Wind and Structures, Vol. 6, No. 2 (2003) 127-140
DOI: http://dx.doi.org/10.12989/was.2003.6.2.127

Effects of corner cuts and angles of attack on the Strouhal number of rectangular cylinders

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(Received October 12, 2001, Accepted June 10, 2002)

Abstract. An investigation into the effect of corner cuts on the Strouhal number of rectangular cylinders with various dimensional ratios and various angles of attack is described. The Strouhal number given as a function of corner cut size is obtained directly from the aerodynamic behavior of the body in a uniform flow through a series of wind-induced vibration tests. For a quick verification of the validity of the Strouhal numbers obtained in this way, they are compared with the approximated the Strouhal numbers based on Shiraishi's early research. The test results show that the Strouhal number of the model with various corner cuts has a fluctuating trend as the angle of attack changes. For each cutting ratio as the angle of attack increases at each cutting ratio above 15^o, the Strouhal number decreases gradually, and these trends are more evident for larger corner cut sizes. However, a certain corner cut size which is effective in reducing the wind-induced vibration can be identified by larger Strouhal numbers than those of other corner cut sizes. Three distinct characteristics of Strouhal number variation can be identified in three regions which are termed as *Region I*, *II*, and *III* based on the general trend of the test results. It is also found that the corner cut is effective in one region (*Region-II*) and less effective in another one (*Region-III*) when only the vortex-induced vibration occurs.

Key words: Strouhal number; corner cut; angle of attack; wind tunnel experiment; rectangular cylinder

1. Introduction

The Rectangular cylinder is a kind of bluff body, with a cross-sectional shape that is basic for civil/architectural structures. The detailed information on the flow around rectangular cylinders is of special interest and of great importance in the study of the aeroelastic instability of structures. The main sources of unstable aerodynamic phenomena with regard to a rectangular cylinder are galloping, flutter, and vortex-induced vibrations (VIV). To prevent or avoid these undesirable phenomena, the corner cut has been widely accepted as one of the effective aerodynamic stabilization methods. Many investigations into this reduction method for aerodynamic stability were

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carried out by a number of researchers in the past (e.g., Inoue 1984, Koenig and Roshko 1985, Shiraishi and Matsumoto 1987, Kwok 1988, Nanjo and Ushino 1990, A. Okajima *et al*. 1991, Kawai 1993, 1997, Shirato and Matsumoto 1994, Suda 1995, Mastumoto 1999, Kareem *et al*. 1999). In order to understand the physical mechanism of aerodynamic and aeroelastic instability of a bluff body, the relation between the flow around bodies with various sectional shapes and their motion should be established. Because of the complicated behavior of the flow field around bluff bodies, the mechanism of generation of aeroelastic instabilities is yet to be clarified.

The Strouhal number is an important nondimensional number which is explanatory of aerodynamic instability phenomena. It takes different characteristic constant values depending upon the cross-sectional shape of the body enveloped by the flow. Since Strouhal (1878) first reported that the vortex-shedding phenomenon may be described in terms of a nondimensional number known as the Strouhal number, many research results have been reported on the Strouhal number (e.g., Vickery 1966, Bearman 1967, Nakaguchi *et al*. 1968, Washizu *et al.* 1974, Lee 1975, Okajima 1982, Shiraishi and Matsumoto 1983, Hasan 1989). In particular, Nakaguchi *et al*. (1968) found that the dimensional ratio (B/D) of a rectangular cylinder is one of the major contributing factors to its aerodynamic characteristics. He also suggested that there is a specific dimensional ratio (B/D) of rectangular cylinders at which the Strouhal number changes abruptly.

However, the majority of aforementioned studies on the Strouhal number carried out by previous investigators concerned the effect of Reynolds number variation for circular cylinders, while for rectangular cross sections, most of these previous studies were limited to one B/D (e.g., a square cylinder) with a single angle of attack of 0^o. The effects of the variation of corner shapes and of angles of attack on the Strouhal number were rarely studied. Moreover, virtually no work has been reported in the published literature on the relation between the corner cut and the Strouhal number.

Therefore, the present study is intended to investigate the effects of corner cuts and angles of attack of rectangular cylinders on the Strouhal number in a uniform flow. Tests on three basic rectangular sections are performed to clarify the aerodynamic characteristics of the body, or more specifically to find out the relations between the Strouhal number and the corner cut ratio at various angles of attack. As the Strouhal number is obtained directly by the aerodynamic behavior of the bodies through wind-induced vibration tests, this study focuses on the relations between the Strouhal number and the vortex-shedding phenomenon. Finally, the Strouhal numbers are compared with the peak amplitudes of vortex-induced vibration of the bodies with corner cuts.

2. Experimental setup and data reduction

2.1. Experimental set-up

The Eiffel type wind tunnel at Korea Advanced Institute of Science and Technology (KAIST) was used in this study. The size of test section of the wind tunnel is 1 m $\times$ 1 m and the test zone is 4 m long. The maximum wind velocity is about 17.0 m/s and the turbulence intensity is 0.15% (uniform flow state).

The aerodynamic response (displacement) caused by the wind-induced vibration in a uniform flow was measured through sectional model tests. The test model was set up to have two response modes, i.e., the across-wind mode and the torsional mode, restraining the movement of test model in the flow direction (Fig. 1). The fluctuating displacements on the model were measured by using a position sensors, a low pass filter (cut-off frequency : 20 Hz), an A/D converter, and a computer.

