0 by changing a water velocity. The aluminum plates and rubber plates were clamped with the plate-spring to vary the reduced mass-damping parameter Cn. An acceleration sensor mounted on the top end of the cylinder, was used to measure the displacement of the oscillating cylinder, by using an integrator. A hot-film probe located along the outer edge of the wake, detected the fluctuating water velocity for calculating the non-dimensional vortex-shedding frequencies, the Strouhal number St_w .

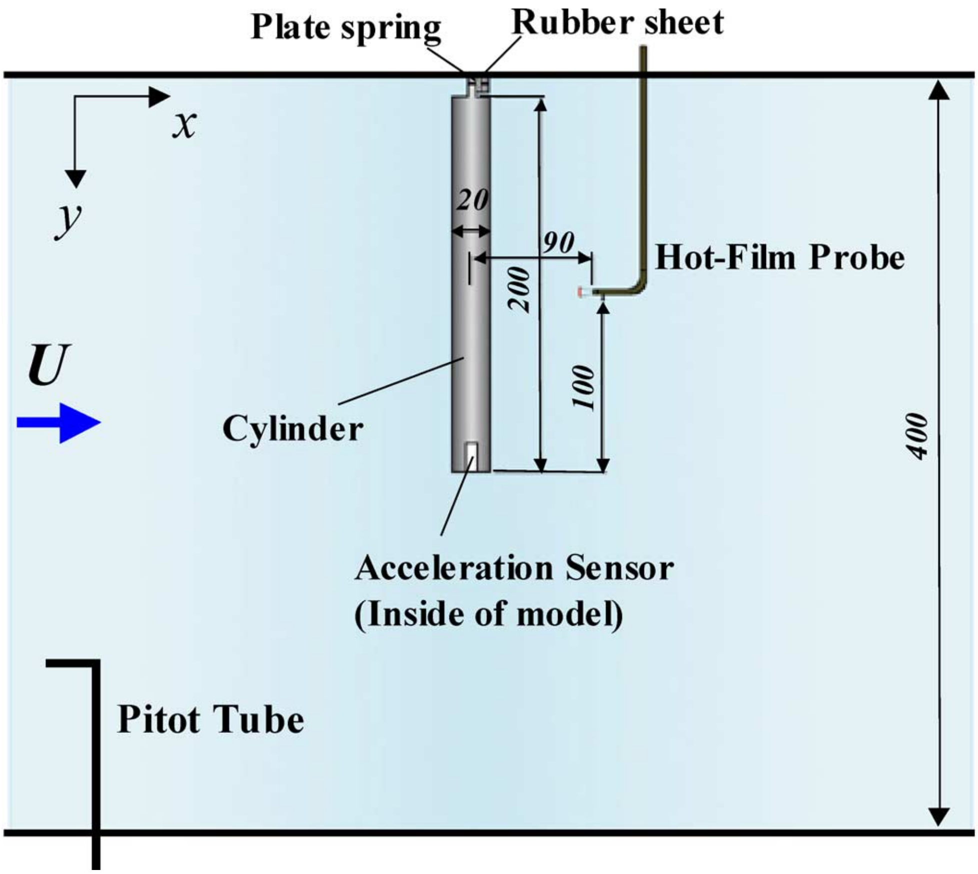

Fig. 3. A cantilevered circular cylinder with a finite span-length of $L = 200$ (the aspect ratio:10).

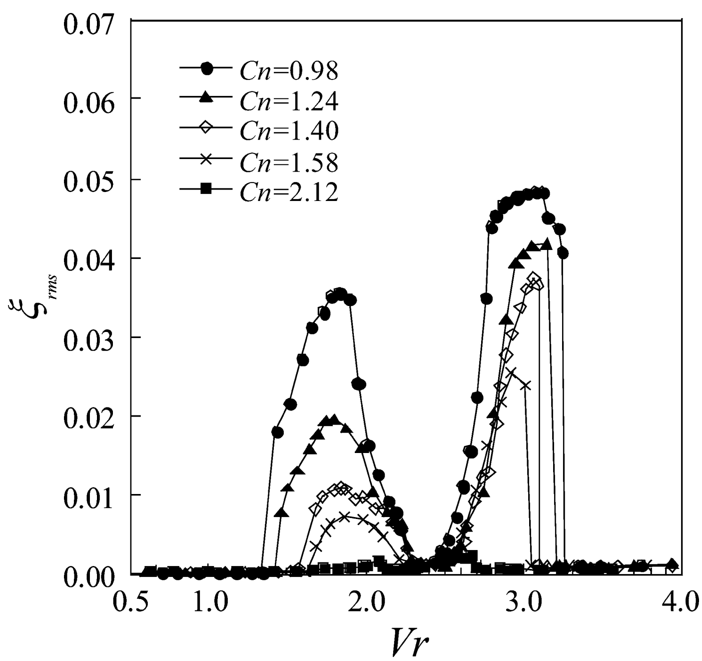

Fig. 4. The response amplitude of a two-dimensional circular cylinder with different values of $Cn = 0.98$ to 2.12.

