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

Tomomichi Nakamura
Osaka Sangyo University
Daito, Osaka, Japan

Tomoki Tsujita
Osaka Sangyo University
Daito, Osaka, Japan

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; however 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. Based on these efforts it has been revealed that stream-wise fluidelastic instability easily occurs in rotated triangular arrays. On the other hand the same instability is hardly observed in square arrays and neither does it easily occur in normal triangular arrays, although the transverse fluidelastic instability is observed in any 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. This paper introduces the experimental results for the case where the rotated triangular arrays are subjected to an inclined flow, which is usually anticipated in practical steam generators.

NOMENCLATURE

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

INTRODUCTION

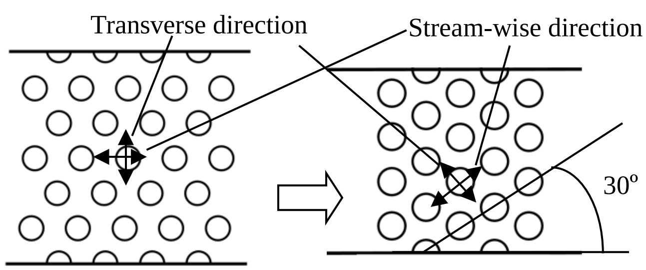
Fluidelastic vibration of tube arrays subjected to cross-flow is a kind of flutter phenomenon which has been studied by investigators for many years since 1966 [1]. It has been considered to occur mainly in the transverse direction of the flow, although the possibility of stream-wise instability may 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 considering the limited amount of data available on the stream-wise fluidelastic instability, the rotated triangular array is clearly the array most susceptible to stream-wise instability [6]. For the other cylinder arrays, the normal triangular array does not easily undergo stream-wise instability [7]; this is also the case for the normal square array [8], although even for these two arrays the transverse fluidelastic instability is easily observed.

It is therefore most important to study the stream-wise instability for the rotated triangular array, including the case of inclined flow. This paper presents the test results for inclined rotated triangular arrays. The inclination angle can be considered from zero to ninety degrees, but tests for arbitrary angles are difficult to achieve [9]. Then, only the case of thirty degrees inclination to the normal flow is examined in this study. Previous related work is reported in [10] and [11].

1. TEST FACILITY

Considering this condition of inclined flow, the rotated triangular array becomes the normal triangular array as shown in Fig.1 The basic concept of this test is the vibration direction is fixed as shown in Fig.1 on the inclined direction.

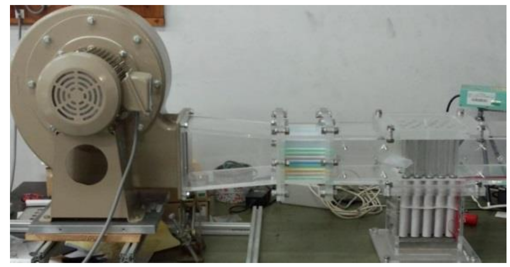


Rotated triangular array   Inclined rotated triangular

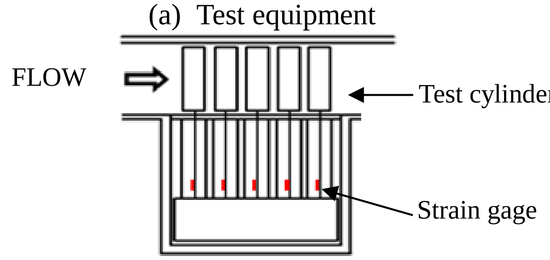
Figure 1 Concept of 30º inclined triangular array

The reason for setting the inclination at 30º is to make the (wall) boundary clear, for any other angle one cannot set the wall straight which would result in some bypass flow effect [9].

