# Effects of Aspect Ratio and Distance between Two Square Cylinders in a Tandem Arrangement on In-Line Oscillation Characteristics

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# EFFECTS OF ASPECT RATIO AND DISTANCE BETWEEN TWO SQUARE CYLINDERS IN A TANDEM ARRANGEMENT ON IN-LINE OSCILLATION CHARACTERISTICS

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## ABSTRACT
When multiple structures, such as the main towers for a bridge, heat exchangers and offshore structures, are placed adjacently in fluid, structures placed in the downstream side are exposed to complicated flow regions, because the separated shear layer reattaches to the downstream structures or interferes with the flow. For this reason, the distance between structures greatly influences changes in flow patterns around the downstream cylinder structures, so that the response characteristics of structures can be altered correspondingly. The purpose of this study is to identify the basic in-line oscillation characteristics of two square cylinders in a tandem arrangement. Based on the supposition of actual structures, spring-supported tests, with both square cylinders elastically suspended, were conducted. Not only the distance between the two cylinders but also the aspect ratio, was also chosen as the parameters. Because it was found by past researches that the in-line oscillation characteristics of single cylinder depends on the aspect ratio, it was thought to be important to confirm it by two cylinders. Furthermore, flow visualization tests were performed by forced-oscillating two cylinders for consideration from the results of the spring-supported test.

## INTRODUCTION
When mass ratio or structural damping is small, in-line oscillation [1] easily occurs. It is known that in-line oscillation is recognized in two wind speed regions, before and after a half of the critical wind speed of Kármán vortex-induced vibration (in the case of square cylinder cross section, $Vcr=V/fD=8.0$, where $V$: wind speed (m/s), $f$: natural frequency (Hz), $D$: model height (m)). It is also known that a symmetric vortex occurs in the lower wind speed region, namely the first excitation region and an alternative vortex occurs in the higher wind speed region, namely the second excitation region.

In the case where there are multiple structures, that is, in the case where heat exchanger, parallel cables of a cable-stayed bridge, cooled reactor, multi-legged chimney, bridges and other offshore structures are placed in the close vicinity, the flow patterns become more complex due to the interference of a separation vortex and the flow reattachment to the structures at the downstream side than the case where a single structure is placed; the response characteristics can become different. In the case of rectangular cross-sections, in particular, it is presumed that the peculiar phenomena such as reattachment of the flow that was once separated occurs; therefore, the response characteristics of the structure changes greatly.

The previous research concerning flow-induced vibration of the two square cylinders mainly focuses on its static characteristics and on the vibration perpendicular to the direction of flow, but there is little research concerning in-line oscillation, that is, the vibration to the direction of flow. Therefore, it is considered necessary to grasp the characteristic of in-line oscillation of the two square cylinders arranged in tandem, and to reflect the results to the wind resistant design of the structures.

In this research, the author et al. focuses on aspect ratio of model and the distance between two cylinders in spring-supported test, among the experiment conditions such as Reynolds number, Scruton number and model support conditions. In the previous research concerning the in-line oscillation of square cylinders arranged in tandem, there are cases where actual structures were presumed and both square cylinders were elastically supported [2]. There is another case where only the square cylinder, to which attention was paid, was elastically supported while another square cylinder was rigidly supported [3]. In the above cases, the research was conducted on the distance between the two square cylinders being variously changed. However, the results of the research made under these support conditions cannot be compared simply because the experiment conditions of Reynolds number, Scruton number and aspect ratio of models were different.

Therefore, the spring-supported tests were conducted under four kinds of aspect ratios in total and three kinds of the distance between two cylinders for the purpose of surveying the effects of differences of aspect ratios and the distance between two cylinders on the in-line oscillation characteristics. Furthermore, the visualization experiments of the flows around the two square cylinders that were excited by the forced-oscillating method were conducted, and the results of spring-supported test were discussed based on the flow visualization test results.

## EXPERIMENTAL SETUP

The spring-supported wind tunnel test had a two-dimensional rigid body. The definition of the distance between the two cylinders is described in Fig. 1. As non-dimensional distance, the three cases of *S/D*=1.0, 2.0 and 3.0 were determined by reference to previous research [3], where *S*: distance between two cylinders, *D*: model height. The spring-supported tests were conducted in a closed circuit wind tunnel (1.8 m high×0.9 m wide) at Kyushu Institute of Technology. Laser displacement detectors were used for measuring an amplitude of the models. The two square cylinder models in wind tunnel of each case is shown in Fig. 2 when aspect ratio is *L*/*D*=3.78, where *L*: model length, *D*: model height. The structural specifications and experimental conditions for spring-supported tests are shown in Table 1.

