Vind and Structures, Vol. 2, No. 3 (1999) 173-187
DOI: http://dx.doi.org/10.12989/was.1999.2.3.173

Aerodynamic stability for square cylinder with various corner cuts

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Abstract. The flow around a structure has been an important subject in wind engineering research. There are various kinds of unstable aerodynamic phenomena with regard to a bluff body. In order to understand the physical mechanism of aerodynamic and aeroelastic instability of a bluff body, the relations between the flow around structures and the motion of body with various section shapes should be investigated. Based on a series of wind tunnel tests, this paper addresses the aerodynamic stability of square cylinder with various corner cuts and attack angles in the uniform flow. The test results show that the models with corner cut produced generally better behavior for the galloping phenomenon than the original section. However, the corner cut method can not prevent the occurrence of the vortex-induced vibration(VIV). It is also shown that as the attack angle changes, the optimum size of corner cut changes also. This means that any one specific size of corner cut which shows the best aerodynamic behaviors throughout all the cases of attack angles does not exist. This paper presents an intensive study on obtaining the optimum size of corner cut for the stabilization of aerodynamic behavior of cylinders.

Key words: square cylinder; corner cut; aerodynamic stability; wind tunnel experiment.

1. Introduction

The construction of large structures such as long span bridges and tall buildings, which are relatively light and flexible, is recently on the increase. However, the increased flexibility and low natural damping enhance the sensitivity of structures to the dynamic action of wind. These may cause the excessive oscillation, and while this perhaps does not pose significant risk in the structural failure, it may cause discomfort to the occupants and generate serious serviceability problems. To understand the aerodynamic characteristics of the structural systems due to wind, the wind tunnel test is dominantly used as a powerful investigative tool and this trend will continue in the foreseeable future although the fields of theoretical and computational fluid mechanics are making fast progress.

A lot of researchers' efforts have been devoted to minimize the wind-induced response of structures. The reduction methods of the wind-induced vibration are divided generally into three main categories. One is the structural system modification, such as the space

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frames and mega frame systems which can lead to an optimal structural configuration that offers an efficient distribution of wind loads in lateral and torsional directions. The other is the incorporation of auxiliary damping systems, such as TMD, TLD, ATMD and HMD which can lead to the increase of effective damping of a structure and the decrease of structural motion. The method in the last category is the aerodynamic modification, like fairing of the bridge girder and shape modification of a structure with sharp edges. These aerodynamic treatments are found to be effective in reducing the vibration of rectangular sections with relatively small dimensional ratios(B/D), such as tall buildings and bridge towers. These treatments are also effective for stabilization of the near wake or cavity by creating pressure connections between the wake and regions of the building with positive exterior pressures.

The corner cut has been widely accepted as one of the effective aerodynamic stabilizing methods. Many investigations on this reduction method, especially on the study of aerodynamic stability, were carried out in the past. Inoue (1984) investigated the stability of suspension bridge tower with various types of side plates through the 2D and 3D experiments. Koenig (1985) also investigated the effects of side plates through the comparison of drag coefficient and flow visualization. Shiraishi (1986) examined the applicability of the corner cut method in the bridge tower of Higashi-Kobe, and proposed that about 2/18D(0.11D) and 3/18D(0.17D) be the optimum sizes of corner cuts for the rectangular section of the tower with B/D=1.46. However, their tests were performed only for the attack angle of 0°. Their study includes the assessment of the stability of the chamfered corner shapes, which was found to be less effective than the corner cut. Nanjo (1990) performed the parametric studies on the relation between various corner cut sizes and aerodynamic stability for the square cylinder, but no attention was given to the effect of attack angles. Suda (1995) focused their investigation on the effect of the attack angles for the square cylinder with corner cut. However, they used 10% corner cut size only and thus their work lacks the variety of corner cut sizes. Kawai (1993, 1995, 1997) carried out the parametric studies on the rectangular cylinders without corner cuts with various attack angles and damping ratios, but in their extended work with the various corner shapes including corner cuts, the effect of changing attack angles was not considered.

The aforementioned studies commonly showed the effectiveness of the corner cut for the aerodynamic stability if the optimum size of corner cut is used. However, the scope of these previous studies are limited mostly to the stability problems at the attack angle of 0°. More work is thus required to investigate the effects of the various sizes of corner cut and various attack angles simultaneously on the aerodynamic stability of structures.

The present paper is concerned mainly with the aerodynamic stability of square cylinder with various corner cuts under different attack angles in the uniform flow. In the previous studies with a single size of the corner modification (Choi, Ryu and Kwon 1998, Choi and Kwon 1999), the corner cut method is generally found to be more effective than other shape modifications, such as chamfered, rounded and half-squared corners. Since there is no definitive consensus of researchers on the benefits of corner geometry modification yet, obtaining the optimum size of corner cut is very important to avoid any unexpected negative effects (Kijewski, Kareem and Tamura 1998). The observations on these problems are also presented in this paper.

