Experimental study on the mechanism of in-flow oscillation of cylinder arrays

Tomomichi NAKAMURA
Osaka Sangyo University, Daito, Japan

Hiroaki KONDO, Shinji NOBUTA, Junpei OKAMOTO, Yutaka TAKAHASHI
Osaka Sangyo University, Daito, Japan

ABSTRACT

The importance of the in-flow oscillation of a single cylinder in cross-flow has been highlighted since an accident in a FBR-type reactor. In-flow oscillations have also been observed in tube arrays. In our previous report an experimental study on this phenomenon has been reported, where a total of nine cylinders in a water tunnel, one single cylinder, two & three cylinders in parallel & in tandem, and a four-cylinders bundle, have been examined. The results indicate that some coupled in-flow motions as in cylinder arrays have been excited both with symmetric shedding vortex and alternate vortex shedding. However, it is required to confirm whether these coupled motions of the cylinder array are caused only by vortex shedding or with another mechanism such as the fluid-elastic instability, or to distinguish the above mentioned two types of vortex mechanisms. Then, the test cylinders and the flow section are modified to examine this mechanism in the present work.

1. INTRODUCTION

The stream-wise oscillation of a circular cylinder caused by cross-flow is known as to be result of alternating vortex shedding behind the cylinder. Similar oscillations due to symmetric vortex shedding became famous after the event of the fast breeder reactor "Monju" in Japan, where a slender cylinder broke with the vibration in the stream-wise direction due to symmetric vortex shedding. A guideline has been developed for a circular cylinder in a pipe (JSME, 1998).

The Karman-type alternating vortex shedding frequency is expressed as a linear function of flow velocity as the following equation,

$$f_K = St\frac{U}{D}. \tag{1}$$

This Karman-type alternating vortex shedding does not act only in the cross-flow (lift) direction, but it does also in the stream-wise direction at double the frequency of the lift direction (King and Prosser, 1973). There has been reported to be another type of vortex shedding with a symmetric vortex shedding behind cylinders with higher Strouhal number.

The JSME's guideline (1998) presents methods to avoid severe accidents for single circular cylinders. This method may not work for arrays of cylinders. One of this paper's authors found a similar vibration is observed even for an array of cylinders (Feenstra et al., 2002), and a similar result had been obtained in Weaver and Abd-Rabbo's earlier work (1985). There are a lot of research works on the flow around a pair of cylinders (King and Johns, 1976; Zdravkovich, 1985 etc.), or around an array of cylinders (Zdravkovich and Stonebanks, 1990). However, there are few detailed research works (Okajima, 2005) on the case where the cylinders are free to move only in the stream-wise direction.

In our previous study (Nakamura et al., 2007) it was found that the above two excitation-mechanisms correspond to stream-wise direction fluid forcing in a cylinder array, and that the excitation frequencies couple with the frequencies of fluid-coupled modes of cylinder arrays, but there was a mixed flow region having both symmetric and alternative shedding vortex. It is the purpose of this paper then to investigate the main mechanism in this region, in particular whether it might possibly be the fluid-elastic mechanism.

2. TEST APPARATUS

2.1 Test loop

Fig.1 shows the whole test apparatus. The main flow is through a square cross sectional pipe of 90 mm section, where water flow is generated by a pump below the main pipe. The tank on the left is a reservoir.

Flow straightening is achieved with a mesh unit composed of an array of straws at the up-stream

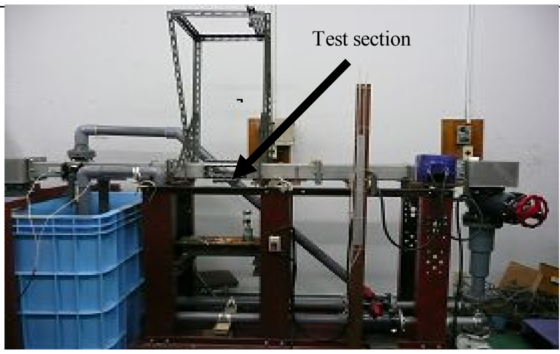


Fig.1 Test apparatus

region of the test section.

The flow velocity is controlled by a valve and an inverter power unit, and measured by an ultrasonic flow velocity sensor at the upstream region of the test section.

2.2 Test cylinders

As indicated in Fig.1, the test section is the square pipe, where the maximum nine cylinders can be set. The cylinders are 20 mm in diameter, and 84 mm in length. These are light weight tubes made by of plastic. They are supported with a stainless steel plate of 1.5 mm thickness and 4 mm in width as shown in Fig.2, on which strain gages are mounted to measure the cylinder response.