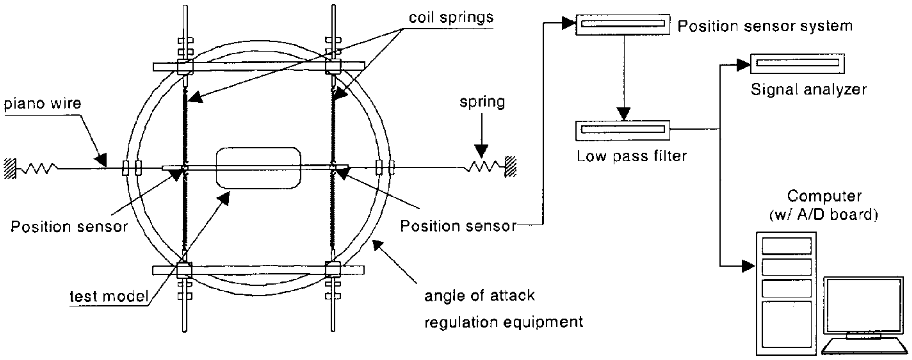


Fig. 1 Experimental setup

The sampling rate was 100 Hz (Δt=0.01sec.) with sampling time of T=10.24sec. (1024 points in total) (Choi and Kwon 1998).

2.2. Test models and conditions

The dimensional ratios (B/D) of two-dimensional rectangular cylinders with various corner cuts used in this test (Fig. 2) are 1.0, 1.5 and 2.0. The tests were performed under various angles of attack (α), i.e., 0^o to 45^o increased by 5 degrees steps, and in various wind velocities increased by 0.2 m/s steps. The positive direction of angle of attack is defined as shown in Fig. 2(a). The Reynolds number of this experiment varied in the range $Re = V \cdot D/\nu = 6.6 \times 10^2 \sim 4.0 \times 10^4$. In this study, the effects of the Reynolds number and damping were not considered. The analyzed test cases are summarized in Table 1 and the test conditions are given in Table 2.

From the wind-induced vibration tests, the three important aerodynamic phenomena, namely, galloping, flutter, and vortex-induced vibration, are observed for all test sections and angles of attack. When α is larger than 15^o, neither the galloping nor the flutter phenomenon occurred but

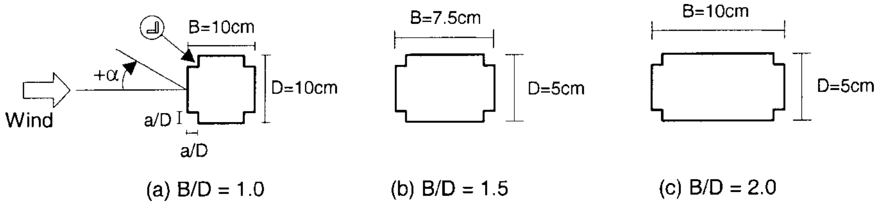


Fig. 2 Cross-sectional shapes of test models

Table 1 Test cases of wind-induced vibration

B/D \ a/D	0.00D	0.04D	0.05D	0.06D	0.08D	0.10D	0.11D	0.12D	0.14D	0.16D	0.17D	0.18D	0.20D
1.0	▣	▣		▣	▣	▣		▣	▣	▣		▣	▣
1.5	▣		▣		▣		▣		▣		▣		▣
2.0	▣		▣		▣		▣		▣		▣		▣

Table 2 Wind tunnel test conditions

(a) without corner cuts

B/D	Mass	δ_b	δ_t	f_b(Hz)	f_t(Hz)
1.0	2.08	0.0140	0.0148	4.281	9.245
1.5	1.76	0.0150	0.0163	4.532	9.485
2.0	1.96	0.0170	0.0180	4.313	9.750

(b) with corner cuts

B/D	Mass	δ_b	δ_t	f_b(Hz)	f_t(Hz)
1.0	2.44	0.0147	0.0152	4.281	9.250
1.5	1.83	0.0155	0.0167	4.532	9.500
2.0	2.04	0.0173	0.0184	4.250	10.25

only the vortex-induced vibration was observed for all the test sections, including the original section without corner cut. Therefore, the investigation focused on the relations between the variation of peak amplitudes of vortex-induced vibration and the Strouhal numbers in the range of angles of attack from 15^{o} to 45^{o}, which is known as the region of vortex-induced vibration (Choi and Kwon 2000a).

2.3. Determination of the Strouhal number

Generally, a fixed bluff body under wind sheds alternating vortices. Thus, the flow separates from the body at the upwind corners and advances by cyclically alternating vortices that are formed in turn at the top and bottom edges and finally swept downstream producing the so-called Karman vortex sheet. The regularity of such wake effects was first reported by Strouhal who pointed out that the vortex-shedding phenomenon may be described in terms of a nondimensional number given by

$$St = \frac{f_s D}{V} \tag{1}$$

where, St is the Strouhal number, and f_s, D, and V are the vortex-shedding frequency, across-wind dimension of the body, and the mean velocity of uniform flow, respectively. It is known that the vortex-shedding frequency is related to the wake width (Roshko 1954). When the separated flows detach suddenly from the surface, this results in a widening of the wake, and the longitudinal vortex spacing will be large, if a constant ratio of the vortex spacing to wake width is presumed. This would lead to a decrease in the vortex-shedding frequency, and thus to a decrease in Strouhal number.