3. Experimental results of a circular cylinder

3.1. Response amplitude ξ_{rms} for two-dimensional circular cylinder

Fig. 4 shows the response curves of in-line oscillation of a circular cylinder at various reduced mass-damping parameters *Cn* ranging from 0.98 to 2.12. The response amplitude ξ_{rms} is the relative amplitude $\xi_{\mathrm{rms}} = x_{\mathrm{rms}}/\mathrm{d}$, where x_{rms} is the root-mean-square displacement response. From this figure, it is confirmed that there are two excitation regions, similar to the experimental results observed by King et al. [2] of the in-line oscillation in a water channel and to those of a wind tunnel study by Okajima et al. [3]. For all values of *Cn*, the excitation oscillation occurs in two regions of *Vr*, one at $2.6 < Vr < 3.2$, which is larger than $Vr_{\mathrm{cr}}/2$, and the other at $1.4 < Vr < 2.3$, which is smaller than $Vr_{\mathrm{cr}}/2$. The response amplitude of the in-line oscillation damps with increasing *Cn* value in the two excitation regions. Furthermore, the response characteristics corresponding to the *Cn* values of the two regions are different. For example, the response amplitude is suppressed to less than $\xi_{\mathrm{rms}} = 0.010$ for $Cn = 1.40$ in the first excitation region, while it remains $\xi_{\mathrm{rms}} = 0.037$ for the same *Cn* value in the second excitation region. This may imply that the two excitation regions have different mechanisms of oscillation.

3.2. Response characteristics for reduced mass-damping parameter

Fig. 5 summarizes the maximum response amplitude ξ_{max} of the oscillation of a circular cylinder with end plates against the reduced mass-damping parameter *Cn* from the data [3] obtained in the wind tunnel and the present water tunnel. It is observed that two excitation regions have inherent response characteristics changing against the *Cn* values. The maximum of the ξ_{rms} values in the first excitation region abruptly falls as *Cn* increases, similar to the experimental results for in-line oscillation in the wind tunnel obtained by Okajima et al. [3,4].

Fig. 6 shows the detailed graph of the conditions for the suppression or avoidance of oscillation, which is quoted from the JSME Standard S012-1998, Guideline for Evaluation of Flow-Induced Vibration of a Cylindrical Structure in a Pipe [5]. The JSME Standard mainly referred to the experimental results obtained by King et al. [2] in the water channel, Okajima et al. [3] and Scruton [1] in the wind tunnel, where the conditions for the suppression or avoidance of the in-line oscillation were established at $Vr < 3.3$ and $Cn > 2.5$. From experimental results of Fig. 5, these values also satisfy the JSME Standard S012-1998 and provide important supporting data.

3.3. In-line oscillation of circular cylinder with splitter plate

Prior experiments of Aguirre [6], who inserted a splitter plate behind the cylinder in a water channel indicated that the oscillation of the first excitation region consists of self-excited oscillation caused by the symmetric eddies. So, Fig. 7 shows the flow-patterns visualized by a smoke-wire technique [4]: a symmetric vortex-pattern appears accompanied by the motion of the cylinder in the first excitation region of Fig. 7(a) and an alternate vortex-street like a Karman vortex-street is observed as shown in Fig. 7(b). Fig. 8(a) shows the in-line oscillation response for a circular cylinder with and without a splitter plate. The length of a splitter plate is approximately $l = 15d$, which is longer than that used in Aguirre's experiment, and the clearance between the cylinder and the plate is very small, approximately 3.0 mm. This figure displays the response amplitude ξ_{rms} against the reduced velocity *Vr* for the reduced mass-damping parameter $Cn = 0.70$. Comparing the oscillation response characteristics of the cylinder with and without a splitter plate, the exciting oscillation region extends up to $Vr = 2.8$ when the splitter plate is inserted. Additionally, each response characteristic at $1/4St_n$ and $1/2St_n$, which is the lock-in region for the oscillatory cylinder without a splitter plate, is very different from that of the oscillatory cylinder without a plate, as shown in Fig. 8(b). According to Naudasher [7], this exciting oscillation of the first region is associated with the symmetric vortices formed in the near wake. Furthermore, he implied that in the absence of splitter plate, the oscillation of the cylinder disappears around $Vr = 2.5$ by the interaction with the formation of alternate vortices. Finally, the oscillation seems to be suppressed by the alternate vortices generated in the range of $Vr = 2.0 \sim 2.8$.

