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STUDY ON STREAM-WISE FLUIDELASTIC INSTABILITY BY AIR CROSS FLOW (ROTATED TRIANGULAR ARRAYS WITH INDEX)

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ABSTRACT

The stream-wise fluidelastic instability of tube arrays has recently been in the limelight due to the practical problem of an event in a steam generator in 2012. Although fluidelastic instability has been studied by many investigators for many years since at least 1968, it has been considered to occur mainly in the transverse direction in steam generators; although the possibility of stream-wise instability may have been anticipated, at least theoretically. Following the confirmation of its existence in the U-bend region of a steam-generator in 2005, some experimental studies have been conducted by a few researchers. Through these efforts it has been revealed that rotated triangular arrays are easily susceptible to stream-wise fluidelastic instability. The same instability is hardly observed in square arrays, although the transverse fluidelastic instability is observed in both arrays. The number of adjacent flexible cylinders plays an important role; for instance, a single flexible cylinder is found to be stable in the stream-wise direction even in rotated triangular arrays. On top of these characteristics, the effect of the pitch-to-diameter ratio plays an important role in the stream-wise fluidelastic instability. Indexing is usually adapted in steam generator design. This paper presents an experimental study on the effect of indexing on the stream-wise fluidelastic instability of rotated triangular arrays.

NOMENCLATURE

f, D:frequency & diameter of cylinder
m:mass of cylinder per unit length
P:pitch of cylinder array in flow direction
Vc, V_∞:critical flow velocity, approaching flow velocity
V_g:gap flow velocity(=P$\times V_\infty$/(P-D))
Vr:non-dimensional flow velocity(=V/(f$\times$D))
δ :logarithmic damping ratio
ς:non-dimensional displacement of cylinder
ρ :mass density of fluid

INTRODUCTION

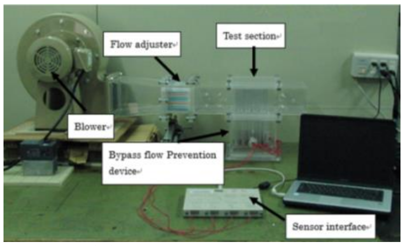
Fluidelastic vibration of tube arrays subjected to cross-flow is a kind of flutter phenomenon which has been studied by investigators since at least 1966 as indicated in the text [1]. It has been considered to occur mainly in the direction transverse to the flow, although the possibility of stream-wise instability may have been anticipated [2]. The possibility of stream-wise fluidelastic instability can be anticipated from the fact that the motion of tubes, when they are unstable, sometimes shows a figure-of-eight orbit. In addition, the first paper on fluidelastic vibrations describes stream-wise fluidelastic instability [3], not transverse direction vibrations. Measured data of the fluidelastic fluid forces had also indicated the possibility of stream-wise fluidelastic instability [2]. Despite the above information, fluidelastic vibration has been considered to occur mainly in the direction transverse to the flow. This view has been reasonably and generally accepted for the design of many heat exchangers. Steam generators for PWR type nuclear power plants in particular, consist of U-bend tubes which can easily move in the transverse direction. Due to this the tubes are supported with anti-vibration bars.

The stream-wise fluidelastic instability of tube arrays has recently been the focus of interest due to the practical problem related to an event in a steam generator in 2012 [4]. However, even after the finding of its existence in the U-bend region in 2005 [5], experimental studies have been conducted only by a few researchers. This is because anti-vibration bars in the U-bend region are considered effective in the in-plane direction, which corresponds to the the stream-wise direction, due to the friction forces at the anti-vibration bars. Even with limited data on the stream-wise fluidelastic instability, the rotated triangular array is the array most easily susceptible to the occurrence of the stream-wise instability [6]. For the other cylinder arrays, the normal triangular array does not easily undergo stream-wise instability [7], and the normal square array is even less susceptible to stream-wise instability [8], although even in these arrays the transverse fluidelastic instability is easily observed.