2. Experimental procedure

2.1. Experimental equipment

The experiments were carried out on the Eiffel type wind tunnel at Korea Advanced Institute of Science and Technology(KAIST) whose test section is 1 m × 1 m and the length of test zone is 4m. The wind velocity is controlled by the fan speed(RPM) and maximum velocity is about 17.0 m/s.

To measure the dynamic response(displacement) caused by the galloping and vortex-induced vibration(VIV), the sectional model tests are carried out in the uniform flow. The test model was set up to have two response modes, i.e., the across-wind mode and the torsional mode. The movement of the test model in the flow direction is restrained. Through the pre-testing, it has been known that the wind-induced vibration occurs only in the across-wind mode and does not occur in the torsional mode (Fig. 1).

2.2. Test model and conditions

The wind tunnel experiment is performed first to measure the aerodynamic response of two-dimensional square cylinder(B/D=1.0) with various corner cuts in the uniform flow. Considering the limited wind tunnel size, the detailed test model was manufactured within the 10% blockage ratio based on the previous study (Choi and Kwon 1998). The sizes of corner cuts are 0.00D(no corner cut) and in the range of 0.04D~0.20D increased by 0.02D a step where D is the overall dimension of square section (Fig. 2).

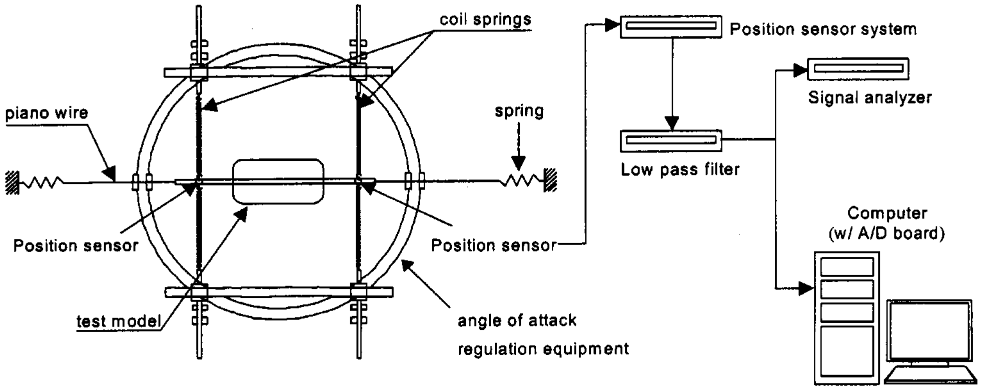

Fig. 1 Set-up of the model and measurement systems

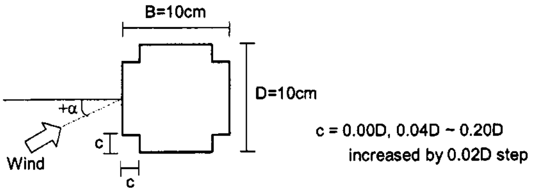

Fig. 2 Cross-sectional shapes of test model (square section with corner cut)

Table 1 Wind tunnel test conditions

Blockage ratio (S/C)	Mass/unit length (kg/m)	Across-wind frequency (Hz)	Logarithmic damping ratio(δ)	Mass-damping parameter $\frac{m\delta}{\rho D^2}$
10.0%	1.05	About 4.0	0.015	1.31

The aerodynamic responses are measured under various attack angles(α), i.e., from 0° to 45° increased by 5 degrees a step, and in the various wind velocities increased by 0.2 m/s a step. The positive direction of attack angle is defined that the upwind side of the model lifts (Fig. 2). Test conditions are given in Table 1.

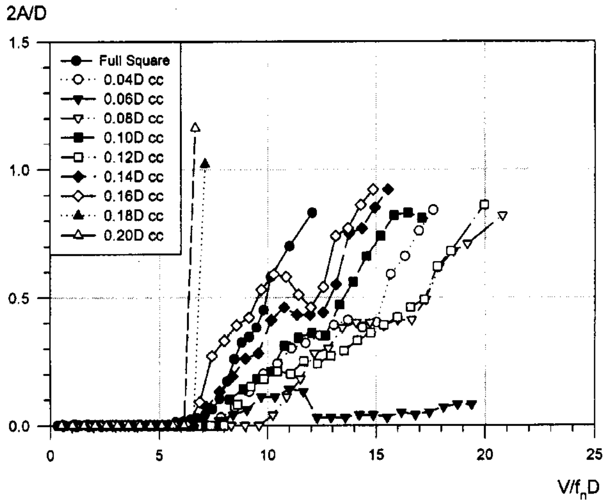

Fig. 3 The aerodynamic behaviors for the square model with cornet cuts ($\alpha = 0°$)