To determine the Strouhal number of a body, three variables in Eq. (1) must be given. Since the across-wind dimension of the body (D) is given and the wind velocity (V) can be determined by the wind tunnel operations, the vortex shedding frequency (f_s), which is the frequency of cyclically alternating vortices, is the only unknown variable. Therefore, most previous studies to determine the Strouhal number focused on determining the vortex shedding frequency. The vortex shedding frequency is generally determined by the power spectral density based on velocity signal data.

The central idea of the proposed method is that the Strouhal number can also be obtained directly by the aerodynamic behavior of the body through wind-induced vibration tests. The signals of the

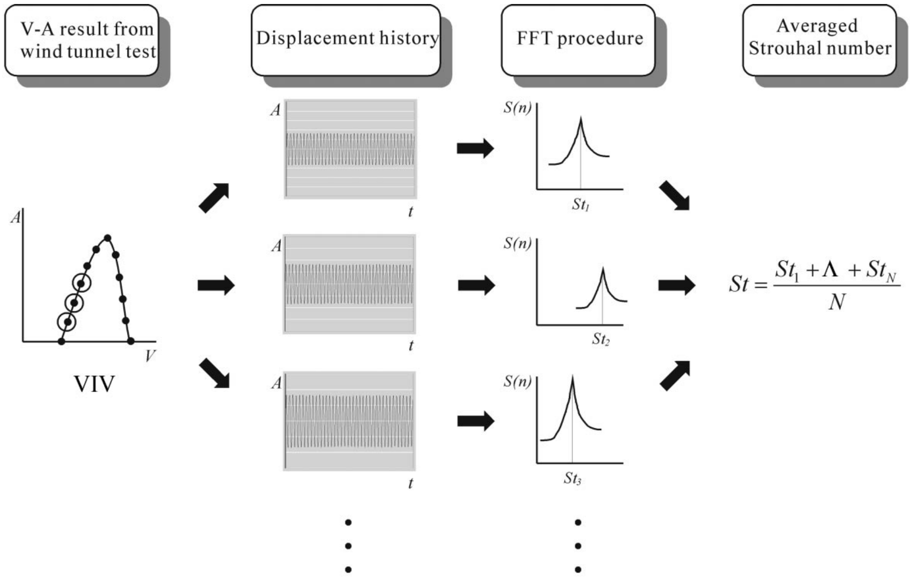


Fig. 3 Procedure of the proposed method to determine the Strouhal number

displacement of the body were first collected from the wind-induced vibration tests, and then the vortex shedding frequency could be obtained directly by the power spectral density obtained from Fast Fourier Transform (FFT) of this signal data (Choi and Kwon 2000b). Once the vortex shedding frequency is determined as discussed above, the Strouhal number can be calculated directly by Eq. (1). From a procedural point of view, this method is similar to previous studies because the Strouhal number is finally determined by using power spectral density of the signal. However, this proposed method has special merits. The Strouhal number can be obtained in the state of vibration of the body even though concept of the Strouhal number is derived from the fixed state of the body. Also, when the aerodynamic behavior of the body is obtained by the wind-induced vibration test, no other tests such as aerodynamic force measurement, the surface pressure test, and hot-wire test are necessary to find out the Strouhal number. These merits may indicate that the proposed method is effective to determine the Strouhal number when the wind-induced vibration test of the body is carried out. Fig. 3 shows the procedure of the proposed method to determine the Strouhal number.

3. Test results

3.1. Variation of the Strouhal numbers of rectangular cylinders without corner cut

Fig. 4 shows variations of the Strouhal numbers of three rectangular cylinders without corner cuts, i.e., B/D=1.0, 1.5 and 2.0, under various angles of attack. The Strouhal number increases with increasing angle of attack (α) until it reaches the maximum value at α=15^{o}, and then decreases as the the angle of attack (α) increases up to 45^{o} for all three test models. This trend is similar to Lee's results (1975), even though his tests were performed in a turbulent flow. The angle of attack α=15^{o} has been known as the point corresponding to the minimum drag coefficient of a rectangular cylinder. The minimum value of the drag is associated with the minimum wake width, and hence

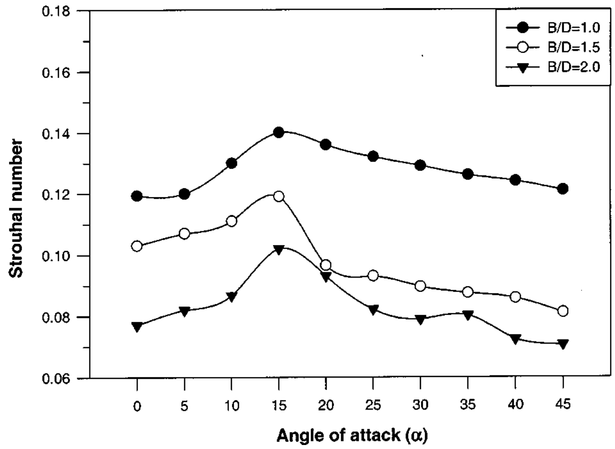


Fig. 4 Variation of the Strouhal numbers of rectangular cylinders without corner cut

with a minimum longitudinal vortex spacing. This would lead to an increase in the frequency of vortex shedding, and thus to an increase in the Strouhal number.