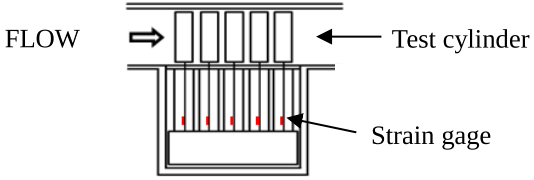
Then, it is most important to study stream-wise instability for the rotated triangular array. The occurrence of the instability, a strong dependence on the pitch-to-diameter ratio, especially in the stream-wise fluidelastic vibration. This paper presents results of tests on the rotated triangular arrays with the “index”. The index is defined as the wider pitch in the flow direction even in the triangular arrays, which is usually adapted for design of steam generators.

1. TEST FACILITY

Fig.1 shows the test equipment. The cylinders, 102mm in length and 20mm in diameter, are supported, as cantilevers, by thin stainless steel plates, 1mm in thickness and 6mm in width, as shown in Fig.1(b).



(a) Test equipment



(b) Measured cylinder

Fig.1 Test equipment

The basic cylinder array geometry is shown in Fig.2. The following pitch ratios of this triangular array are tested: P_0/D=1.2, 1.33 and 1.5, where P_0 indicates the original pitch. In gap with the side wall are set half dummy tubes as indicated in Fig.2. As the test on the effect of the index, the pitch P in Fig.2 is changed in each test to three patterns, as $P=P_0$, $P=1.15P_0$, and $P=1.3P_0$, while the pitch in the transverse direction T is constant in each case as $T=\sqrt{3}P_0/2$.

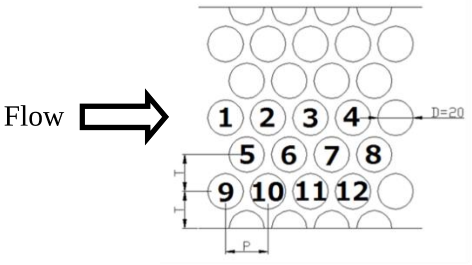


Fig.2 Basic cylinder array

All tests have been conducted with all cylinders flexible except the half-cylinder dummies at wall. Cases with only the center line cylinders flexible (No.1 to 4 plus one), have also been done.

A thin plate cover is also introduced below the flexible tubes to minimize bypass flow into the protrusion below the test section containing tube supports. Each cylinder is supported by a thin plate limiting motion to only the stream-wise direction or the transverse direction depending on plate orientation.

The vibrational characteristics are shown in Table 1. In this table, all cylinders are supported flexibly for each test case.

Table 1 Vibrational characteristic of monitored cylinders

P/D		1.2	1.33	1.5
Freq. (Hz)	Stream-wise	6.1-6.6	6.1-6.6	6.1-6.7
	Transverse	6.1-6.6	6.1-6.6	6.1-6.7
Damping ratio (%)	Stream-wise	0.22-0.91	0.27-0.69	0.22-0.89
	Transverse	0.12-1.36	0.19-0.55	0.11-0.71

Air flow comes from a blower [Syowa Electric AH-H07-L313], and the flow velocity, controlled by an inverter [Mitsubishi Electric FR-D720-0.75K], is measured by an anemometer [Sato AM-4204] located just upstream of the cylinder array. The velocity has also been checked downstream of the cylinder arrays. The range of Reynolds number is $Re=2.0\times10^3 - 3.7\times10^3$, based on V_∞ and the diameter of the cylinder. All flow velocities are expressed as the gap flow velocity, related to the upstream velocity by

$$V_g = V_\infty \times P/(P-D) \quad (1)$$

The cylinder response is measured by strain gages [Kyowa KFWS-2N-120-C1-11 L3M2R] mounted on the surface of the support plates. The response data are converted from strain to displacement based on the static measurement with a sensor interface [Kyowa PCD-300A]. Measurement cylinders that we focus on are mainly in the central region of each array, as indicated in Fig.3. In addition, each support plate is covered with a paper cylinder to prevent the bypass flow from the bottom hole of each cylinder.

2. TEST RESULTS(STREAM-WISE DIRECTION)

The following results are introduced for each cylinder array, with spacing from P/D=1.2 to P/D=1.5. As there are many data, only the case of fully flexible array is described in this section. The cylinder response is expressed as a non-dimensional form ς (=rms displacement/D), which shows a bit smaller number, but it becomes larger after the cylinder becomes unstable and impacts with adjacent cylinders.