Fig.2 shows the test equipment. The cylinders, 102mm in length and 20 mm in diameter, are supported by thin stainless steel plates, 1 mm in thickness and 6 mm in width, as cantilevers as shown in Fig.2(b). The basic cylinder array geometry and the vibration direction are shown in Fig.3(a). The following pitch ratios of this triangular array are tested: P/D=1.2, 1.33 and 1.5. In the gap with the side wall are set half dummy tubes as indicated in Fig.3(a). All tests have been conducted with all cylinders flexible.

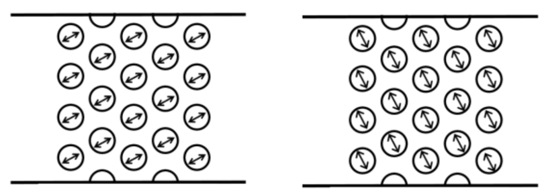


(a) Test equipment

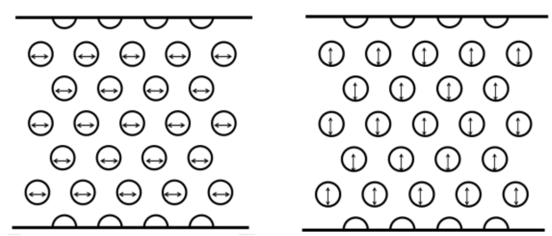


(b) Measured cylinder

Figure 2 Test equipment



(a) Inclined rotated triangular array
(Stream-wise)   (Transverse)



(b) Normal rotated triangular array
(Stream-wise)   (Transverse)

Figure 3 Tested flexible direction

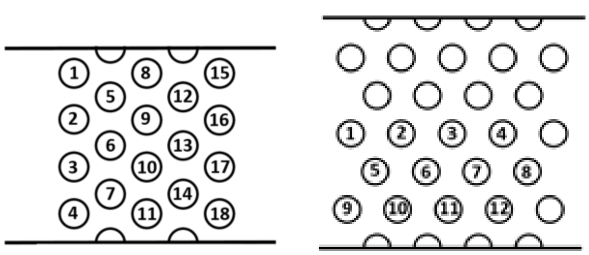
In addition, the normal and rotated triangular arrays are tested for comparison with the above tests as shown in Fig.3(b).

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

The number of instrumented cylinders is shown in Fig.4, and their vibrational characteristics are shown in Table 1. In this table, all cylinders are supported flexibly for each test case. All cylinders are measured for the case of the inclined model, but partial cylinders are monitored for the normal model, specifically only No.1 – 4 cylinders are monitored mainly in the transverse direction.

Table 1 Vibrational characteristic of monitored cylinders

Array	P/D		1.2	1.33	1.5
Inclined	Freq. (Hz)	Stream-wise	6.2-6.5	6.2-6.6	6.1-6.4
		Transverse	6.2-6.6	6.2-6.6	6.1-6.5
	Damping ratio (%)	Stream-wise	0.23-0.49	0.28-0.53	0.27-0.73
		Transverse	0.28-0.75	0.21-0.76	0.19-0.83
Normal	Freq. (Hz)	Stream-wise	6.2-6.6	6.1-6.6	6.1-6.6
		Transverse	6.2-6.5	0.29-0.55	0.11-0.38
	Damping ratio (%)	Stream-wise	0.20-0.47	0.24-0.55	0.18-0.38
		Transverse	0.46-0.59	0.39-0.55	0.11-0.58



(a) Inclined model (b) Normal model

Figure 4 Number of measured cylinders

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=2.0×10^3 – 3.7×10^3, 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.4. 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(INCLINED MODEL)

The following results are introduced on each cylinder array, from P/D=1.2 to P/D=1.5. As there are many data, only the case of all cylinders flexible is described in this section. The response of the cylinders is expressed a non-dimensional displacement ς (=rms displacement/D).

2.1 Results of P/D=1.2

Fig.5(a) shows the example response of measured cylinders in the stream-wise direction, where the flow velocity gradually increases, and Fig.5(b) shows the response in the transverse direction.