It is also observed that the Strouhal number decreases as the dimensional ratio increases from B/D=1.0 to 2.0 for all angles of attack (Fig. 4). This trend is similar to Nakaguchi's results (Nakaguchi *et al.* 1968) in the range of B/D=1.0~2.0, even though his tests were performed at an angle of attack of 0^{o} only.

3.2. Verification of the Strouhal number obtained by the aerodynamic behavior of the body

The reduced velocity (V_r) is a nondimensional velocity expressed by Eq. (2). Introduce eqautions at this point in which V_r is approximated by a reciprocal of the Strouhal number and the vortex-shedding frequency (f_s) is approximated by the natural frequency of the body (f_n). For a quick verification of the validity of this approximated Strouhal number, a method based on the Shiraishi's early work (Shiraishi and Matsumoto 1983) is used. Shiraishi suggested that the reduced velocity at the peak amplitude of vortex-induced vibration almost coincides with a reciprocal of the Strouhal number of the Karman type vortex-induced vibration for the relatively small dimensional ratio (B/D). As f_s can be closely approximated by f_n in the case of Karman type vortex-induced vibration (Lock-in), a reciprocal of V_r can closely represent the Strouhal number, i.e., $St \approx 1/V_r$ (Eq. 2).

$$V_r = \frac{V}{f_n D} \approx \frac{1}{St} \tag{2}$$

Two test results from Shiraishi's and this study for six cases, i.e., three dimensional ratios (B/D=1.0, 1.5 and 2.0) with two cutting ratios (0.00D(no corner cut) and 0.20D) for each B/D are shown in Fig. 5. In the figure, the Strouhal numbers obtained by tests in this study were compared with the approximated Strouhal numbers obtained by the reciprocal of reduced velocity ($1/V_r$) within the range of angles of attack from 15^{o} to 45^{o}, which is the occurrence region of vortex-induced vibration of the test models (Shiraishi and Matsumoto 1983). The axes in the figures are scaled to angle of attack versus Strouhal number. From the results of rectangular cylinders, the Strouhal numbers obtained by the proposed method and the approximated Strouhal numbers are in

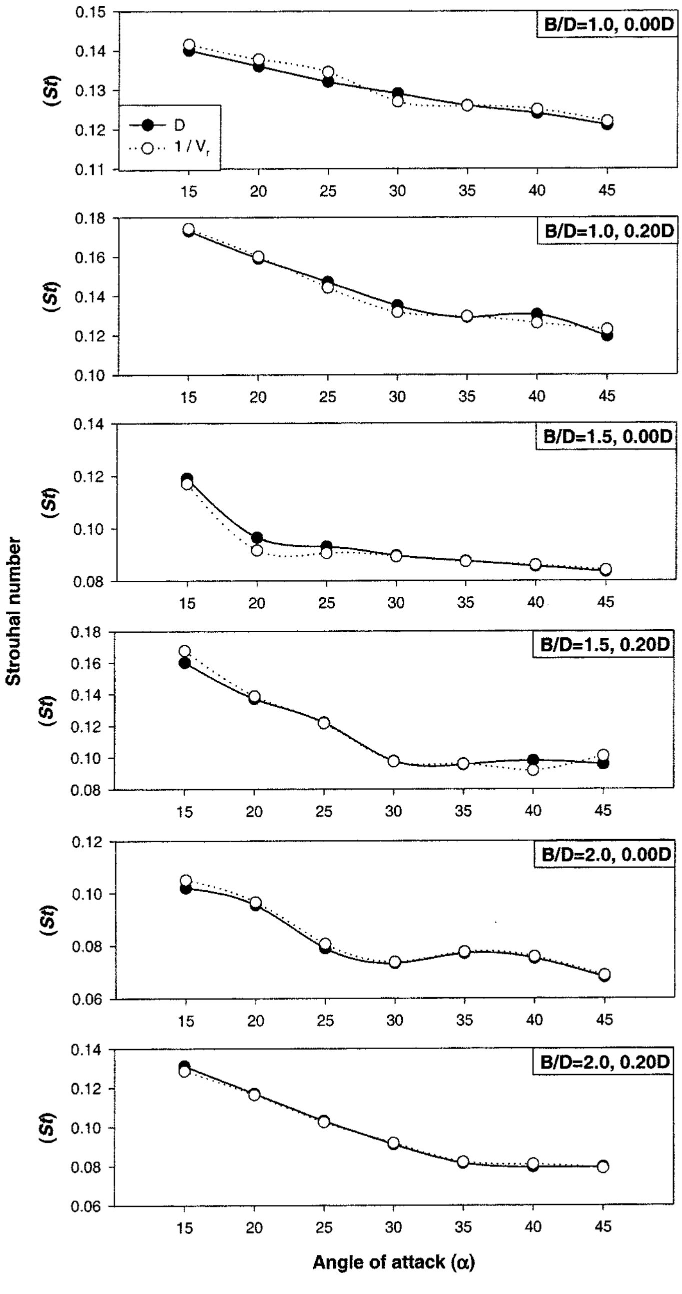


Fig. 5 Verification examples of the Strouhal number

good agreements.