2.1 Results of P/D=1.2

Fig.3(a) shows the typical measured response of the cylinders for the case of the original pitch P=P_0 in the stream-wise direction; where the flow velocity gradually increases. Figs.3(b)&(c) show the corresponding results for arrays of the index, P=1.15P_0 and P=1.3$P_{0,}$ respectively. The number in the figure identify the measured cylinder as indicated in Fig.2. From these results, Cylinder No.3 is the easiest cylinder to become unstable, and the critical flow velocity does not change so much depending on the index. The critical flow velocity has been judged mainly by the trend as shown in the figures, but it is clear also from the frequency spectrum as shown in Fig.4.

2.2 Results of P/D=1.33

Similar introduction of the test results are shown here for the test pattern of P/D=1.33. Fig.5(a)-(c) shows the example response of measured cylinders at the case of original pitch P_0=1.33 in the stream-wise direction. Even in this case, Cylinder No.3 is the most unstable in each case. However, there is no significant difference on its natural frequency and the damping ratio.

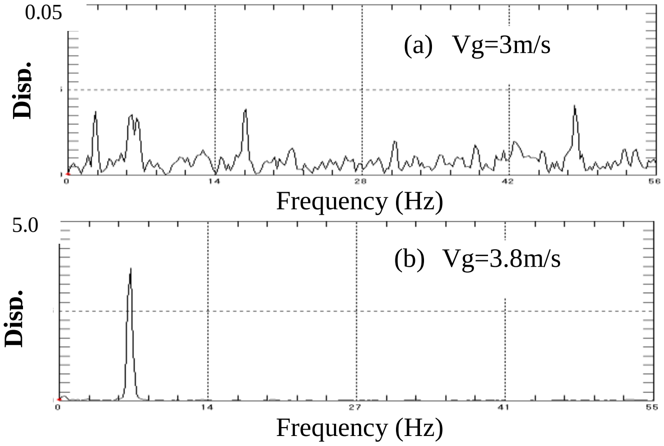


Figure 4 Examples of frequency spectrum

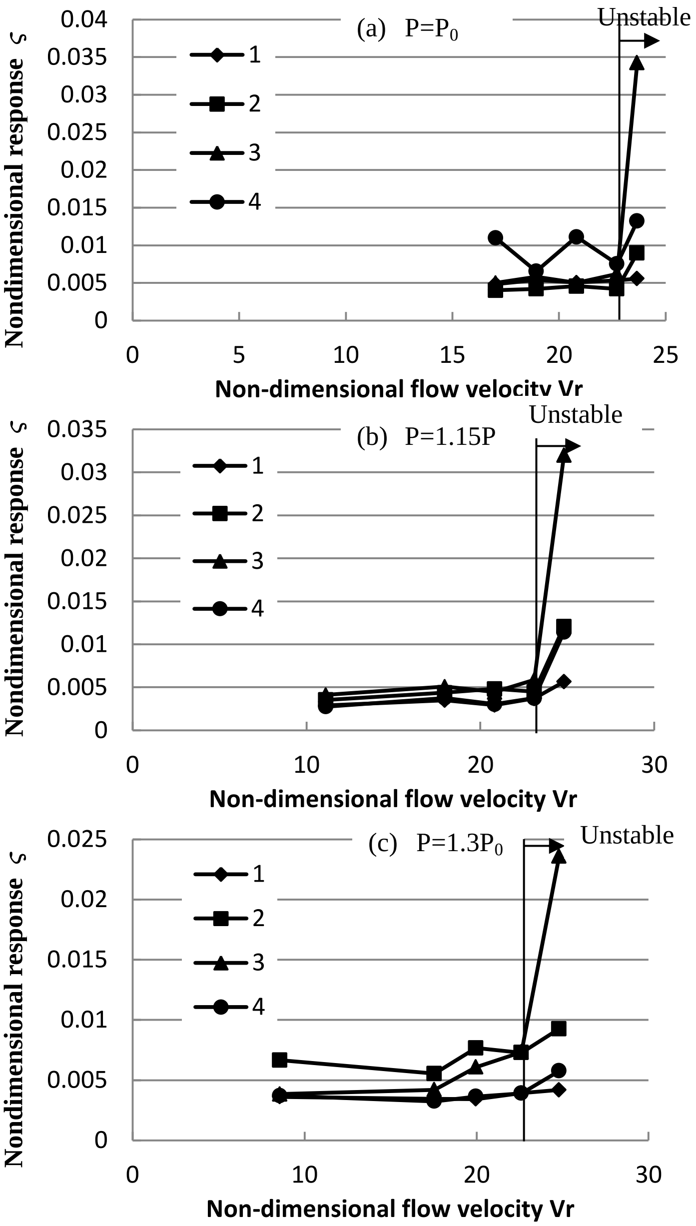


Figure 3 RMS response of selected cylinders(P_0/D=1.2)