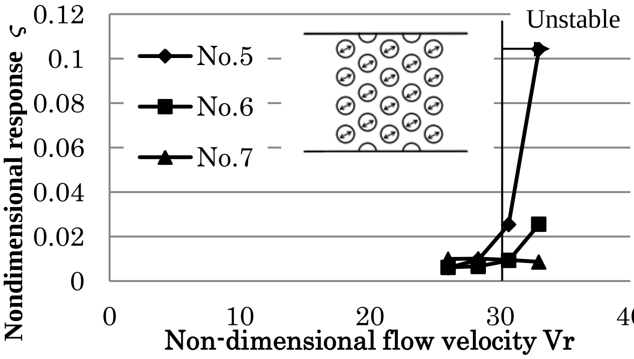
The numbers in the figure identifies the measured cylinder as indicated in Fig.4. From these results, Cylinder No.5 is the cylinder that is the most unstable in the stream-wise direction, however, almost all cylinders become unstable in the transverse direction.

Comparing the two figures (a) and (b), it is evident that the non-dimensional critical flow velocity in the transverse direction is lower than that in the stream-wise direction, although the word “transverse direction” does not exactly correspond to the transverse direction as shown in Fig.3. This point is discussed later.

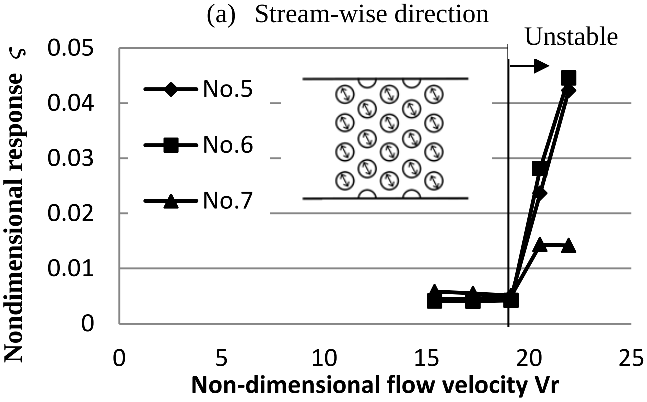
2.2 Results of P/D=1.33

Similar test results are shown here for the test pattern of P/D=1.33. Fig.6(a) shows the example response of measured cylinders in the stream-wise direction, where the flow velocity gradually increases, and Fig.6(b) show the response in the transverse direction.

In this case, the non-dimensional critical flow velocity in the transverse direction is lower than that in the stream-wise direction. However, many cylinders become unstable even in the stream-wise direction in this case. This is a different from the case of P/D-1.2.

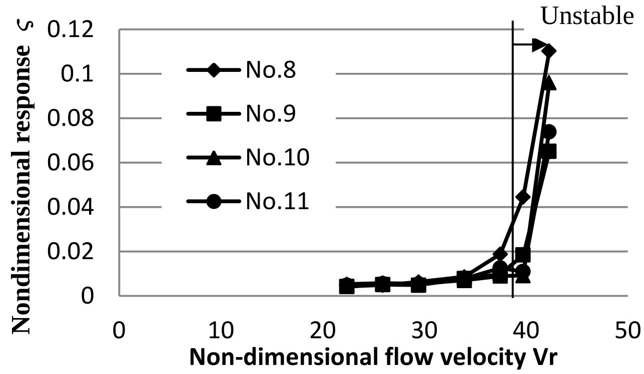


(a) Stream-wise direction

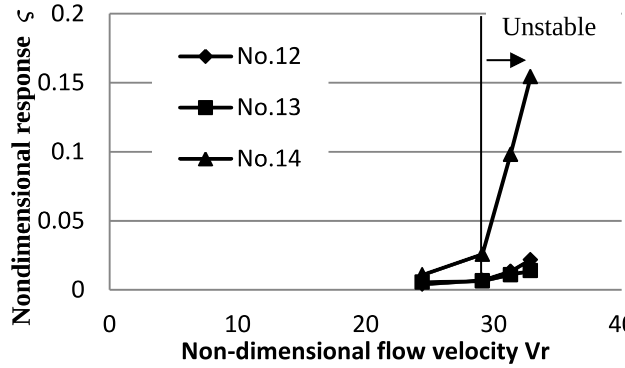


(b) Transverse direction

Figure 5 RMS response of selected cylinders(P/D=1.2)