4. Experimental results of cantilevered circular cylinder

4.1. Amplitudes of the cantilevered cylinders and the effect of aspect ratio of 5 to 21

Fig. 9(a) shows the relative amplitude of in-line tip displacement ξ_{rms} against the reduced velocity *Vr* with an aspect ratio of 10. The Strouhal number St_w of the wake vortex frequency is also shown in Fig. 9(b), and the reduced mass-damping parameter *Cn* is 0.24. It is found that the response amplitude of the cylinder shows only one excitation region in the range of $Vr = 1.2$ to 3.4. There is an increase in in-line amplitude at $Vr = 1.2$ to 2.2 and a decrease to $Vr = 3.4$. The maximum value

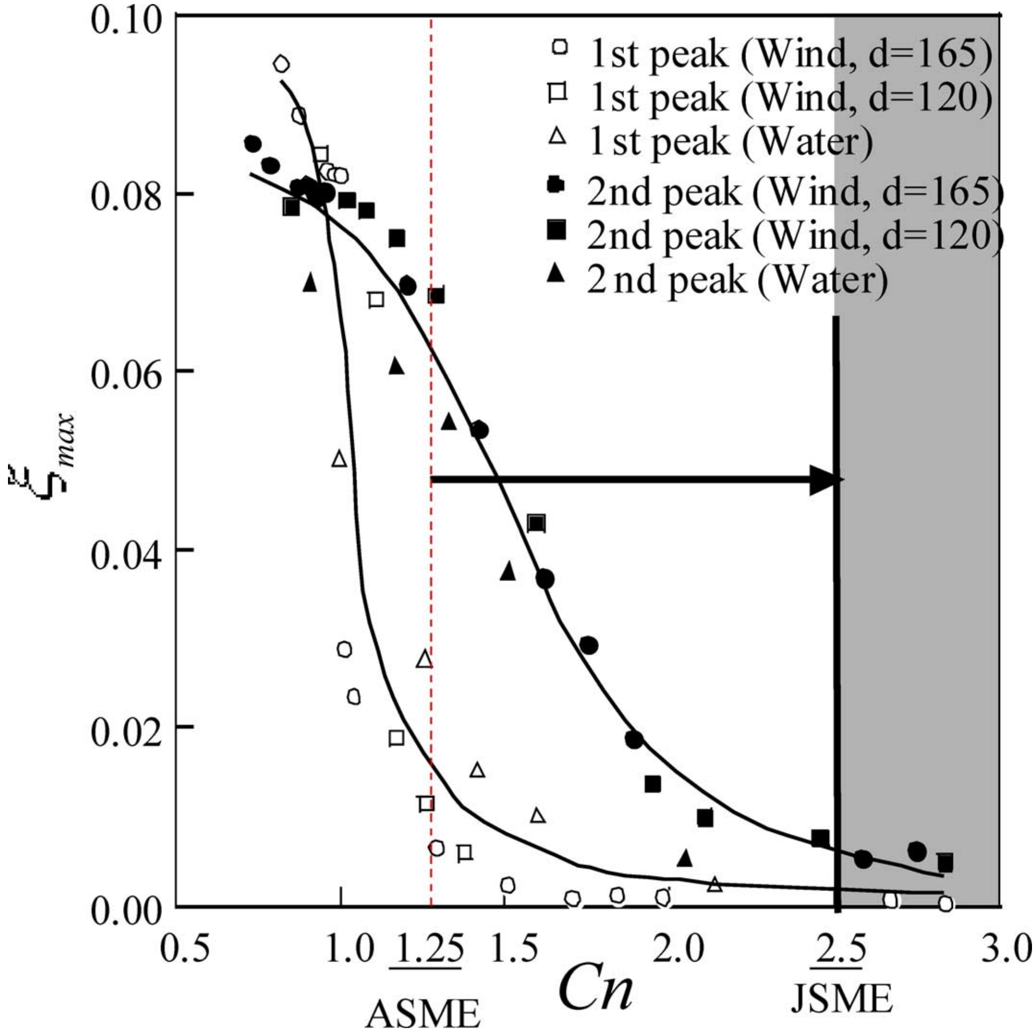

Fig. 5. The maximum response amplitude of a circular cylinder versus the reduced mass-damping parameter *Cn* obtained in the wind tunnel [3] and the water tunnel.