For this pitch-to-diameter ratio, the critical flow velocity increases depending on the index, and it is irregular in the case of P=1.15P_0. This is a difference with the result for P_0/D=1.2.

2.3 Results of P/D=1.5

Fig.6(a)-(c) shows the responses of the measured cylinders for the case of all cylinders flexible in the stream-wise direction, where the flow velocity gradually increases.

Even in this case, Cylinder No.3 becomes unstable before the other cylinders do. It may depend on the position of this cylinder, which is just in the center of its line.

The trend of the critical flow velocity on the index is not clear as for the previous pitch-to-diameter ratio. This comes from the fact that the response becomes a bit larger before the onset of the instability.

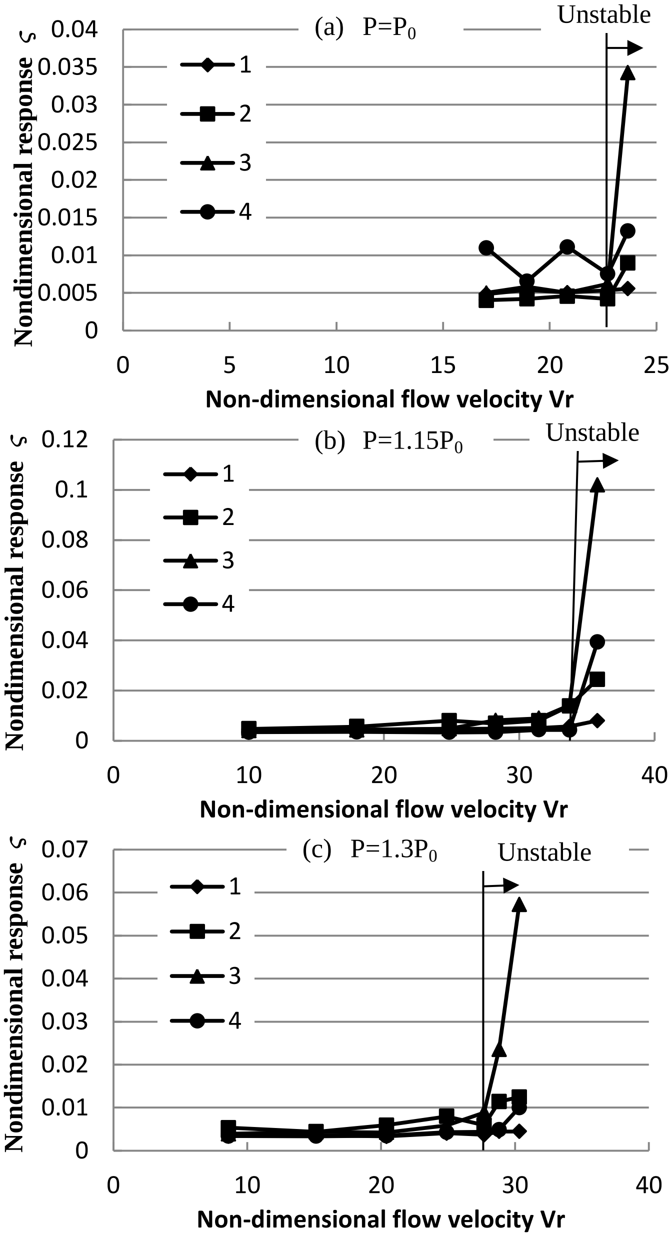


Figure 5 RMS response of selected cylinders(P_0/D=1.33)

3. TEST RESULTS(TRANSVERSE DIRECTION)

These test results shown in this chapter, 3.1-3.3, are not the main concern of this paper, but it is important to compare the above results and to consider the effect of indexing.