(a) Stream-wise direction



(b) Transverse direction

Figure 6 RMS response of selected cylinders(P/D=1.33)

2.3 Results of P/D=1.5

Fig.7(a) shows the response of measured cylinders in the stream-wise direction, where the flow velocity gradually increases, and Fig.7(b) shows the response in the transverse direction.

Almost similar results with the case of P/D=1.33 are obtained from these figures. A detail discussion is presented later.

3. TEST RESULTS(NORMAL MODEL)

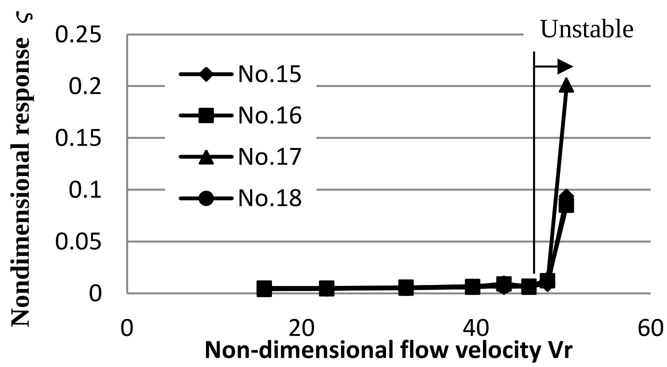
In this section, the refference data with the above results are described for the model shown in Fig.3(b). All figures are presented following the same format as the results above.

3.1 Results of P/D=1.2

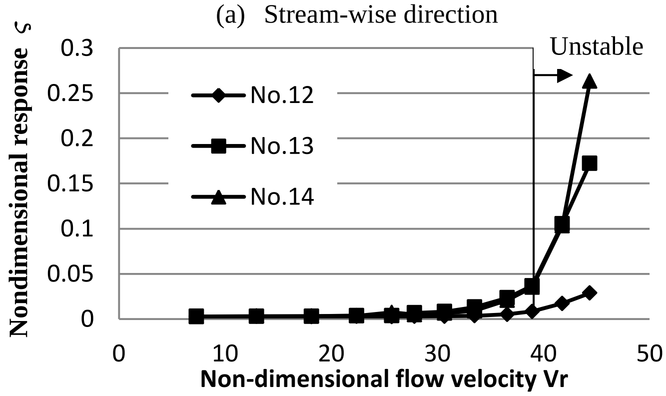
Fig.8 shows the stream-wise response of the measured cylinders and the transverse direction, where the flow velocity gradually increases, where the flow velocity gradually increases.

3.2 Results of P/D=1.33

Fig.9 shows the response of measured cylinders in the stream-wise direction and the transverse direction, where the flow velocity gradually increases.