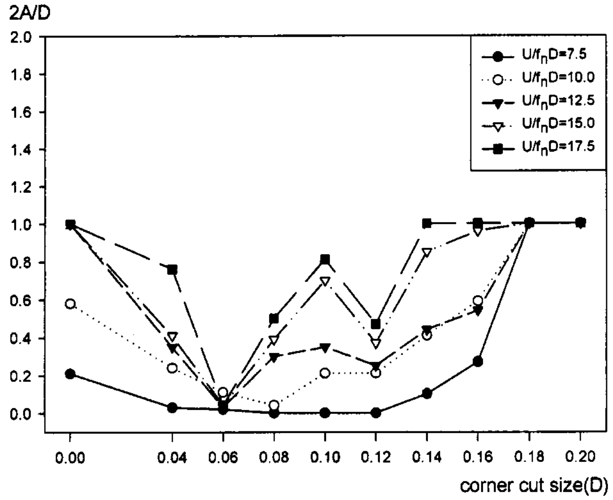

Fig. 4 The aerodynamic behaviors for the various sizes of corner cut ($\alpha = 0°$)

3. Test results

The two important aerodynamic phenomena of this model to be investigated are the galloping and the vortex-induced vibration(VIV). As the galloping is the oscillation of divergent type, this phenomenon must be checked at the onset velocity. The VIV is the limited oscillation which occurs within a certain range of wind velocity only and leads gradually to the problems of structural fatigue and of serviceability. Therefore, it is desired that both phenomena be avoided or kept minimum whenever possible.

For the easy evaluation and comparison, all the test values are converted into the non-dimensional values. For example, in Figs. 3 and 5, the horizontal axis(x-axis) is scaled to the reduced velocity ($V_r = V/F_nD$) and the vertical axis(y-axis) is scaled to the non-dimensional

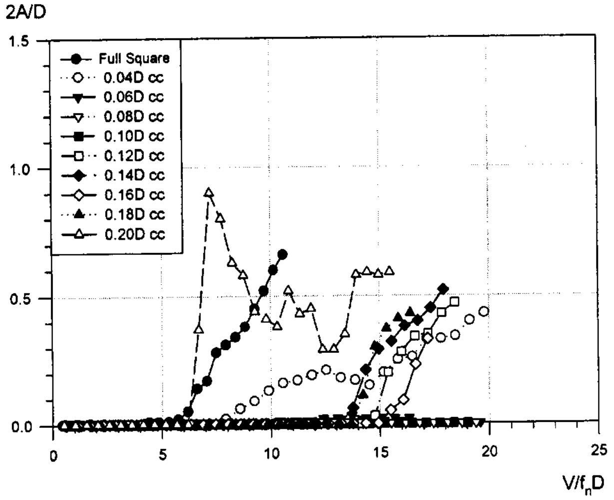

Fig. 5 The aerodynamic behaviors for the square model with corner cuts ($\alpha = 5^{\circ}$)

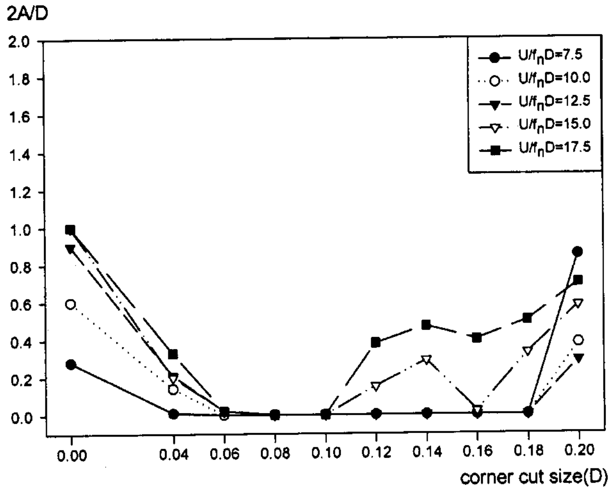

Fig. 6 The aerodynamic behaviors for the various sizes of corner cut ($\alpha = 5^{\circ}$)

response (2A/D). The axes of Figs. 4 and 6 are scaled to the various sizes of corner cut versus the non-dimensional response.

3.1. Case of 0° attack angle

Figs. 3 and 4 show the test results with attack angle of 0°. The galloping phenomenon occurs at the onset-reduced velocity of about 6.0 for the original square section (no corner cut). Kawai's experimental results (Kawai 1993, 1995, 1997) also showed almost the same onset-reduced velocity even though there is a difference between the test conditions of two studies. When the corner cuts are introduced to the original square model, the aerodynamic behaviors are improved in both studies. However, the galloping phenomenon occurred

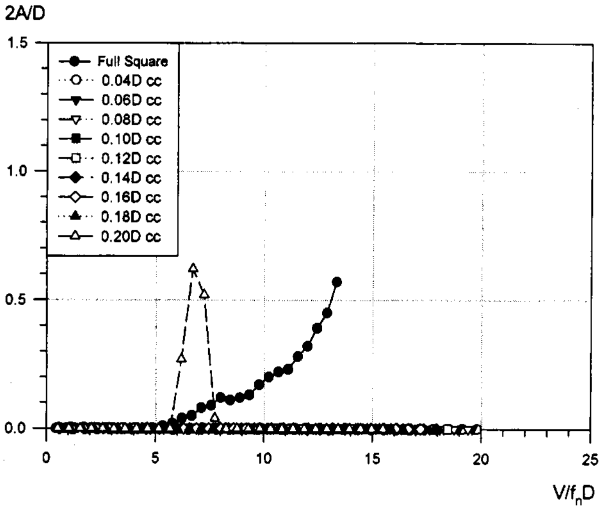

Fig. 7 The aerodynamic behaviors for the square model with corner cuts ($\alpha = 10^{\circ}$)