3.3. Variation of the Strouhal numbers of rectangular cylinders with angles of attack

Fig. 6 shows the variation of the Strouhal number for the case of B/D=1.0 with different corner

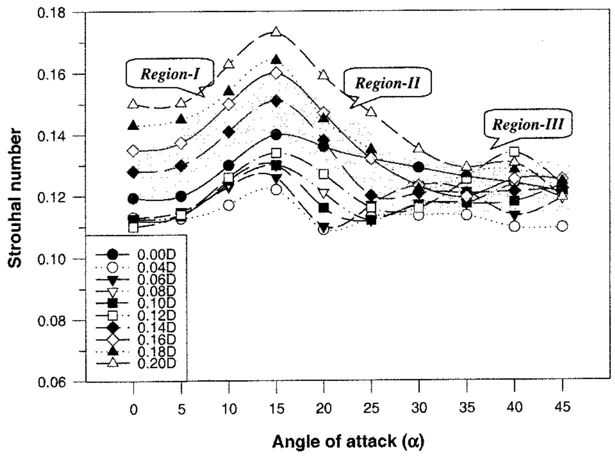


Fig. 6 Variation of the Strouhal numbers with angles of attack (B/D=1.0)

cuts. The Strouhal numbers in the figure vary from 0.11 to 0.17 for the entire range of angles of attack (i.e., 0^o~45^o). When the corner cut is introduced, the changes of Strouhal number show a trend that is similar to that of the original section without corner cut. That is, the Strouhal number of the test models increases as the angle of attack (α) increases from 0^o to 15^o; and reaches the maximum value at α=15^o, then it decreases as α increases up to 30^o, and finally has an approximately uniform value between the angles of attack of 30^o and 45^o. These trends are common to all cutting ratios.

For the cases B/D=1.5 and 2.0, the general trends of the Strouhal number variation are similar to the those for B/D=1.0 (Figs. 7 and 8). When corner cuts are introduced to the original section, the increasing and decreasing trends of the Strouhal number as the angle of attack increases are shown more clearly in Figs. 7 and 8. Indeed, the rectangular cylinders with various corner cuts have relatively larger values of the Strouhal number than those of the original section for all angles of

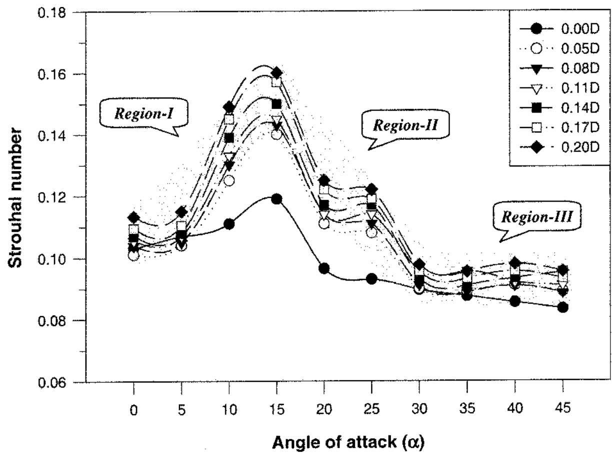


Fig. 7 Variation of the Strouhal numbers with angles of attack (B/D=1.5)

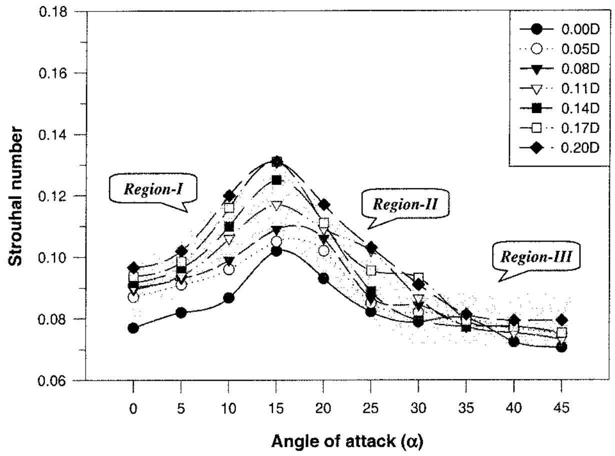


Fig. 8 Variation of the Strouhal numbers with angles of attack (B/D=2.0)

Table 3 The ranges of minimum and maximum values of *St*

B/D	Range of *St*	Remark
1.0	0.11 ~ 0.17	The minimum and maximum values of St decrease as B/D increases
1.5	0.08 ~ 0.16	
2.0	0.065 ~ 0.13	

attack, as shown in Figs. 7 and 8. It is also observed in the figures that the Strouhal number varies from 0.08 to 0.16 for B/D=1.5, and from 0.065 to 0.130 for B/D=2.0 for the various corner cut ratios and in the entire range of angles of attack. As seen, the minimum and maximum values of the Strouhal number decrease as the dimensional ratios increase (Table 3). These trends are similar to the results obtained from the test results of the original sections (Fig. 4). This means that the bluff body of larger dimensional ratio shows more unstable aerodynamic behavior for all the angles of attack.