Smoke flow visualizations around the models during oscillating condition were conducted in a small-sized wind tunnel (0.4m high×0.4m wide) at Kyushu Institute of Technology. It was presumed that wind speeds of *V*=0.6–1.0 m/s in the wind tunnel were good for visualization, so eventually *V*=0.8 m/s was selected as the onset wind speeds of motion-induced vortex excitation. Accordingly, the experimental Reynolds number was $(Re)_D=1.1\times10^3$. The models used for the flow visualization test were square prisms whose base was a square with 20-mm sides. The models were excited by a forced oscillation system. At least eight photos per cycle were taken of the models, using a high speed camera. Figures 3 and 4 show the schematic illustration of experimental setup for smoke flow visualization and the forced oscillation system, respectively. The test conditions are shown in Table 2. All wind tunnel tests were carried out in a smooth flow.

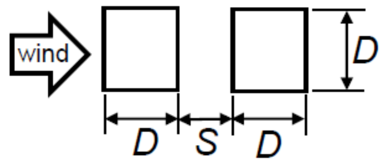
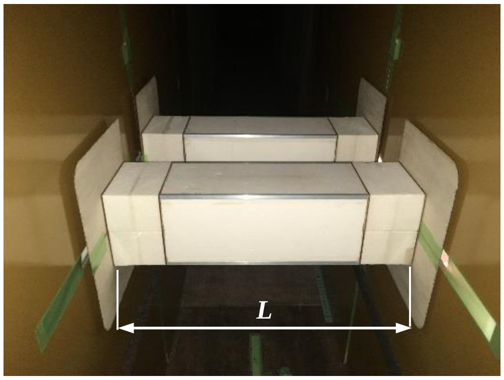
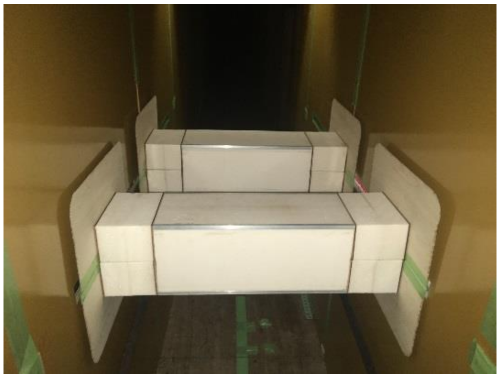



**FIGURE 1:** DEFINITION OF DISTANCE BETWEEN TWO CYLINDERS




(a) *S/D*=1.0



(b) *S/D*=2.0

(c) *S/D*=3.0

**FIGURE 2:** TWO SQUARE CYLINDER MODELS IN WIND TUNNEL (ASPECT RATIO: *L/D*=3.78)

**TABLE 1:** TEST CONDITIONS FOR SPRING-SUPPORTED TESTS (ASPECT RATIO: $L/D$=2.44, 3.11, 3.78 AND 4.44)

| $S/D$ | Square cylinder | Natural frequency $f$ (Hz) | Mass per unit length $m$(kg/m) | Structural damping (Logarithmic decrement) $\delta$ | Air density $\rho$ (kg/m$^3$) | Scruton number $Sc=2m\delta/\rho D^2$ |
|---|---|---|---|---|---|---|
| 1.0 | Upstream | 4.34-5.21 | 5.33-12.2 | 0.002-0.005 | 1.24-1.27 | 1.34-1.38 |
| | Downstream | 4.34-5.23 | 5.56-12.6 | 0.002-0.005 | | 1.34-1.54 |
| 2.0 | Upstream | 4.29-5.26 | 5.24-12.4 | 0.002-0.005 | 1.24-1.26 | 1.24-1.26 |
| | Downstream | 4.27-5.25 | 5.51-13.0 | 0.002-0.005 | | 1.24-1.26 |
| 3.0 | Upstream | 4.31-5.26 | 5.24-12.9 | 0.002-0.005 | 1.24-1.27 | 1.28-1.38 |
| | Downstream | 4.29-5.28 | 5.47-13.5 | 0.002-0.006 | | 1.45-1.54 |