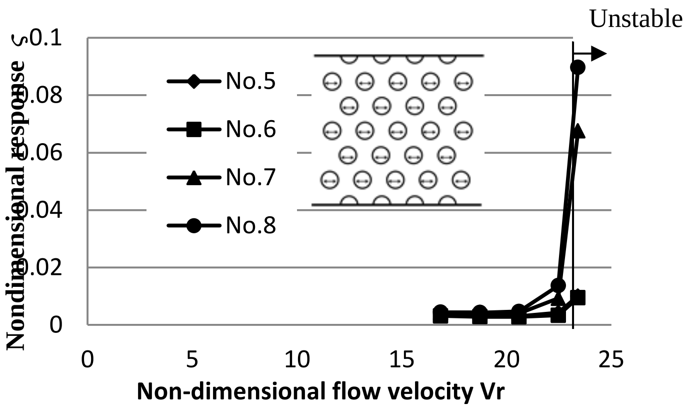


(a) Stream-wise direction

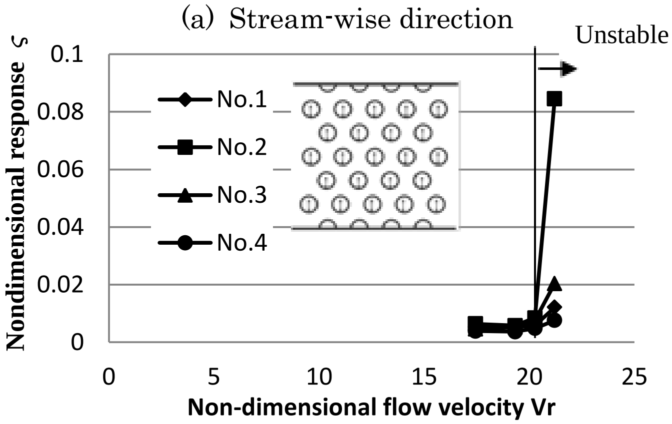


(b) Transverse direction

Figure 7 RMS response of selected cylinders(P/D=1.5)

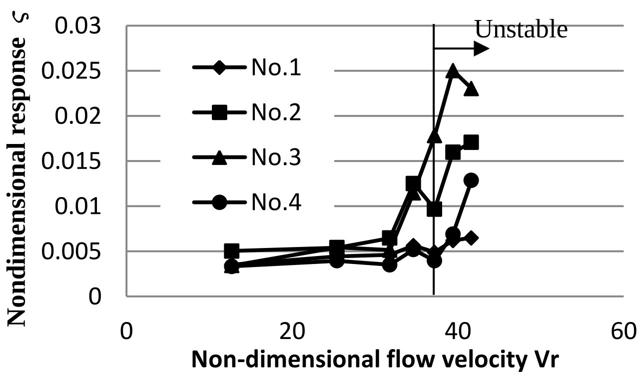


(a) Stream-wise direction

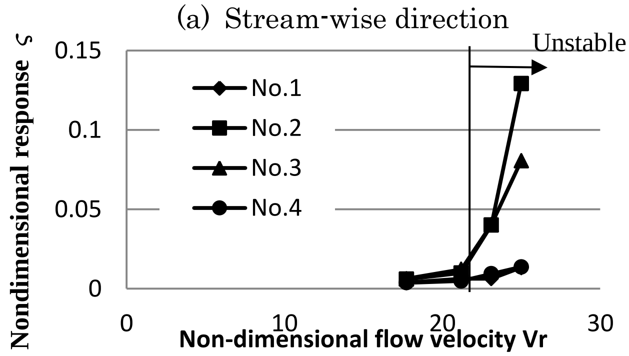


(b) Transverse direction

Figure 8 RMS response of selected cylinders(P/D=1.2)