The three distinct characteristics of Strouhal numbers variation can be identified in three categories based on the general trend of the test results as shown in Figs. 6, 7 and 8. *Region-I* : where the Strouhal number increases as the angle of attack increases from 0^o to 15^o for all dimensional ratios; *Region-II* : where the Strouhal number decreases as the angle of attack increases from 15^o to 30^o; *Region-III* : where the Strouhal numbers are relatively uniform in the range of angles of attack from 30^o to 45^o for each corner cut ratio (Table 4). These trends are more evident for the larger dimensional ratios. From the results, it is also observed that there exist two angles of attack of special interest, i.e., $\alpha=15^o$ and 30^o. At the angle of attack $\alpha=15^o$, the increasing trends of

Table 4 The regions classified by the characteristics of the Strouhal number

Region	Range of α	Trends of *St* as α increases	Remark
Region-I	0°~15°	Increase	Main galloping region: corner cut is very effective
Region-II	15°~30°	Decrease	Corner cut is effective for VIV
Region-III	30°~45°	Uniform	Corner cut is less effective for VIV

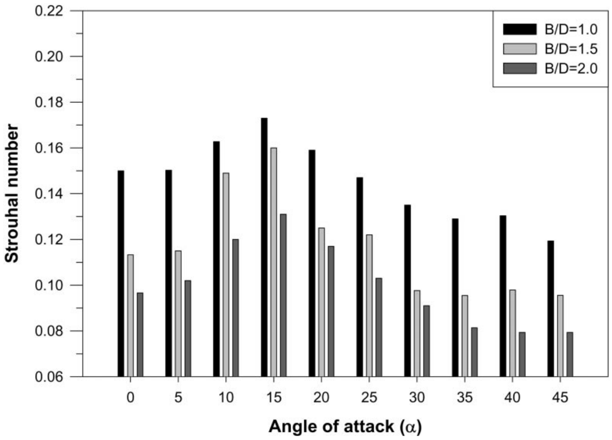


Fig. 9 Variation of the Strouhal numbers for corner cut size 0.20D

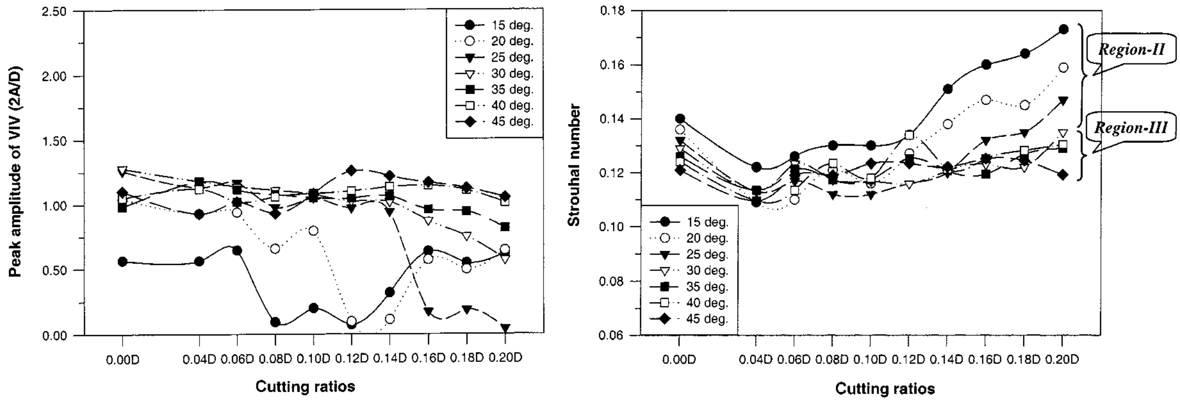
Strouhal number as a function of angle of attack abruptly change into decreasing trends and at α=30^o the decreasing trends of Strouhal number change into uniform values. This behavior is general and not much affected by specific angles of attack, dimentional ratios (B/D) and even corner cut ratios.

The Strouhal numbers of the models with corner cuts decrease as the dimensional ratio increases for all angles of attack. As an example, Fig. 9 shows the variation of the Strouhal numbers for different dimensional ratios with the same cutting ratio, i.e., 0.20D. This trend is similar to the test results of rectangular cylinders without corner cuts in the range of B/D=1.0~2.0 as shown in Fig. 4.

3.4. The peak amplitude of vortex-induced vibration and the Strouhal number

For an easy evaluation of the effect of corner cuts and that of angles of attack on the Strouhal number, the variation of the peak amplitude of vortex-induced vibration is compared with the variation of the Strouhal number of test model. As mentioned earlier, the occurrence of vortex-induced vibration was observed for all test sections when the angle of attack is larger than 15^o (Choi and Kwon 2000a) but no vortex-induced vibration was observed in the range of angles of attack from 0^o to 15^o. Therefore, in this section, the comparisons were made in the range of angles of attack from 15^o to 45^o only.