of $\xi_{\rm rms}$ is 0.090 at $Vr = 2.2$. The lock-in phenomenon of St_w to $1/2St_c$ occurs at $Vr = 2.2$ to 3.0. The characteristics of this response amplitude is very different from the response curve of a two-dimensional cylinder because the cylinder shows two excitation regions in the same Vr range as shown in Fig. 9(a). The lowest point of the amplitude is placed at approximately $Vr = 2.5$ of a curve for the cylinder. Also, the phenomenon of lock-in St_w to $1/2St_c$ appears in the second excitation region of $Vr = 2.5$ to 3.5. When the reduced mass-damping parameter *Cn* are changed for this cylinder with the aspect ratio of 10, the amplitudes $\xi_{\rm rms}$ decreases in proportion to an increase of the *Cn* from 0.32 to 1.53 as shown in Fig. 10. It is noted that all curves show only one excitation region with maximum points at $Vr = 1.9$ to 2.1, different from the two excitation regions for the circular cylinder.

Fig. 11 shows clearly the effect of aspect ratio on the amplitude of cantilevered cylinders with the aspect ratio of 5 to 21 at almost the same values of $Cn = 0.25$. In the case of a cylinder with an aspect ratio of 5, it is found that the response characteristics of the cylinder show one excitation region in the range $Vr = 1.7$ to 3.2. There is an increase in in-line amplitude from $Vr = 1.7$ to 2.2 and a rapid decrease at $Vr = 2.4$, with the maximum value of $\xi_{\rm rms} = 0.097$ at $Vr = 2.2$. On the other hand, the cylinders with aspect ratios of 14 and 21 have two excitation regions. The maximum amplitudes of the first excitation regions and the amplitudes between $Vr = 1.7$ to 2.1 are almost equal for all aspect ratios. The amplitudes of the second excitation region are low for small aspect ratios. It seems that the aspect ratio strongly affects the second excitation region and more than the first excitation region. The St_w is very difficult to detect because there was no clear frequency peak in the wake.

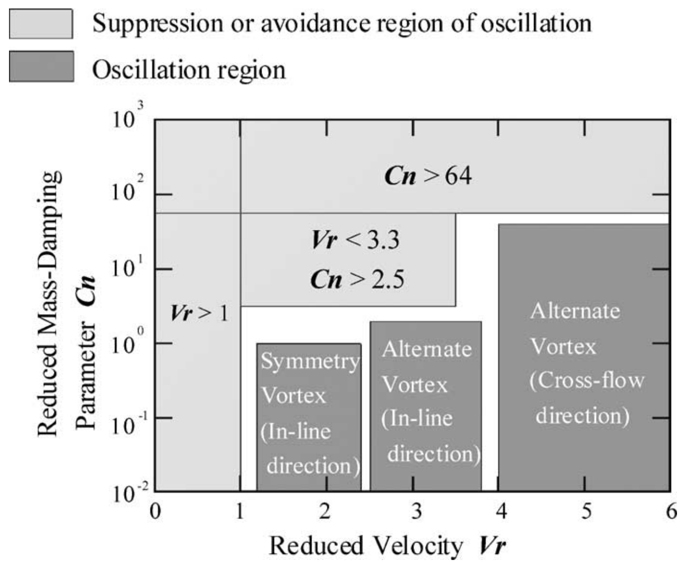

Fig. 6. The conditions for the suppression or avoidance of flow-induced vibration of a cylindrical circular structure in pipe of JSME Standard, S012-1998 [5].