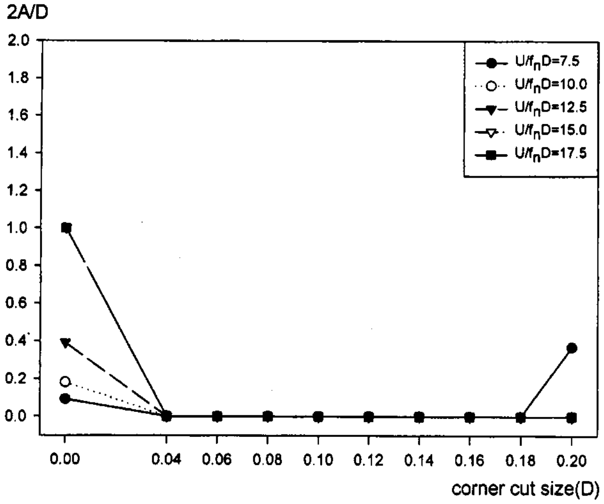

Fig. 8 The aerodynamic behaviors for the various sizes of corner cut ($\alpha = 10^{\circ}$)

inevitably in all the cases except the case of the corner cut of 0.06D in this study. In the cases of 0.04D and 0.08D~0.12D, the improved aerodynamic behaviors are observed (Figs. 3 and 4) and the onset-reduced velocities become a little larger than that of the original section with no corner cut. These should be considered as a favorable effect of corner cut. In cases of 0.18D and 0.20D, the behaviors show the worst divergence at even lower reduced velocity. The size 0.06D shows the best aerodynamic stability where no galloping occurs.

3.2. Case of 5° attack angle

In the case of 5° attack angle, the galloping phenomenon occurs at the onset-reduced

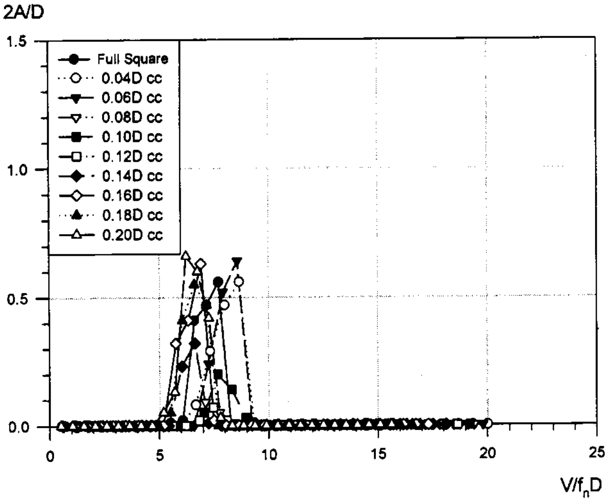

Fig. 9 The aerodynamic behaviors for the square model with corner cuts ($\alpha = 15^{\circ}$)

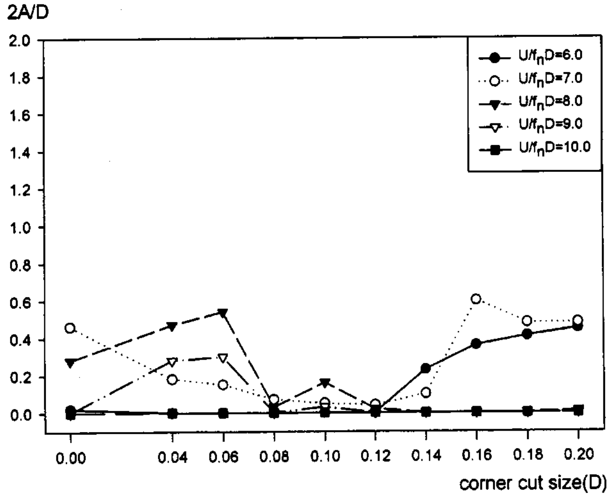

Fig. 10 The aerodynamic behaviors for the various sizes of corner cut ($\alpha = 15^{\circ}$)

velocity of about 6.0 for the original section (Fig. 5) which is almost the same to the case of $\alpha = 0^\circ$. However, the aerodynamic behaviors of the square with corner cut become more improved than in the case of $\alpha = 0^\circ$ (Fig. 6) and it is observed that no galloping occurred in the cases of 0.06D~0.10D. In cases of 0.04D and 0.12D~0.18D, some galloping phenomena occurred, but the overall behaviors are much improved and the onset-reduced velocity become much larger than that of the original section (Fig. 6). In case of 0.20D, the behavior is very complex and somewhat unpredictable.