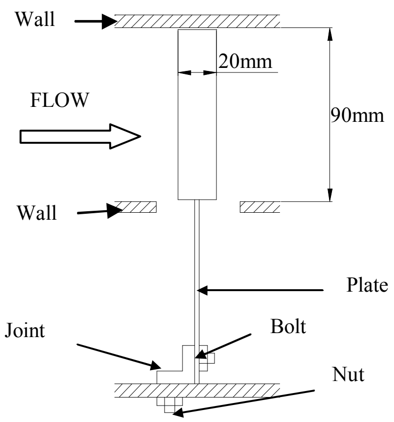


Fig.2 Concept of test cylinders

Every cylinder can move only in the in-flow direction. Some of these cylinders have a rectangular plate, “protrusion,” protruding to a 2-mm height normal to the cylinder surface to prevent vortex separation from the surface as shown in Fig.3. This is a new mechanism to investigate the difference with the vortex shedding and instability.

The cylinder motion is measured by the strain gages and by a high-speed digital video camera. The results are compared with the visualized vortex motion. The test loop is modified to obtain lower flow velocities to examine the occurrence of the phenomena at the initial stage with increasing the by-path flow of the loop; this could not achieved with the previous test loop.

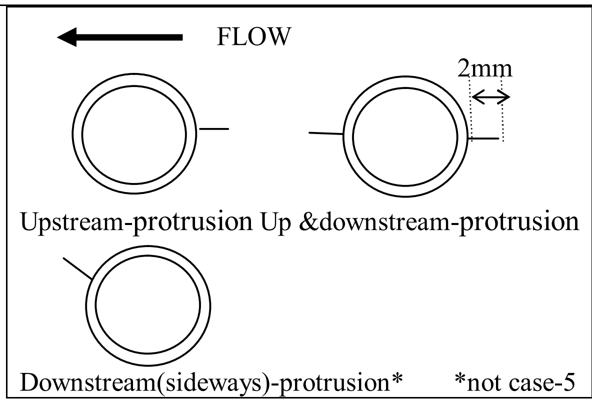


Fig.3 Measured cylinder arrays with projection

Table 1 shows the tested cylinder arrays, including the case of a single cylinder, where the pitch, P, between cylinders is a constant value of P=30 mm, corresponding to P/D=1.5. Measured natural frequencies and corresponding damping ratios of the test cylinders in water are around 9Hz and 2 %, respectively. All cylinders have the same average vibrational characteristics.

Table 1 Measured cylinder patterns

Single	Tandem	Parallel	Square
1 cylinder	2 cylinders	2 cylinders	2 by 2 cylinders
	3 cylinders	3 cylinders	

2.3 Test method

Cylinder responses are measured via strain gages mounted on the support plates as flow velocity is increased. In some cases the flow is observed with a high speed digital video camera, while injecting black ink into the flow in the upstream region.

For the case of the single cylinder pattern, the position of the plates was tested at nine different orientations on the cylinder surface to examine the effect of blocking vortex shedding from the surface of the cylinder. Three orientations are set for the cases of cylinder arrays from this result.

For the cylinder array, the flow velocity is expressed as gap flow velocity using the following relation.

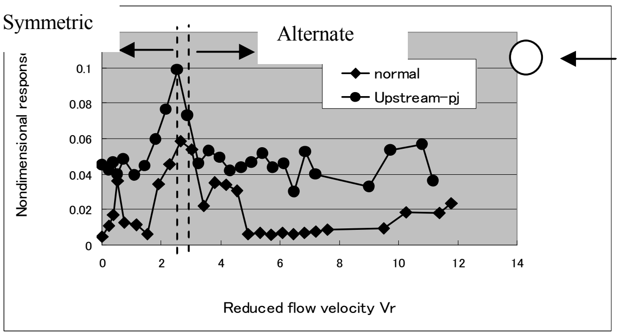
$$U_G = \frac{P}{P-D} U_\infty \qquad (2)$$