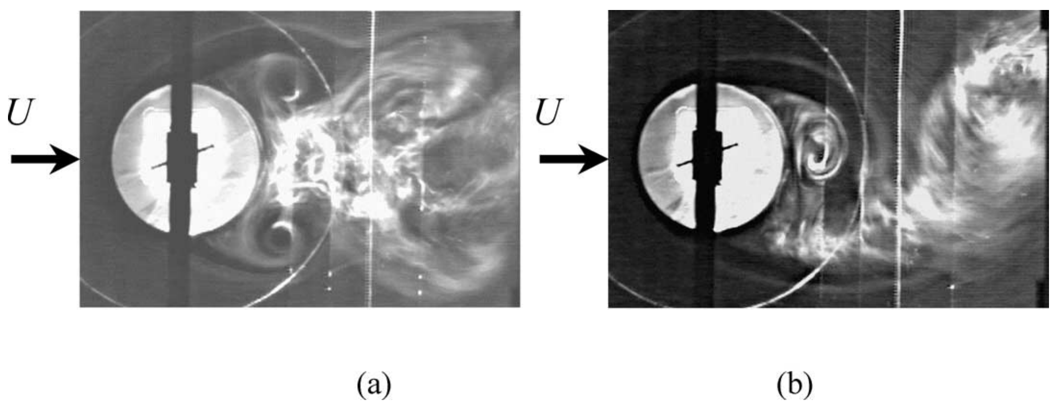

Fig. 7. Flow visualizations of the vortex structure for two excitation regions of a circular cylinder in the wind tunnel [4]: (a) symmetry vortices in the first excitation region ($Vr = 2.3$); (b) alternate vortices in the second excitation region ($Vr = 3.2$).

4.2. Amplitudes of cantilevered cylinders with an end plate

To clarify the effect of aspect ratio on excitation regions, an end plate was attached to the top end of the cantilevered cylinder. The end plate makes the flow two-dimensional along the cylinder, preventing the three-dimensional flow over the top end of the cylinder. Therefore, it reduces the influence of end effects on flow.

Fig. 12 shows the effect of an end plate of 60 mm diameter attached to the top end of cantilevered cylinders with aspect ratios of 10. This figure shows that the cylinder with an end plate has two excitation regions, in contrast to the cylinder without an end plate: that is, the first excitation region is from $Vr = 1.1$ to 2.3, a valley from $Vr = 2.3$ to 2.7 and the second excitation region from $Vr = 2.7$ to 3.3. It is clear that the influence of end-effect is seen in the appearance of two excitation regions, relating to the steepness of a valley and to the growth of the second excitation region. The lock-in phenomenon of St_w to $1/2St_c$ occurs from $Vr = 1.9$ to 3.3. That is, the lock-in phenomena begin at the end of the first excitation region and finish at the end of the second excitation region.

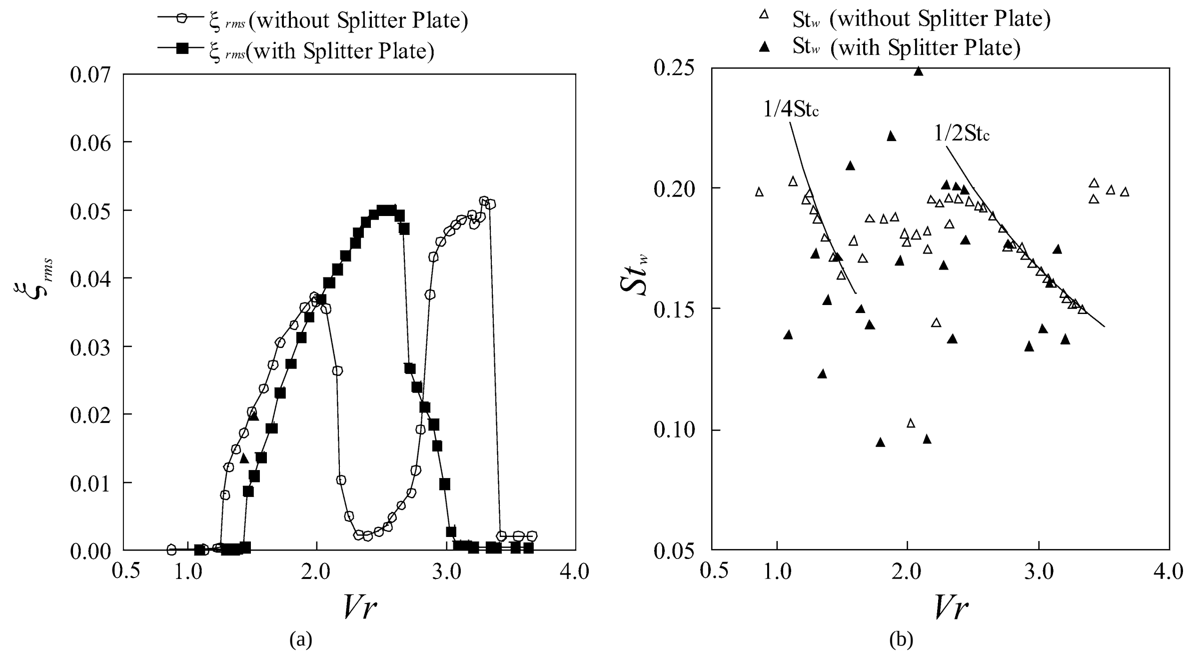

Fig. 8. (a) The response amplitudes and (b) the wake Strouhal numbers of two-dimensional and cantilevered circular cylinders for $Cn = 0.70$ with and without the splitter plate.