3.1 Results of P/D=1.2

As in the case of the stream-wise vibration, Fig.7 shows the results of the largest rms response in each case, where the flow velocity is gradually increased. In this figure, the number indicates the selected cylinder.

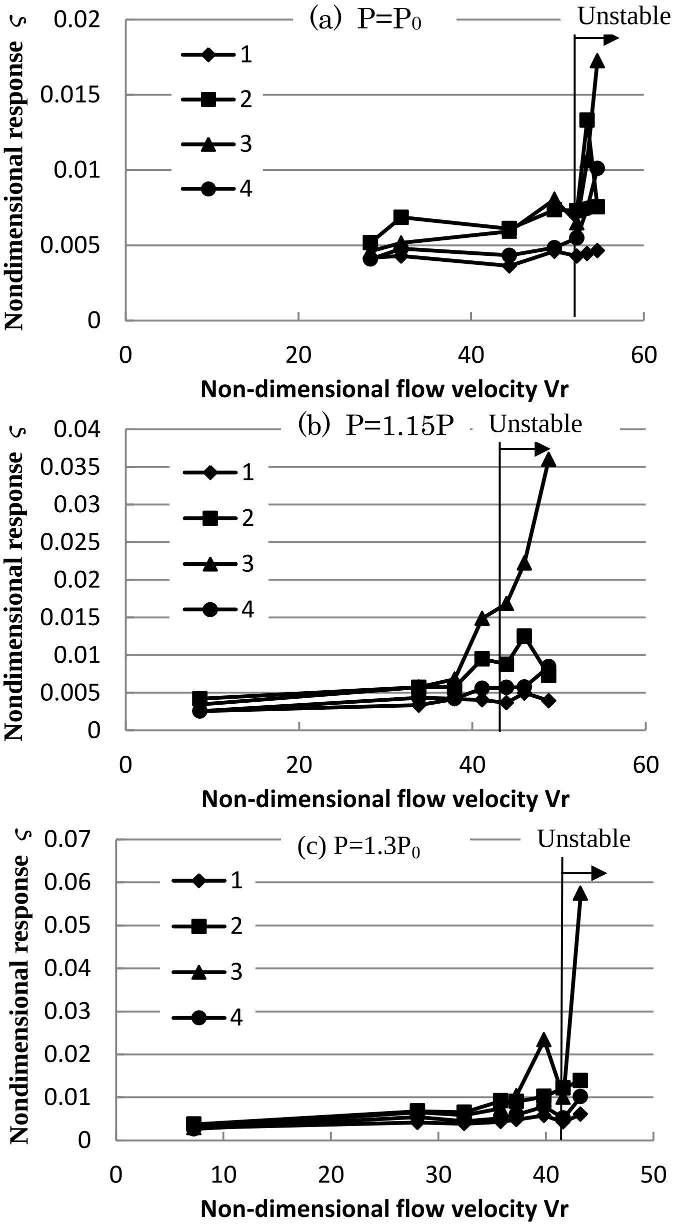


Figure 6 RMS response of selected cylinders(P_0/D=1.5)

There is a difference with the results for the stream-wise vibration. The difference is that all cylinders become unstable at the same flow velocity. The critical flow velocity depends on the array index.

3.2 Results of P/D=1.33

Fig.8 shows the response of selected cylinders which shows the largest response depending on the index, where the flow velocity is gradually increased. In this figure, the number indicates the selected cylinder.

This result shows a similar trend for the occurrence of instability, where almost all cylinders become unstable at the same flow velocity. And there is a trend on the effect of the index, where the index increases the critical flow velocity.