3. TEST RESULTS

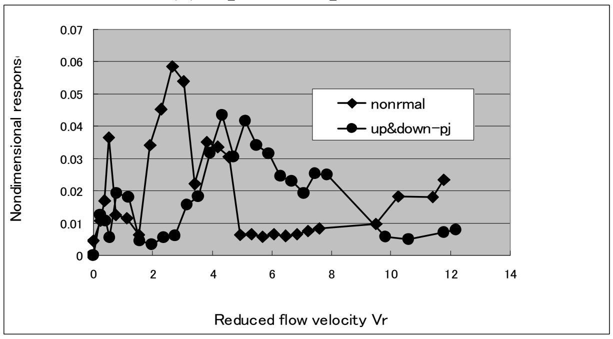
3.1 Single cylinder

Nine orientations of the plates in the case of a single cylinder are examined to compare the differences in the response to the result of single cylinder without protrusion. Fig.4 shows an example of results, where the response amplitude, x, of the cylinders is non-dimensionalized by the cylinder diameter as

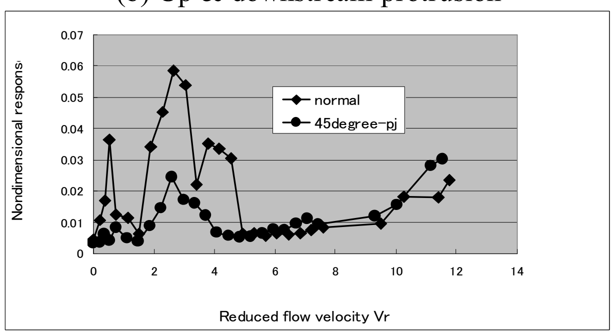
$$\xi = x / D . \qquad (3)$$



(a) Upstream-protrusion



(b) Up & downstream-protrusion



(c) Downstream (sideways)-protrusion

Fig.4 Response of single cylinder

Fig.4(a) shows the comparison between the response of a bare cylinder (expressed as "normal") and the case where the protrusion is set on the upstream surface. This case shows that the upstream protrusion seems to have a great effect on the response. However, on the data of the bare cylinder there are three peaks in Vr=0.5, 2.5,and 4, where the peak of Vr=4 corresponds to the alternating shedding vortex and the peaks for lower reduced flow velocities correspond to symmetric shedding vortexes, and Vr=0.5 (St=2) corresponds to a rarely reported higher Strouhal number, which is in the region of symmetric shedding vortex.

Fig.4(b) shows the comparison between the response of the bare cylinder and the case where two plates are set on the upstream and downstream sides. There is no peak now at Vr=2.4. It may therefore be considered that symmetric vortex shedding has disappeared in this case.

Fig.4(c) shows the comparison of the case where the plate is oriented at 45 degrees from the downstream position. This result seems to eliminate the alternating vortex shedding at Vr=4, but the symmetric vortex shedding at Vr=2.5 remains.

Then, the following tests have been conditioned with these three cases with projections.

3.2 Two cylinders in tandem

At first, a pair of bare cylinders is examined as in Fig.5, where two cylinders have a peak in the range from Vr=2 to 4. From the observation by a high-speed camera, the symmetric vortex shedding is observed up to Vr=3, and it swithches to the alternate vortex shedding from Vr=3.2.

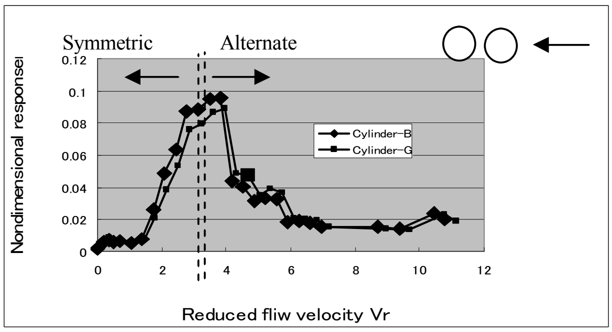


Fig.5 Two cylinders in tandem (Normal surface)

Fig.6 shows the result of cases with the three types of protrusions. Although there seems to be no great difference among these four cases, there are some difference on the region of the vortex shedding. In the case of the upstream protrusion, the symmetric shedding vortex appears up to Vr=4, and it continues to Vr=4.3 in the case of upstream & downstream protrusions, where the over all peak

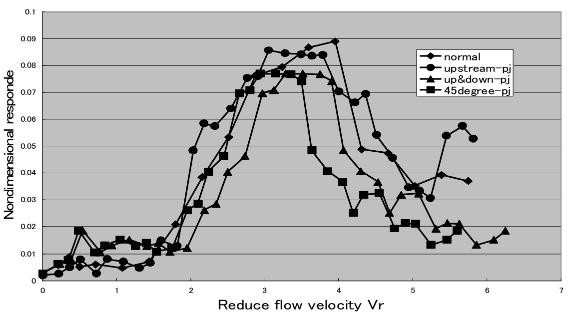


Fig.6 Two cylinders in tandem (Comparison)

comes from the symmetric shedding vortex. In the case of 45-degree protrusion, symmetric vortex shedding appears only up to Vr=3.5.