3.3. Case of 10° attack angle

The galloping phenomenon occurs only for the original section (Fig. 7). When the

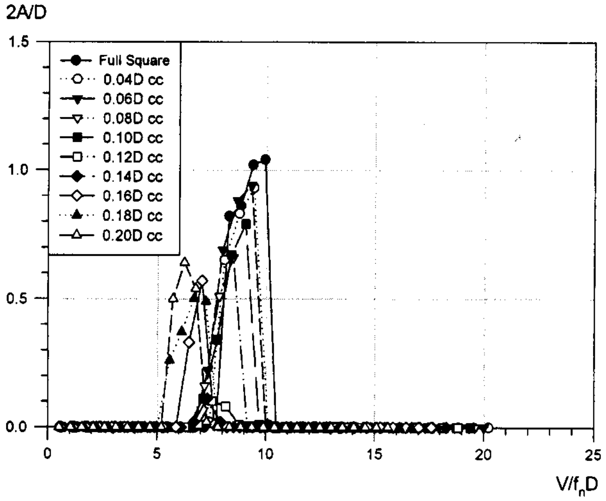

Fig. 11 The aerodynamic behaviors for the square model with corner cuts ($\alpha = 20^\circ$)

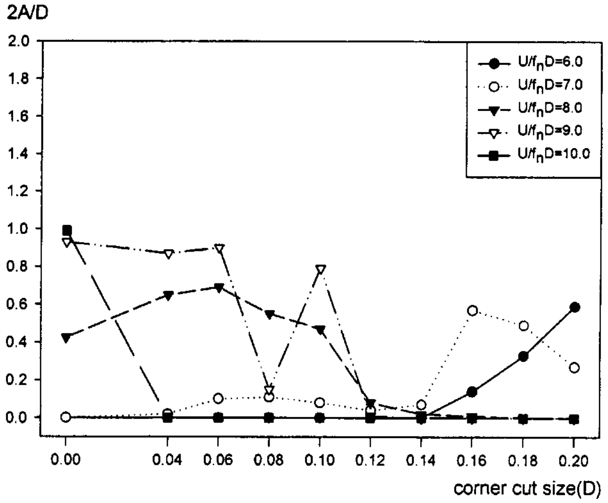

Fig. 12 The aerodynamic behaviors for the various sizes of corner cut ($\alpha = 20^\circ$)

corner cut is used at this attack angle, the galloping behaviors are effectively suppressed regardless of the corner cut sizes. However, in case of 0.20D, a very large vortex-induced vibration in the range of $V_r = 5.7$ and 7.8 is shown.

3.4. Cases of 15° and 20° attack angles

No galloping phenomena are shown at these attack angles (Figs. 9 and 11), but vortex-induced vibration occurred for all the sections including the original section when α is larger than 15°, that is the known critical occurrence point of the galloping phenomenon.

At $\alpha = 15°$, the models with 0.08D, 0.10D and 0.12D corner cuts show the best behavior of which the onset and extinction-reduced velocities of VIV are larger than those of the original

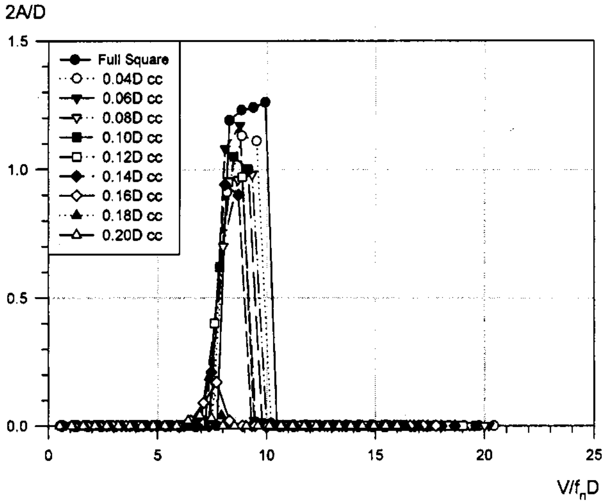

Fig. 13 The aerodynamic behaviors for the square model with corner cuts ($\alpha = 25°$)

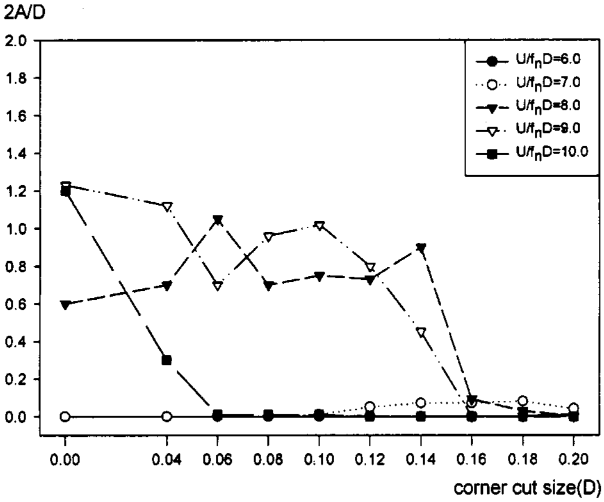

Fig. 14 The aerodynamic behaviors for the various sizes of corner cut ($\alpha = 25°$)

section and the amplitude of response is smaller. In cases of 0.14D, the Fig. 10 shows a little more improved behaviors in terms of the amplitudes of VIV than other cases.