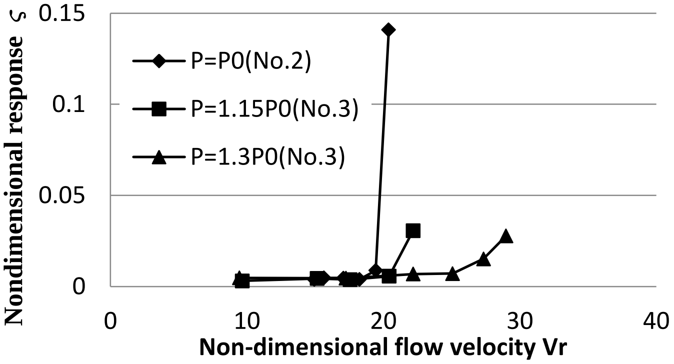


Figure 7 RMS response of selected cylinders(P_0/D=1.2)

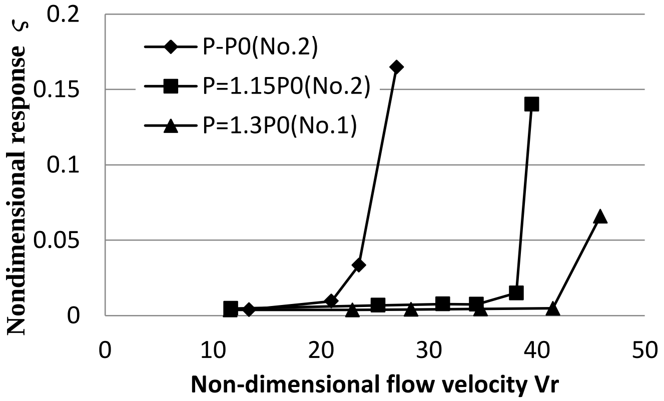


Figure 8 RMS response of selected cylinders(P_0/D=1.33)

3.3 Results of P/D=1.5

Similarily to the above results, Fig.9 shows the largest response depending of the index, where the flow velocity gradually increases. In this figure, the numbers indicates the selected cylinder.

The results for this pitch spacing are different from the above two cases. Here, only one cylinder becomes unstable, similarily to the results for the stream-wise direction. However, the trend with the index is similar to the above two cases.

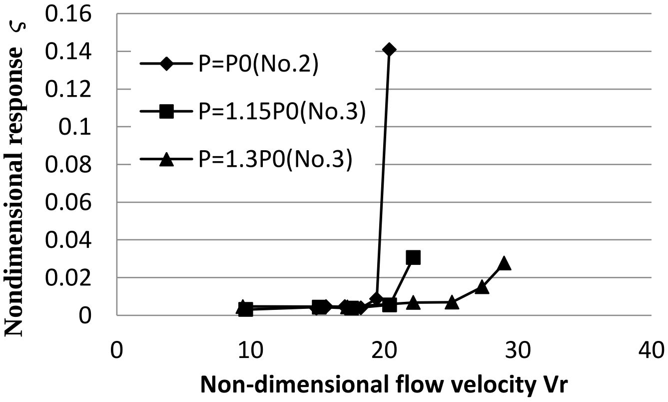


Figure 9 RMS response of selected cylinders(P_0/D=1.5)

4. DISCUSSION

At first, the critical flow velocities presented above are summarized in Table 2, indicating also the constant K defined by Eq.(2).

$$\frac{Vc}{fD} = K\sqrt{\frac{m\delta}{\rho D^2}} \tag{2}$$

where the parameters are m=1.489kg/m, ρ =1.2kg/m^3, D=0.02m.

Table 2 Summary of measured critical flow velocity

Cylinder array			$\frac{m\delta}{\rho D^2}$	$\frac{V_g}{fD}$	K
P/D	Vib. direction	Index			
1.2	Stream-wise	P=P_0	12.1	26.0	7.5
		P=1.15P_0	14.9	32.7	9.6
		P=1.3$_0$	17.9	34.9	8.2
1.33		P=P_0	16.2	32.9	8.2
		P=1.15P_0	12.3	39.4	11.2
		P=1.3$_0$	10.6	42.8	13.1
1.5		P=P_0	18.5	42.8	10.0
		P=1.15P_0	11.6	46.2	13.6
		P=1.3$_0$	14.8	45.4	11.8
1.2	Transverse	P=P_0	17.7	20.3	4.8
		P=1.15P_0	16.6	34.5	8.5
		P=1.3$_0$	15.7	40.4	10.2
1.33		P=P_0	17.7	21.2	5.0
		P=1.15P_0	13.2	37.8	10.4
		P=1.3$_0$	14.2	43.7	11.6
1.5		P=P_0	12.5	19.2	5.4
		P=1.15P_0	14.9	17.7	3.9
		P=1.3$_0$	17.2	25.6	6.2

(1) Effect of index

Fig.10 shows the trend of the K-factor in Eq.(2) on the index with the parameter of pitch-to-diameter ratio. This figure indicates that the basic trend is increasing critical factor K with indexing. However, the trend is not so simple.