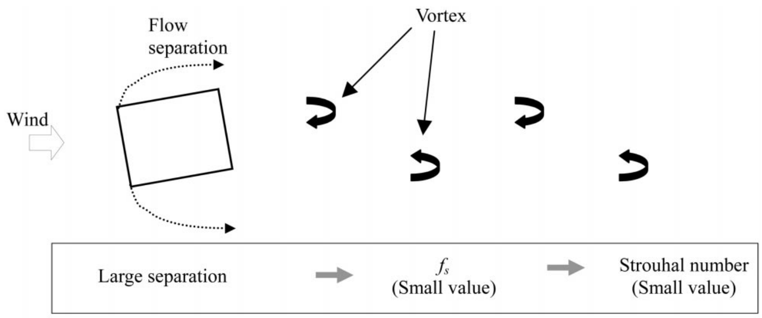
Fig. 10(a) shows variations of peak amplitudes of vortex-induced vibration due to the different corner cuts at each angle of attack obtained by wind tunnel tests for the test model having B/D=1.0 and Fig. 10(b) shows variations of the Strouhal number at each angle of attack. As the corner cut size increases, the Strouhal number shows generally an increasing trend even though it fluctuates up and down (Fig. 10(b)). Since the test models in this study have relatively small dimensional ratios, the Karman vortex stress will dominate when the test models are subjected to wind. Thus, the flow separates at the upwind corners and advances generating the cyclically alternating vortices that are formed in turn at the top and bottom edges and finally swept downstream. Fig. 11 illustrates a schematic diagram of flow separation and vortex-shedding from the test model. The figure shows that the flow separation at the leading edge is closely related with the change of the vortex-shedding frequency (f_s) and also with the Strouhal number. The basic principle of corner cut effect is two



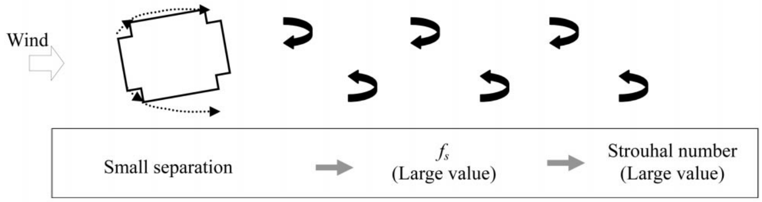
(a) Variation of the peak amplitudes of vortex–induced vibration

(b) Variation of the Strouhal numbers at each angle of attack

Fig. 10 The Strouhal number for B/D=1.0 with corner cuts



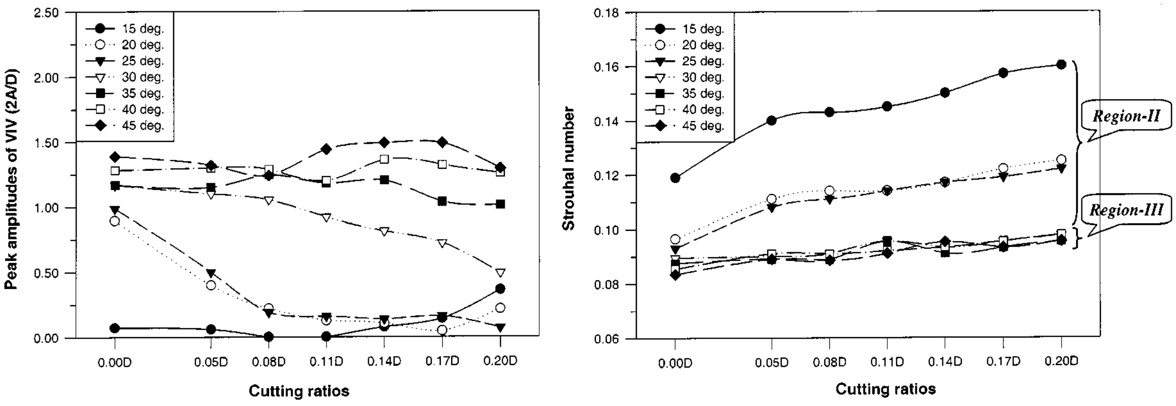
(a) No corner cut



(b) Effective size of corner cut

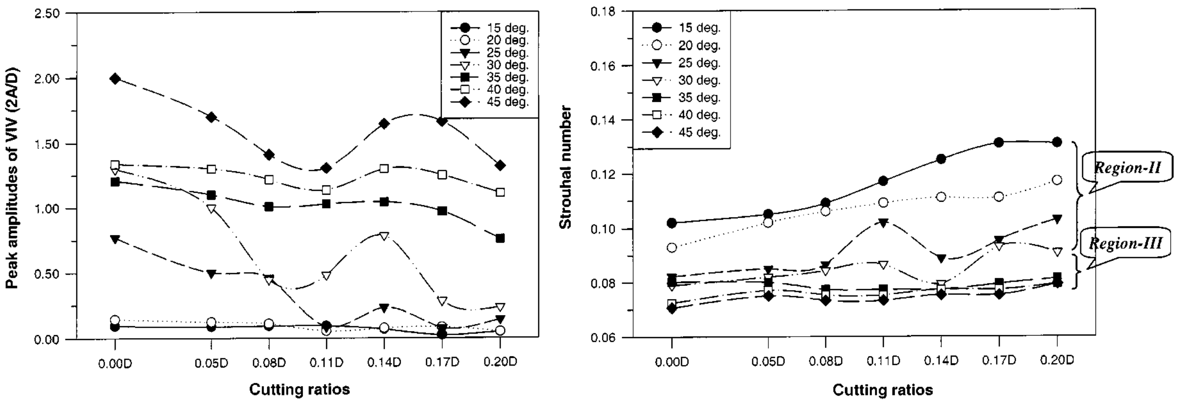
Fig. 11 A schematic diagram of flow separation and vortex-shedding

folds : 1) the minimization of separation width as the separation starts from the front edge of corner cut and reattaches to the rear edge corner cut, and 2) the resulting decrease of vortex-shedding interval behind the body (Fig. 11). Therefore, if a certain size of corner cut effectively minimizes the separation width, a larger Strouhal number will result. However, in the cases of corner cut range of 0.04D~0.10D, the Strouhal numbers for the angles of attack from 15° to 45° have smaller values than those of other cutting ratios, including the original section with no corner cut. This indicates that these cutting ratios (0.04D~0.10D) are less effective for stabilization of the vortex-induced vibration of the original section (no corner cut). As the effective ranges of cutting ratios at angles of