These results do not correspond to the results observed in Fig.4. However, it is reasonable that the upstream and downstream protrusions prevent the alternate vortex shedding, and that 45-degree protrusion prevents symmetric vortex shedding. This indicates that the peak of the response can be caused by single vortex shedding and by mixed vortex shedding.

3.3 Three cylinders in tandem

Similarly to Fig.5, Fig.7 shows the response of three cylinders with no protrusion. There are differences in the peaks depending on the position of the cylinders, which is the same result as reported in the previous paper (Nakamura et al, 2007). As a result, the peak of the down stream cylinder shifts to higher flow velocity, and the symmetric vortex shedding is observed up to Vr=5, which is the case for almost all peaks.

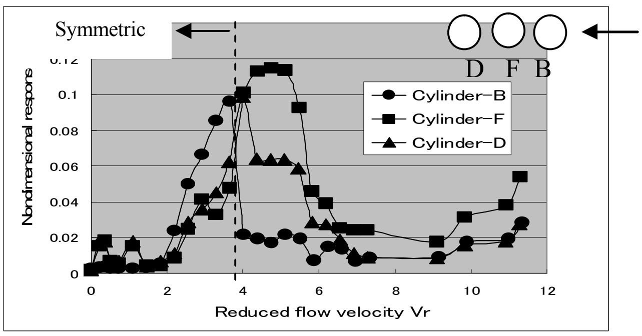


Fig.7 Three cylinders in tandem (Normal surface)

Fig.8 shows the results of cases with protrusions. In these three graphs, there is no clear difference with the result of the bare surface cylinder in Fig.7. This comes from the fact that almost all peaks correspond to the symmetric vortex shedding for three cylinders in tandem.

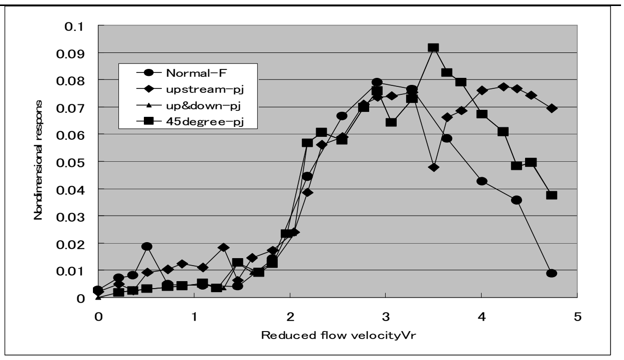


Fig.8 Three cylinders in tandem (Comparison)

3.3 Two cylinders in parallel

At first, the measured results of two bared cylinders in parallel is shown in Fig.9. There are two peaks, Vr=2 and Vr=8, but the latter peak corresponds to the alternate shedding vortex, where cylinders tend to oscillate in the cross-flow direction.

From the high-speed camera observation, the symmetric shedding vortex is observed up to Vr=2, and the alternate vortex shedding appears from Vr=3.5.

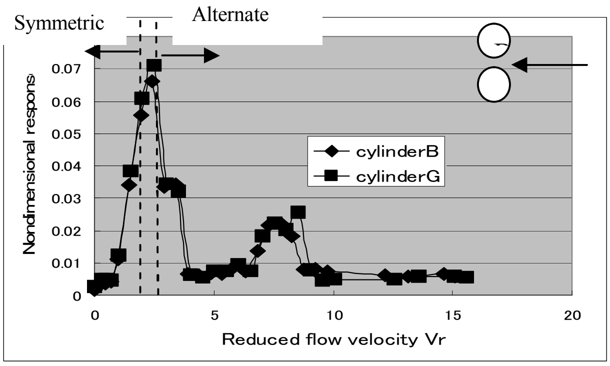


Fig.9 Two cylinders in parallel (Normal surface)

Fig.10 shows the results of cases with protrusions. In the cases of upstream and downstream protrusion, there seems to be a slight shift of the peaks, but from the high speed camera observation the symmetric shedding vortex appears only up to Vr=1.7~2, and these peaks correspond to the alternate vortex shedding or the alternate motion of the cylinders. The last phrase means that the motion of cylinders is the same phase at lower flow velocity and it changes to the out-of-phase at higher flow.