In general, the trend of K depending on the index is not strong enough to consider in the design for the stream-wise fluidelastic instability, but it can be expected for the transverse direction on the pitch to diameter ratio P/D=1.2 and 1.33, while it is another story on P/D=1.5, where this case has no clear trend on the index.

Considering the above trend, it is safety usage to ignore the effect of index for the design at least.

(2) Effect of number of flexible cylinders

The trend with the number of flexible cylinders is discussed from the data of one line (column) flexible. These data are not explained above, but a summary is presented in Table 3.

From this table, it is clear that the effect of the index is not significant on the instability for the stream-wise direction, but

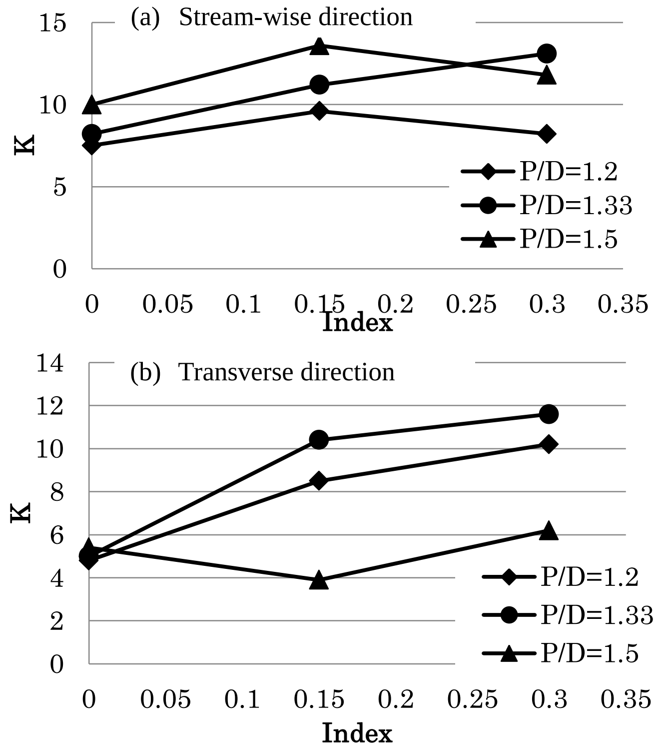


Figure 10 Effect of index

Table 3 Measured critical flow velocity (One line flexible)

Cylinder array			$\frac{m\delta}{\rho D^2}$	$\frac{V_g}{fD}$	K
P/D	Vib. direction	Index			
1.2	Stream-wise	$P=P_0$	17.9	37.2	8.8
		$P=1.15P_0$	13.6	44.6	12.1
		$P=1.3_0$	13.4	50.3	13.7
1.33		$P=P_0$	14.9	70.6	18.3
		$P=1.15P_0$	24.1	76.3	15.6
		$P=1.3_0$	21.8	81.4	17.4
1.5		$P=P_0$	13.2	81.6	22.4
		$P=1.15P_0$	14.7	64.4	16.8
		$P=1.3_0$	18.3	83.6	19.6
1.2	Transverse	$P=P_0$	14.9	30.1	7.8
		$P=1.15P_0$	14.0	27.4	7.3
		$P=1.3_0$	14.9	97.7	25.3
1.33		$P=P_0$	17.2	35.1	8.5
		$P=1.15P_0$	18.5	37.6	8.8
		$P=1.3_0$	23.5	110.9	22.9
1.5		$P=P_0$	20.0	17.9	4.0
		$P=1.15P_0$	18.3	64.7	15.1
		$P=1.3_0$	16.8	52.7	12.9

there is some effect for the transverse direction. This result is not easily understood physically.

5. CONCLUSION

The stream-wise fluidelastic instability is less prevalent, compared with the transverse one, but both are in a similar region. The effect of array indexing is not evident for the stream-wise fluidelastic instability, but it is of some significance in general for the transverse fluidelastic instability.

In total, it is safety usage to ignore the effect of index for the design at least.

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