(a) Stream-wise direction

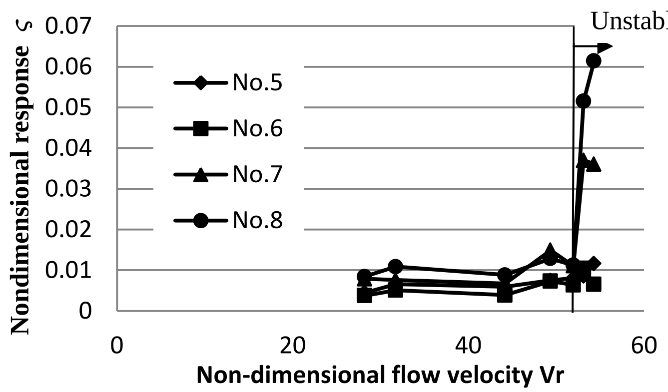


(b) Transverse direction

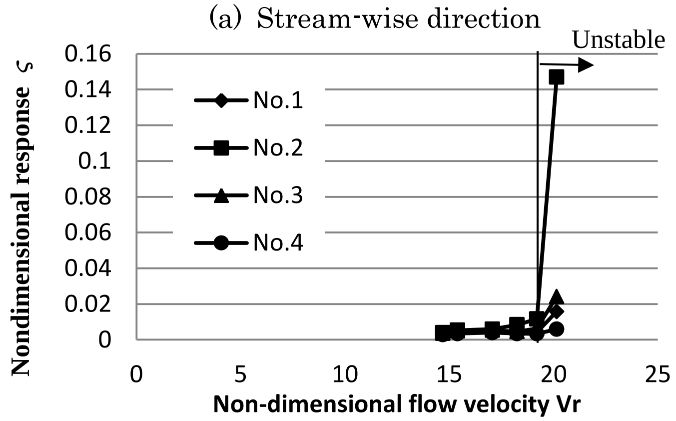
Figure 9 RMS response of selected cylinders(P/D=1.33)

3.3 **Results of P/D=1.5**

Fig.10 shows the response of measured cylinders in the stream-wise direction and the transverse direction, where the flow velocity gradually increases.



(a) Stream-wise direction



(b) Transverse direction

Figure 10 RMS response of selected cylinders(P/D=1.5)

4. DISCUSSION

At first, the above mentioned critical flow velocities are summed up in Table 2; also presented is the corresponding constant K defined by Eq.(1).

$$\frac{Vc}{fD} = K\sqrt{\frac{m\delta}{\rho D^2}} \tag{1}$$

Where the parameters are m=1.489kg/m, ρ=1.2kg/m^3.

The stability map is shown in Fig.11; almost all data are plotted in a small vicinity. Generally, the constant K for the stream-wise direction is larger than that for the transverse direction.

(1) Effect on position

The test model to check the effect of the flow attack angle has a doubt about the bias of the flow due to the inclined motion of cylinders. Then, the cylinders, which show the large amplitude when the array becomes unstable, are checked and they are indicated in Fig.12 as

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	Model			
1.2	Stream-wise	Inclined	13.7	30	8.1
		Normal	8.98	22	7.3
1.33		Inclined	14.0	38	10.1
		Normal	11.6	40	11.7
1.5		Inclined	15.7	48	12.1
		Normal	8.60	52	17.7
1.2	Transverse	Inclined	19.1	19	4.4
		Normal	17.8	20	4.7
1.33		Inclined	14.6	29	7.6
		Normal	17.8	23	5.5
1.5		Inclined	16.8	39	9.5
		Normal	12.5	19	5.4

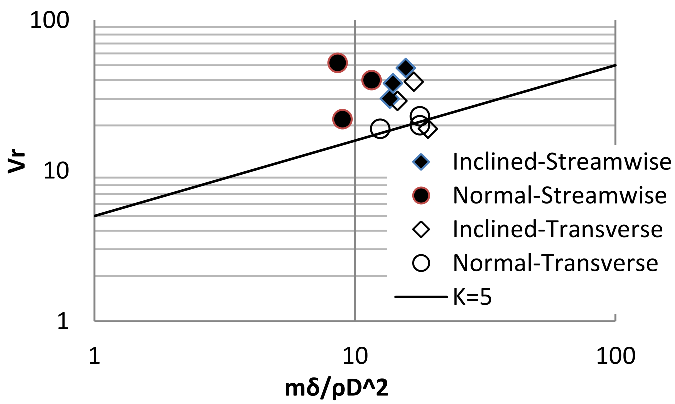


Figure11 Stability map

the colored symbol. However, there is no clear trend on the location of the un-stabled cylinders. Then, this inclined model test is estimated to have no exact bias.

(2) Effect of vibration direction

Fig.13 shows the trend of the critical factor, K, on the pitch to diameter ratio, P/D. The followings are obtained:

1) In the stream-wise direction, the trend, where the larger P/D corresponds to larger K, is clear for the case of the normal flow direction. However, its effect decreases for the case of the inclined vibration.
2) In the transverse direction, this trend is completely different. For the case of the normal flow direction, there is no clear trend on the effect of P/D on K. However, a clear trend appears for the case of the inclined vibration.