The case with 45-degree protrusion does not show any clear peak, but the flow character is similar to the other cases.

3.4 Three cylinders in parallel

Similarly to Fig.9, Fig.11 shows the response of

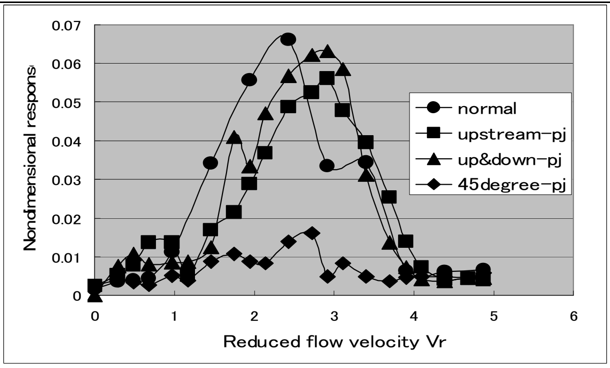


Fig.10 Two cylinders in parallel (Comparison)

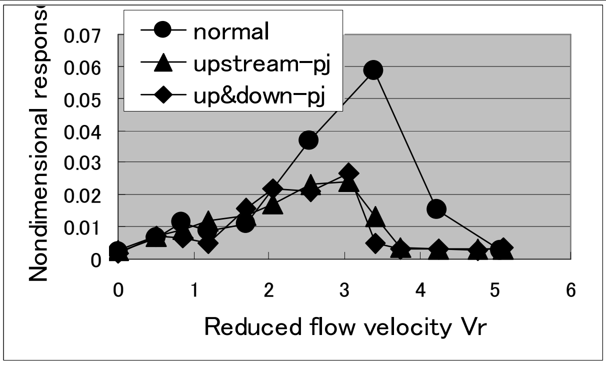


Fig.12 Three cylinders in parallel (Comparison)

three cylinders with no protrusion. In this case, there are two peaks as in Fig.9, and the peak at higher flow velocity shows severe oscillations in the cross-flow direction due to the alternate shedding vortex. The symmetric shedding vortex appears up to Vr=2, and even at the lower peak the flow seems to be dominated by an alternate vortex shedding.

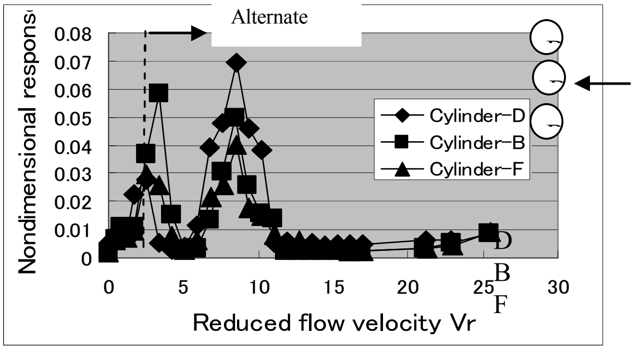


Fig.11 Three cylinders in parallel (Normal surface)

In this cylinder array pattern, the protrusion is set only upstream and downstream. The measured results are shown in Fig.12. This figure shows the data of the center cylinders in each case. The protrusions seems only to decrease the amplitude of the response, but in the case of up & downstream protrusions overall peak shows the alternate vortex shedding although in the other cases the first part seems to be the symmetric vortex shedding.

In these cases, the oscillation of the cylinders is in the cross-flow direction.

3.5 Two-by-two cylinders array

At first, the measured results of two bare cylinders are shown in Fig.13, where a peak from Vr=2 to Vr=4 is observed. However, the vibration mode of the cylinders shifts as shown in Fig.14. At first, all cylinders oscillate in the same phase. Secondly it switches to another mode and so on.

Symmetric vortex shedding is observed up to Vr=2.2, and it turns to the alternate shedding from Vr=2.5. Then, the first region of the peak corresponds to symmetric vortex shedding and the other parts to alternate shedding.