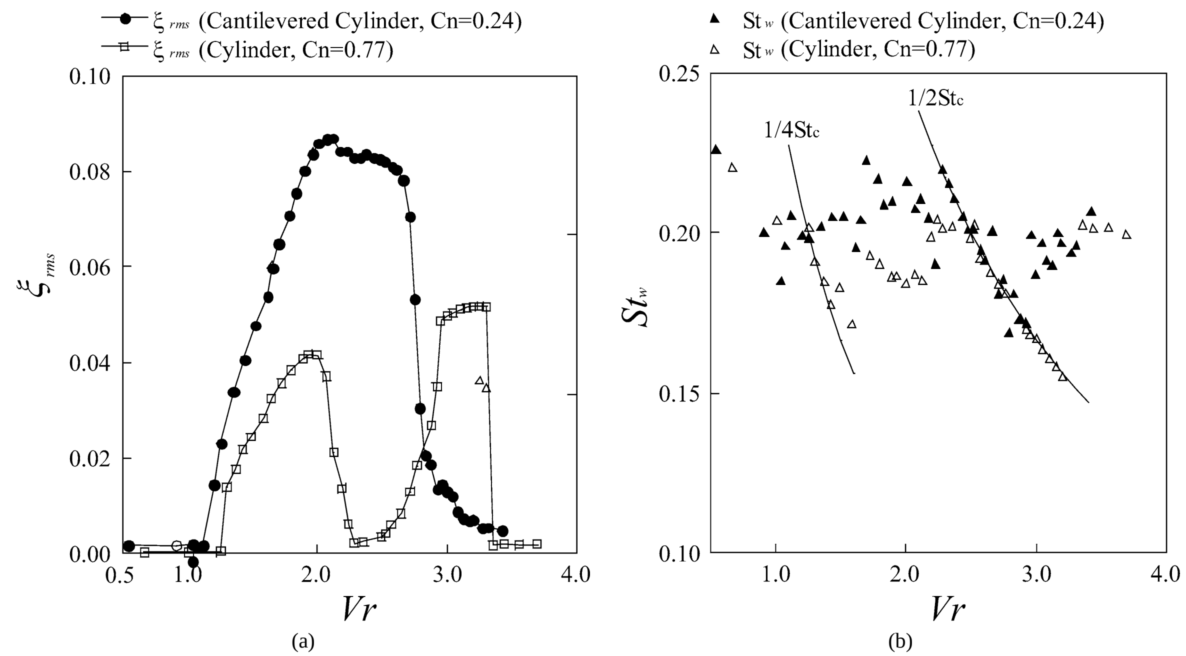

Fig. 9. (a) The response amplitudes and (b) the wake Strouhal number of a cantilevered cylinder with the aspect ratio of 10 for $Cn = 0.24$, compared with the results of a two-dimensional circular cylinder for $Cn = 0.77$.

4.3. Amplitudes of cantilevered cylinders with a splitter plate

A splitter plate was placed in the wake to prevent vortices from alternate-shedding in order to clarify the excitation mechanism of the single excitation region that appears for the cylinder with an aspect ratio of 10. Fig. 13 shows the effect of a splitter plate on the response curve of a cylinder, compared with the results of the cylinder without a splitter plate.