(a) Variation of the Peak amplitudes of vortex–induced vibration (b) Variation of the Strouhal numbers at each angle of attack

Fig. 12 The Strouhal number for B/D=1.5 with corner cuts



(a) Variation of the Peak amplitudes of vortex–induced vibration (b) Variation of the Strouhal numbers at each angle of attack

Fig. 13 The Strouhal number for B/D=2.0 with corner cuts

attack $\alpha=20^o$ and 25^o are 0.12D~0.14D and 0.16D~0.20D, respectively (Fig. 10(a)), from the viewpoint of the amplitude (Choi and Kwon 2000a), the Strouhal numbers for these cutting ratios are larger than for other cutting ratios (Fig. 10(b)). This means that the flow separation from the body is restrained when the effective corner cut size is used, and this results in an increase of the Strouhal number.

In the cases B/D=1.5 and 2.0, the trends of peak amplitudes and Strouhal numbers are somewhat different from those for B/D=1.0 at each angle of attack (Figs. 12(a),(b) and 13(a),(b)). Similarly to the results for the case B/D=1.0, the Strouhal number increases as the corner cut size increases for each angle of attack. However, the Strouhal number has smaller variation, which is different from the results for the case B/D=1.0. It has been found that there exist two different regions which show different characteristics of corner cut effects. The Strouhal numbers within the *Region-II* ($\alpha=15^o$~30^o) are relatively larger than those of *Region-III* ($\alpha=30^o$~45^o) (Fig. 12(b)). As mentioned earlier, a large Strouhal number results from a decrease of the separation width and, therefore, it can be tentatively concluded that the effectiveness of corner cuts in *Region-II* may be better than that in

Region-III.

As the best behavior of all the cutting ratios are shown at the angles of attack from 15^o to 30^o (Figs. 12(a) and 13(a)) for the cases B/D=1.5 and 2.0, the Strouhal numbers in this range of angles of attack have larger values than those of the original section (Figs. 12(b) and 13(b)). These trends are well reflected in the results of the Strouhal number; in other words, the flow separation from the body is restrained, and this results in consequent increase of the Strouhal number when the effective corner cut sizes are used.

From the results for cases B/D=1.0, 1.5 and 2.0 at the angles of attack ranging from 15^o to 45^o, it is observed that the effectiveness of corner cut to reduce the peak amplitude of the vortex-induced vibration can be identified in two regions; namely, the effective region ($\alpha=15^o\sim30^o$) and a less effective region ($\alpha=30^o\sim45^o$) The effective and less effective regions well coincide with *Regions-II* and *III* that are defined in the previos section (Table 4). Therfore, it can be concluded that there is an angle of attack for each B/D, above which the corner cut has little effect and the Strouhal number remains almost constant. This angle of attack is termed as a critical angle of attack. In the cases B/D=1.0, 1.5 and 2.0, this angle is 30^o.

4. Conclusions

The present study investigates into the effect of corner cuts on the Strouhal number of rectangular cylinders (with B/D=1.0, 1.5 and 2.0) for angles of attack ranging from 0^o to 45^o in a uniform flow.

The Strouhal number of the test models increases as the angle of attack(α) increases from 0^o to 15^o and reaches the maximum value at $\alpha=15^o$, then decreases as α increases up to 30^o, and finally has a generally uniform value between the angles of attack of 30^o and 45^o. Also, the Strouhal number decreases as the dimensional ratio increases from B/D=1.0 to 2.0 for all the angles of attack. These trends are shown for all cutting ratios.

The characteristics of the Strouhal number variation can be distinctively classified into three categories based on the general trend of the test results; 1) *Region-I* (up-hill region): where the Strouhal number increases as the angles of attack increases from 0^o to 15^o for all dimensional ratios. This region is known as the galloping dominated region. 2) *Region-II* (down-slope region) : where the Strouhal number decreases as the angle of attack increases from 15^o to 30^o. Instead of the galloping phenomenon, vortex-induced vibrations start to occur in this region. 3) *Region-III* (plane region) : where the Strouhal numbers are relatively uniform in the range of angles of attack from 30^o to 45^o for each corner cut ratio.

There exist two angles of attack of special interest, i.e., $\alpha=15^o$ and 30^o at which the characteristics of Strouhal number variation change abruptly. These two critical angles of attack form the boundaries of the three characteristic regions of Strouhal number variation and of two regions of different effectiveness of corner cuts for the vortex-induced vibration. The angle of attack $\alpha=15^o$, where the Strouhal number reaches the highest point, coincides with the occurrence point the minimum drag coefficient of a rectangular cylinder. And also, this angle is the dividing point between the region dominated by galloping and the region dominated by vortex-induced vibrations. The angle of attack 30^o, above which the Strouhal number shows little change, is the dividing point of the effective and the less effective regions for the corner cut in the region dominated by vortex-induced vibrations.

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