At $\alpha = 20^{\circ}$, the VIV occurs similarly to the case of $\alpha = 15^{\circ}$ (Fig. 11). The amplitudes of VIV of the sections with corner cuts are smaller than that of the original section. As seen in the following section, this trend continues until the attack angle becomes larger than 30°. In cases of 0.12D and 0.14D, better behaviors than other cases are shown (Fig. 12). Since the test model in this study has a relatively small dimensional ratio(B/D), the appearance of Karman type VIV only is observed. Thus, the flow separates at the upwind corners and advances by cyclically alternating vortices that form by turns at the top and bottom edges and finally are swept downstream.

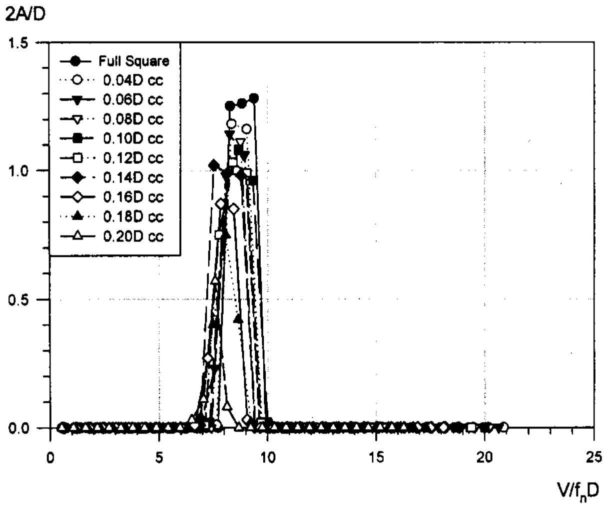

Fig. 15 The aerodynamic behaviors for the square model with corner cuts ($\alpha = 30^{\circ}$)

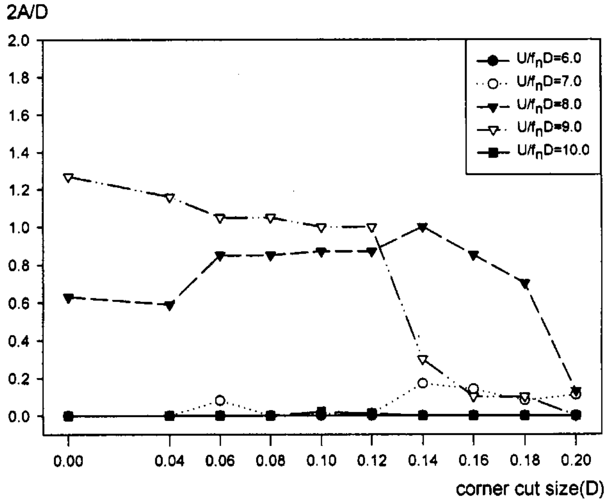

Fig. 16 The aerodynamic behaviors for the various sizes of corner cut ($\alpha = 30^{\circ}$)

3.5. Cases of 25°~45° attack angles

The responses of VIV at these attack angles have larger amplitude than the cases of $\alpha = 15^\circ$ and 20° (Fig. 13). The onset-reduced velocities of models at these attack angles are shown to be almost the same, but the extinction-reduced velocities of models are shown to be a little different. In cases of 0.16D, 0.18D and 0.20D at $\alpha = 25^\circ$, the squares with corner cuts show better behaviors than other cases. Up to the attack angle 30°, the amplitudes of VIV of the squares with corner cuts are smaller than that of the original section (Fig. 15). At $\alpha = 30^\circ$, the model with corner cut of 0.20D behaves best.

In cases of the attack angles of 35° and larger, the characteristics of VIV of the squares with corner cuts are nealy the same regardless of sizes of corner cuts and it is difficult to

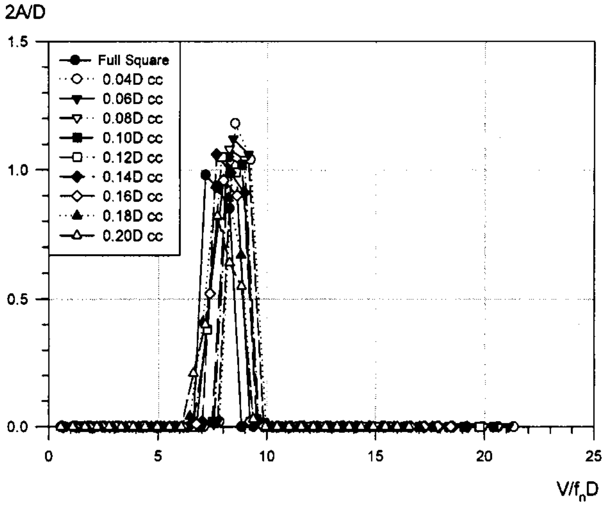

Fig. 17 The aerodynamic behaviors for the square model with corner cuts ($\alpha = 35^\circ$)