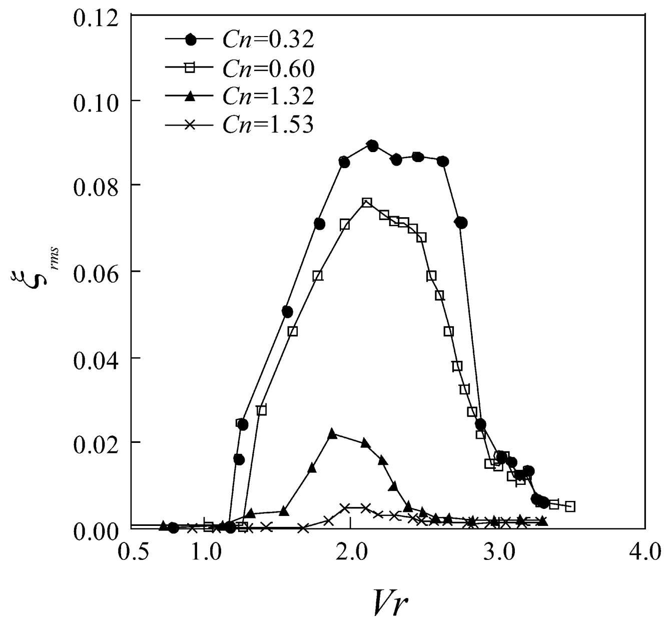

Fig. 10. The response amplitudes of a cantilevered cylinder with the aspect ratio of 10 for different values of $Cn = 0.32$ to 1.53.

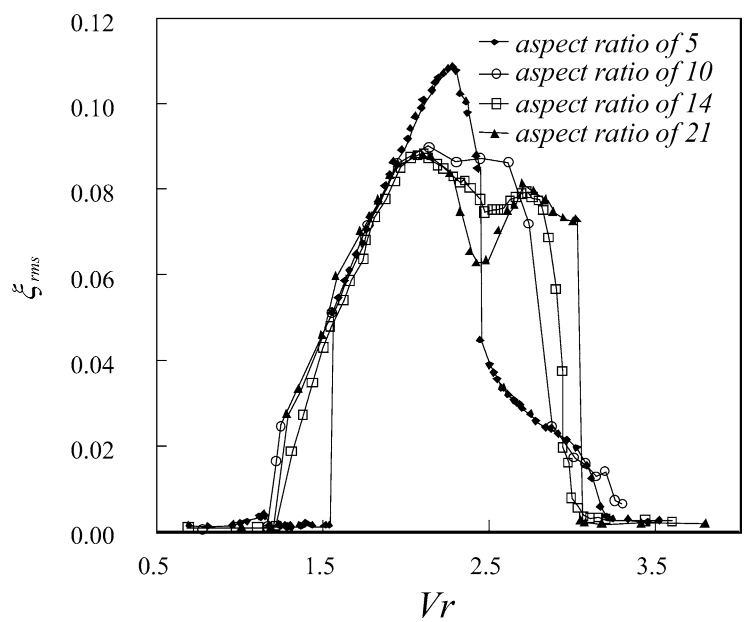

Fig. 11. The response amplitudes of a cantilevered cylinder with different aspect ratios of 5 to 21. ($Cn \approx 0.25$).

It is found that the response amplitude of the cylinder with a splitter plate has only one excitation region in the range of Vr from 1.1 to 3.0. That is, it consists of an increase of amplitude from $Vr = 1.1$ to 2.8 and a rapid decrease from $Vr = 2.9$ to 3.0, with a maximum ξ_{rms} of 0.12 at $Vr = 2.8$. It is noteworthy that the amplitude of the cylinder with a splitter plate grows still from $Vr = 2.2$ to 2.8, but both curves are almost equal from $Vr = 1.1$ to 2.2. Clearly, symmetrical vortices occur at $Vr = 1.1$ to 2.2, and the alternate vortices suppress the amplitude of oscillation between $Vr = 2.2$ to 3.0. Although the response amplitude of the cylinders with aspect ratios of 14 and 21 has two peaks, the response amplitude of the cylinder with a splitter plate has a single excitation region, like that of the cylinder supported at both ends as shown in Fig. 8(a).

The amplitude of the cylinder placed with a splitter plate in the wake is greater than that of a cylinder without a splitter plate, at $Vr = 2.2$ to 2.8, and is almost equal between $Vr = 1.1$ to 2.2.