*Model height: $D$=0.180m

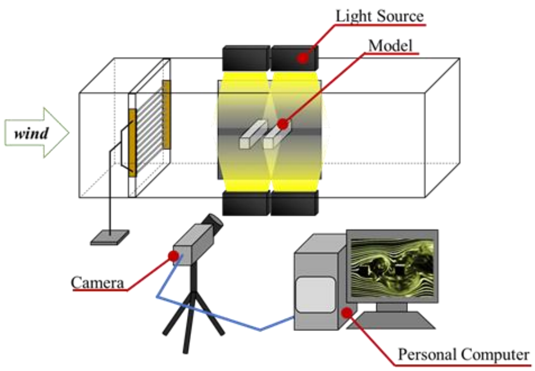



**FIGURE 3:** SCHEMATIC ILLUSTRATION OF EXPERIMENTAL SETUP FOR FLOW VISUALIZATION

**FIGURE 4:** FORCED OSCILLATION SYSTEM

**TABLE 2:** TEST CONDITIONS FOR FLOW VISUALIZATION

| $S/D$ | Reduced wind speed $Vr=V/fD$* | Frequency of forced oscillation method $f$ (Hz) | Non-dimensional amplitude $A/D$* | Phase difference** (deg.) | Square cylinder |
|---|---|---|---|---|---|
| 1.0 | 4.7 | 8.51 | 0.02 | +9 | Upstream |
| | | | 0.04 | | Downstream |
| 2.0 | 4.5 | 8.93 | 0.02 | -68 | Upstream |
| | | | 0.04 | | Downstream |
| 3.0 | 4.5 | 8.83 | 0.02 | +61 | Upstream |
| | | | 0.04 | | Downstream |

*$V$=0.8m/s, $D$=0.02m, **As the definition of phase difference, when the phase of the square cylinder on the upstream side advances more than the phase of square cylinder on the downstream side, it is defined as positive, and in contrary cases, it is defined as negative.

## RESULTS AND DISCUSSION

### Spring-supportred Tests

First of all, Fig.5 shows the results of confirming the validities of the experimental facility and measurement methods to be used in this research by comparing the response of a single square cylinder with that of previous research [4]. The results of this test were almost identical to those of previous tests, so their validities were able to be confirmed.

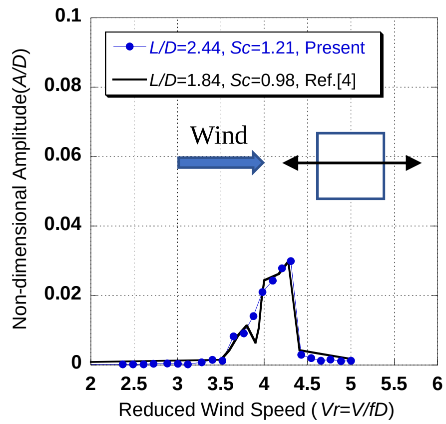
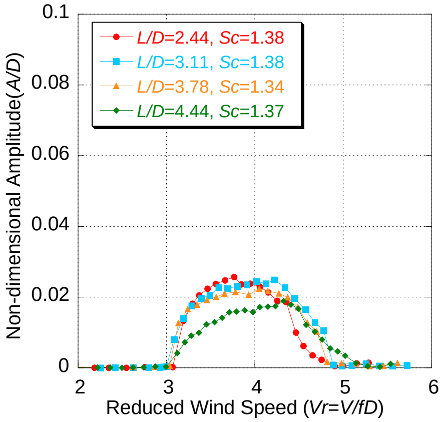


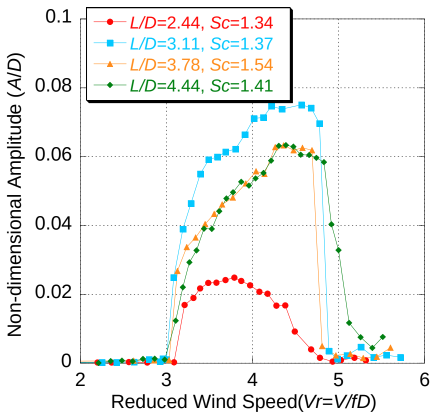

**FIGURE 5:** COMPARISON BETWEEN PRESENT RESULT AND PAST RESEARCH [4] (SINGLE SQUARE CYLINDER)

The results of a spring-supported test that compared four cases of $L/D$ = 2.44, 3.11, 3.78 and 4.44 at a non-dimensional distance of $S/D$ = 1.0 are shown in Fig.6. Vibrations were confirmed in the approximate range from reduced wind speed $Vr = V/fD$= 3.0 to $Vr$ = 5.0, where $V$: wind speed (m/s), $f$: natural frequency (Hz), $D$: model height (m), of both square cylinders on the upstream and downstream sides of all cases. It is known from Fig. 6 (a) that the effect of the aspect ratio of the square cylinder on the upstream side on the response is small. It is also known from Fig.6 (b) that the maximum response amplitude of the square cylinder on the downstream side was the maximum in the case of $L/D$ = 3.11 and the minimum in the case of $L/D$ = 2.44. $L/D$ = 3.78 and 4.44 are slightly smaller than the maximum response amplitude of $L/D$ = 3.11 and showed similar tendency with $L/D$ = 3.11. Therefore, in the case of $S/D$ = 1.0, there was a slight tendency that the larger the aspect ratio becomes, the larger the maximum response amplitude tends to become for the square cylinder on the downstream side. Based on the results of a flow visualization experiment, the reason why the response of the square cylinder on the downstream side was largely developed more than that at upstream side will be explained in the results and discussion section of smoke flow visualization to be described later.