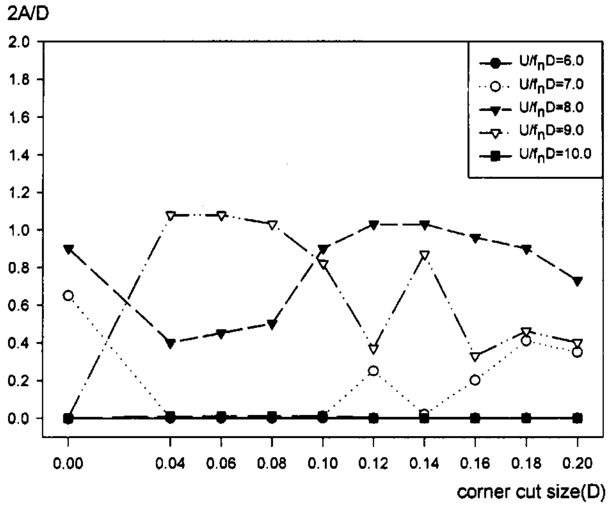

Fig. 18 The aerodynamic behaviors for the various sizes of corner cut ($\alpha = 35^\circ$)

distinguish any better corner cut values. Thus, the onset and extinction-reduced velocities of squares with corner cuts are concentrated in the range of approximately 6.0~10.0.

3.6. General observations

From the above experimental results, it is observed that the aerodynamic behaviors of the test models can be divided into three main categories; (1) The galloping dominant region at the relatively small attack angles ($\alpha = 0°$~$10°$), (2) The transient region between the regions of galloping and vortex-induced vibration with relatively small amplitude of response ($\alpha = 15°$, $20°$), (3) The vortex-induced vibration dominant region at the relatively large attack angles ($\alpha = 25°$~$45°$). Also from the test results, it is shown that in the range

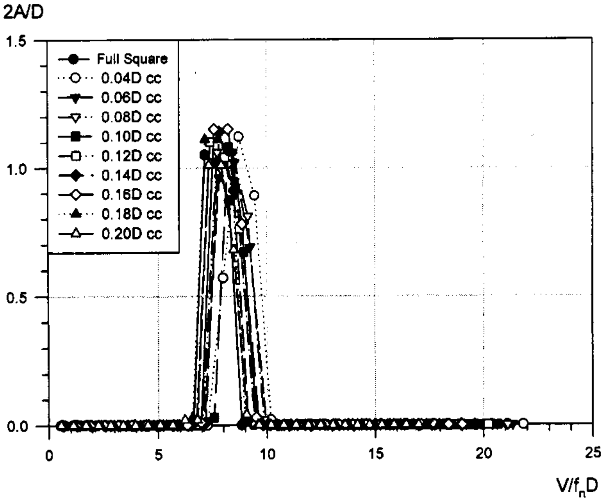

Fig. 19 The aerodynamic behaviors for the square model with corner cuts ($\alpha = 40°$)

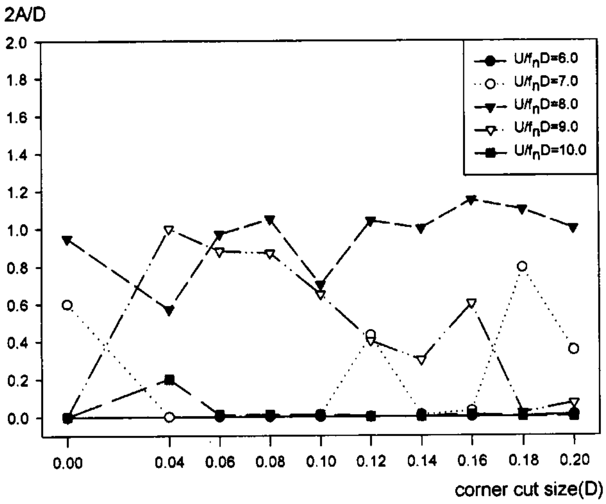

Fig. 20 The aerodynamic behaviors for the various sizes of corner cut ($\alpha = 40°$)