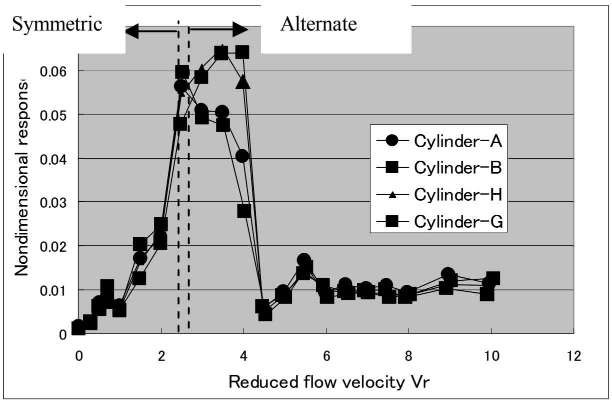


Fig.13 Two-by-two cylinder array (Normal surface)

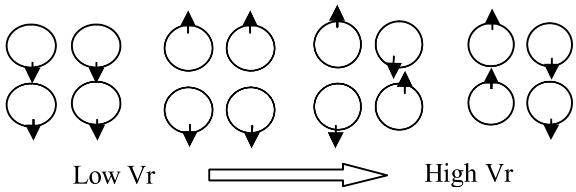


Fig.14 Vibration mode of cylinders

Fig.15 shows the results of cases with protrusions. In the cases of upstream and downstream protrusion, there seems to be a slight shift of the peaks, but basically it is similar to Fig.13. However, 45-degree protrusion destroys the alternate vortex shedding, and the response decreases.

4. DISCUSSION

Summing up the above results, Table 2 shows the estimated resonant range both by the symmetric and the alternate vortex shedding in terms of the Strouhal number (=1/Vr).

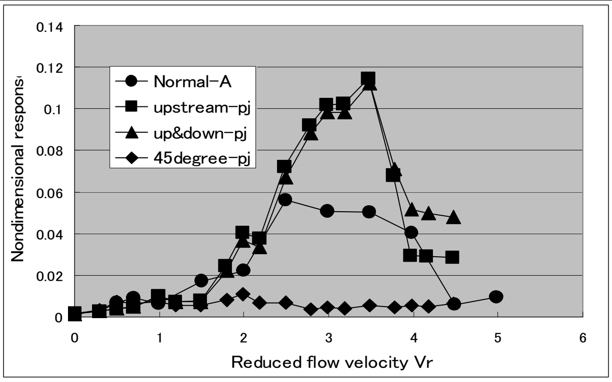


Fig.15 Two-by-two cylinder array (Comparison)

In this model, the resonance Strouhal number due to the symmetric vortex shedding is from St=0.2 to 1.0, and it can be larger for the case of parallel and square arrays. This result shows that the Strouhal number for the alternate vortex of the tube array is much larger than that of the single tube.

The effect of the protrusions widens the resonant range, and it shows the resonant peak can be created only by the symmetric shedding vortex. This means that the symmetric vortex has to be considered in the design for the wide range of Strouhal number (=0.2~1.0) in the in-flow direction.

Table 2 Resonant range in Strouhal number

Array		Protrusion	Symmetric	Alternate
Single		Normal	0.33~	~0.29
		Upstream	0.33~	~0.31
		Up&down	0.33~0.67	~0.29
		45-degree	0.45~0.53	~0.14
Tandem	2	Normal	0.36~0.59	~0.29
		Upstream	0.25~0.63	~0.22
		Up&down	0.25~0.56	~0.22
		45-degree	0.29~0.56	~0.28
	3	Normal	0.21~0.5	Not clear
		Upstream	0.22~0.67	Not clear
		Up&down	0.22~0.56	Not clear
		45-degree	0.29~0.56	~0.24
Parallel	2	Normal	0.4~1.0	~0.26
		Upstream	0.36~1.43	~0.3
		Up&down	0.5~0.56	~0.45
		45-degree	No peak	~0.45
	3	Normal	0.67~1.0	~0.34
		Upstream	0.4~0.67	~0.33
		Up&down	No peak	~0.27
Square (2 by 2)		Normal	0.45~0.67	~0.34
		Upstream	0.33~0.63	~0.33
		Up&down	0.29~0.56	0.67~0.77
		45-degree	0.53~	Not clear

In addition, a small peak has been observed at St=2.0 in Fig.4. This can also be considered in design.

5.CONCLUSION

The effect of sheet plates axially attached on the surface of cylinders is not so clear, but it shows that the resonance of cylinders is not only by the combination with the alternate shedding vortex, it can be caused by the symmetric vortex shedding itself. This result suggests that the symmetric shedding vortex in the in-flow direction has to be considered from the Strouhal number 0.2 to 1.0, and possibly 2.0 also.

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