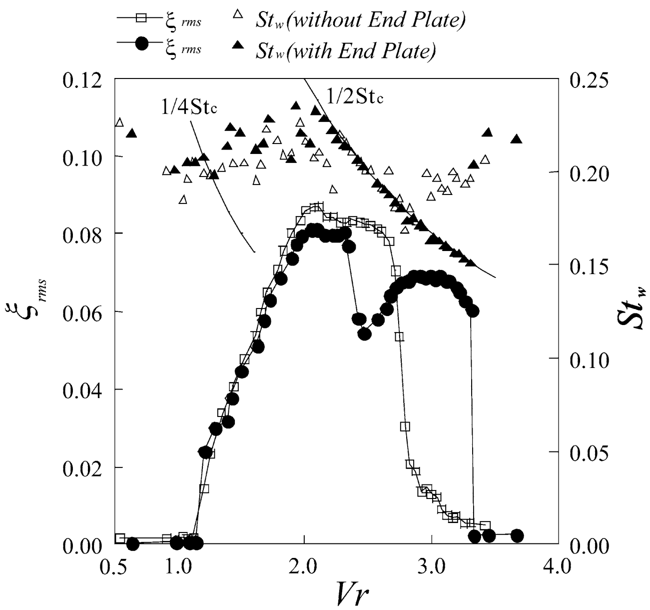

Fig. 12. The response amplitudes and the wake Strouhal number of a cantilevered cylinder with the aspect ratio of 10, with and without the end plate for $Cn = 0.24$.

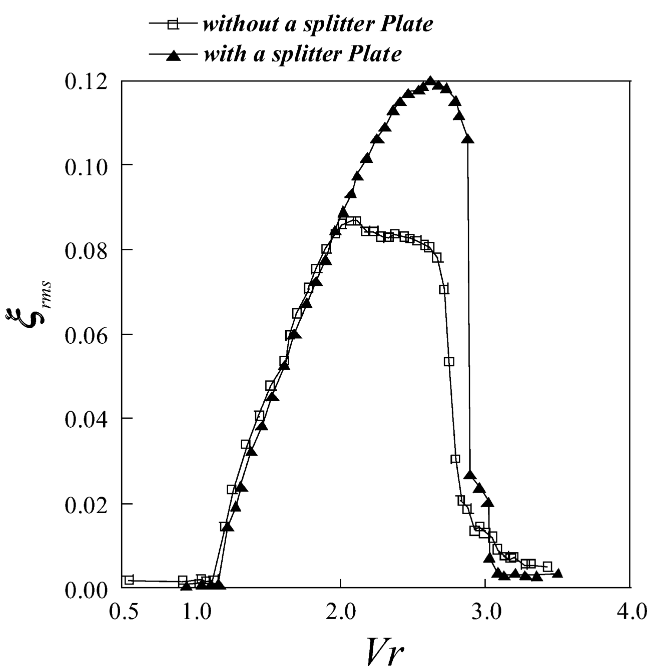

Fig. 13. The response amplitude of a cantilevered cylinder with the aspect ratio of 10, with and without the splitter plate for $Cn = 0.24$.

5. Conclusions

Flow-induced in-line oscillation of a circular cylinder was experimentally studied by free-oscillation tests in a water tunnel at subcritical Reynolds numbers. The rigid cylinder models were either elastically supported at both ends, or cantilevered using plate springs to oscillate in the in-line direction in a uniform flow. The vibration mechanism was investigated using a cylinder with an end plate or inserting a splitter plate in the wake. The main conclusions obtained from these experiments are as follows:

Circular cylinder elastically supported at both ends

(1) It is confirmed that two types of excitation phenomena appear at approximately half of the resonance flow velocity.
(2) The response amplitudes are sensitive to the reduced mass-damping parameter in the first excitation region with symmetric vortices, while the alternate vortex streets are periodically shed and locked-in with the oscillation of the cylinder in the second excitation region.

Cantilevered circular cylinder

(1) The response characteristics of cylinders with aspect ratios of 5 and 10 show single excitation region in the range of Vr from 1.0 to 4.0, in contrast to the cylinders with aspect ratios of 14 and 21. Most notably, the aspect ratio affects the depth of valley between the first and second excitation regions and the amplitudes of the second excitation regions.
(2) The cylinders with an end plate have two excitation regions, even at an aspect ratio of 5. The valley for a cylinder is steeper than that for a cylinder without the end plate.
(3) The amplitude of the cylinder with the splitter plate in the wake is greater than that of a cylinder without the splitter plate, at $Vr = 2.2$ to 2.8, and is almost equal between $Vr = 1.1$ to 2.2. This clearly shows that symmetrical vortices induce the vibrations from $Vr = 1.7$ to 2.2 and signifies that alternate vortices suppress the amplitude from $Vr = 2.2$ to 3.0.
(4) The publication "Guideline for Evaluation of Flow-Induced Vibration of a Cylindrical Structure in a Pipe" by the Japan Society of Mechanical Engineers, Standard JSME S012-1998 [5] is certified to include the case of a cantilever-shaped cylinder with a finite span.

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