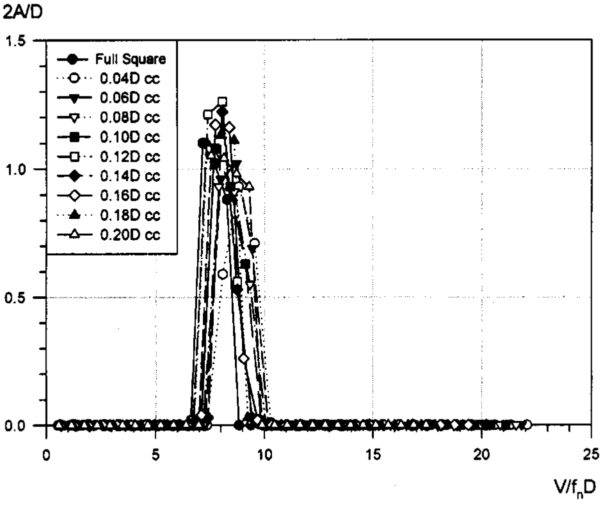

Fig. 21 The aerodynamic behaviors for the square model with corner cuts ($\alpha = 45°$)

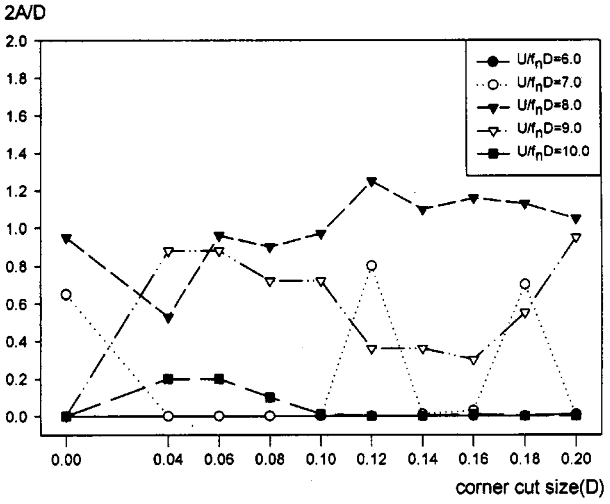

Fig. 22 The aerodynamic behaviors for the various sizes of corner cut ($\alpha = 45°$)

of small attack angles (0°~10°), the corner cut effect on aerodynamic stability for the galloping phenomenon is clear and increases as the attack angle is increased. The corner cut effects on stability for the vortex-induced vibration in the range of large attack angles (15°~45°) are not so large as the case of galloping phenomenon at the small attack angles and the sizes of corner cut do not make any significant difference. Thus, the optimum size of corner cut is important for stabilization of the aerodynamic behavior of cylinders only when the attack angle is small.

Table 2 shows the effective sizes of corner cut at each attack angle. As the attack angle changes, the optimum size of corner cut changes also. This means that it is hard to define any one specific size of corner cut as the best one for the aerodynamic behaviors throughout all the cases of attack angle. However, based on the overall behaviors of squares with different

Table 2 The effective sizes of corner cut at each attack angle

Attack angle(α)	Ineffective	Moderatelly effectives	Highly effective	Remarks
0	0.18D, 0.20	D0.04D, 0.08D~0.12D	0.06D	Galloping dominant region
5	0.20D	0.04D, 0.12D~0.18D	0.06D~0.10D	
10	-	0.20D	0.04D~0.18D	
15	-	0.14D	0.08D, 010D, 0.12D	Trasient region
20	-	0.16D, 0.18D, 0.20D	0.12D, 0.14D	
25	-	-	0.16D, 2.18D, 0.20D	VIV dominant region
30	-	0.16D, 0.18D, 0.20D	-	
35	-	-	-	
40	-	-	-	
45	-	-	-	

corner cut sizes and attack angles, the sections with larger corner cut ratios, for example, 0.18D and 0.20D, should be avoided.

4. Conclusions

The present paper is concerned with a parametric study on the aerodynamic stability of square cylinder with various corner cuts. A series of tests were carried to investigate into the galloping phenomenon and vortex-induced vibration of the square cylinders with various sizes of corner cut and different attack angles in the uniform flow.

From the experimental results, aerodynamic behaviors for the test models can be divided into main categories, i.e., the galloping dominant region ($\alpha = 0^\circ \sim 10^\circ$), the transient region($\alpha = 15^\circ$, 20°), and the vortex-induced vibration dominant region ($\alpha = 25^\circ \sim 45^\circ$). The test results also show that the corner cut has the effect of increasing the aerodynamic stability for the galloping phenomenon with the increasing attack angle in the range of small attack angles ($0^\circ \sim 10^\circ$). Especially, the case of corner cut size of 0.06D at $\alpha = 0^\circ$ shows the best aerodynamic stability where neither galloping nor VIV occurs. The corner cut effect on stability for the vortex-induced vibration in the range of large attack angles ($15^\circ \sim 45^\circ$) is not so significant as the case of galloping phenomenon at the small attack angles and the sizes of corner cut do not make any significant difference. However, the amplitudes of VIV of the sections with corner cuts are smaller than the original section until the attack angle becomes larger than 30°.

As the attack angle increases, the optimum size of corner cut is also increased gradually. Even if it is hard to define any one specific size of corner cut as the best one for the aerodynamic behaviors throughout all the cases of attack angles, the corner cut is one of the effective methods to improve the aerodynamic behaviors of square cylinder.

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(*Communicated by Managing Editor*)