These trends can be explained from the fact that the instability generally occurs at lower flow velocity in the transverse direction. For the case of inclined vibration, the vibration is not exactly in the stream-wise direction, and it includes the effect of the transverse direction when the cylinder oscillates even in the stream-wise direction.

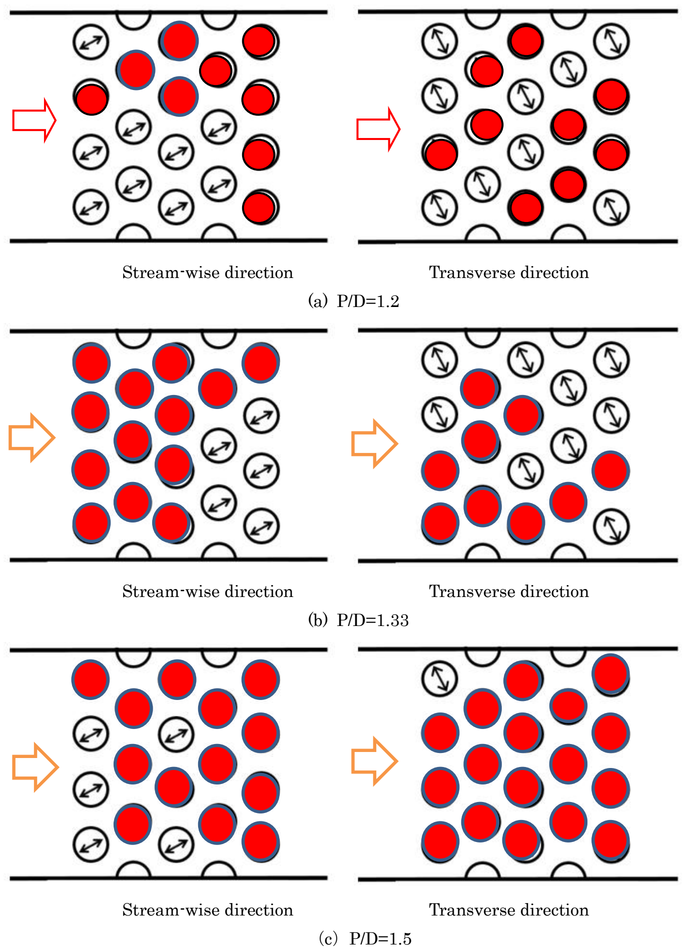


Figure 12 Location of un-stabled cylinder

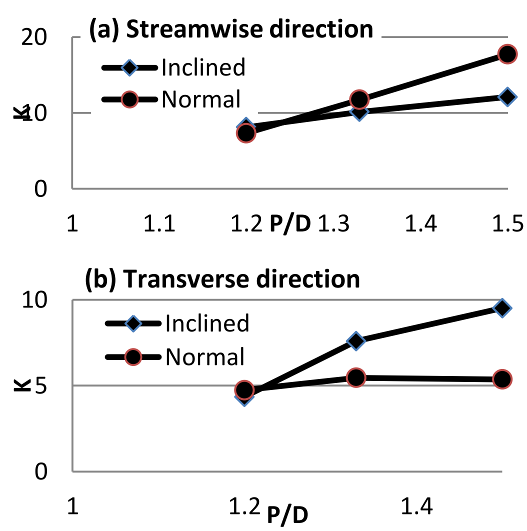


Figure 13 Trend on P/D ratio

5. CONCLUSION

The stream-wise fluidelastic instability generally hardly occurs, compared with the transverse one, but both are in a similar range of reduced velocities. The effect of the flow attack angle seems to decrease the critical flow velocity in the stream-wise fluidelastic instability, but this comes from the effect of the transverse direction fluidelastic instability. As for the boundary on the critical flow velocity in the transverse direction, the inclined flow gives a larger critical factor.

ACKNOWLEDGMENTS

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