The results of spring-supported test in the case of non-dimensional distance $S/D$ = 2.0 are shown in Fig.7. Focusing on the response diagram of the square cylinder on the upstream side of Fig.7 (a), vibration is expressed from the neighborhood of reduced wind speed $Vr$ = 3.0 in all four cases with different aspect ratios. Regarding response amplitude, the response does



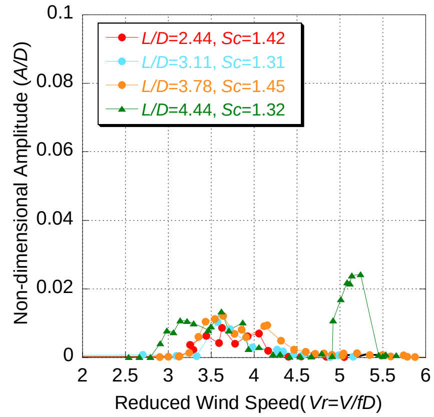

(a) Upstream Square Cylinder



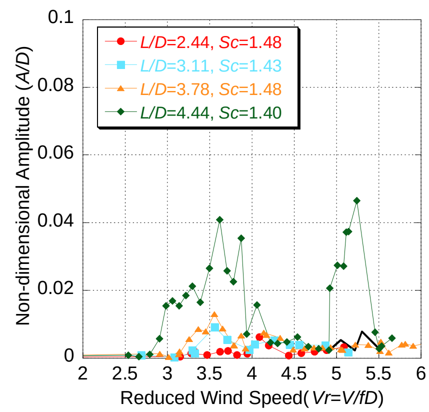

(b) Downstream Square Cylinder

**FIGURE 6:** RESULTS OF SPRING-SUPPORTED TEST (*S/D*=1.0)

not grow so much in any aspect ratio and all of them exhibited a response amplitude of the same degree. Meanwhile, as shown in Fig.7 (b), a vibration is expressed from the same reduced wind speed for the square cylinder on the downstream side as that of the upstream side. The larger the aspect ratio becomes, the larger the maximum response of the square cylinder on the downstream tends to become. Therefore, it was confirmed that in the case of non-dimensional distance *S/D* = 2.0, aspect ratio gives almost no impact on the response of the square cylinder on the upstream side, but has an impact on the response of the square cylinder on the downstream side. The response in the case of reduced wind speed *Vr* = 4.8-5.5 of the square cylinder on the upstream side of aspect ratio of *L/D* = 4.44 was increased when it was given an initial displacement of around *A/D* = 0.01, but it was decreased when the initial displacement was smaller than that, so this response is unstable with a limit cycle. Although a similar vibration was observed in reduced wind speed *Vr* = 4.8-5.5 in the square cylinder on the downstream side with aspect ratio of *L/D* = 4.44 as shown in Fig.7 (b), this was thought to be excited by the vibration of the square cylinder on the upstream side. It is not clear the reason why the response of downstream cylinder with aspect ratio of *L/D* = 4.44 in reduced wind speed *Vr* = 2.8-4.0 became much larger than those of other aspect ratios.



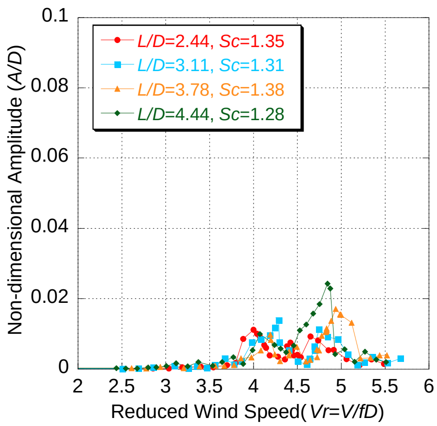

(a) Upstream Square Cylinder



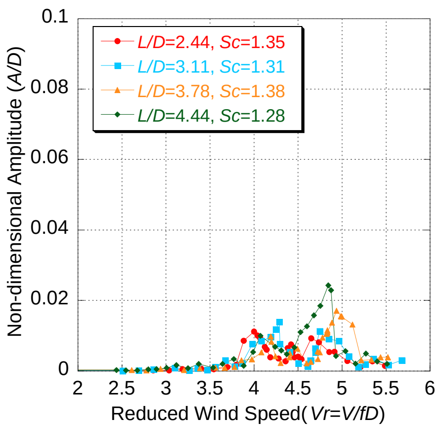

(b) Downstream Square Cylinder

**FIGURE 7:** RESULTS OF SPRING-SUPPORTED TEST (*S/D*=2.0)

The results of a spring-supported test at a non-dimensional distance *S/D* = 3.0 are shown in Fig.8. As shown in a response diagram of the square cylinder on the upstream side of Fig.8 (a), the first excitation region appeared at the reduced wind speed of approximately *Vr* =3.8-4.4 and the second excitation region appeared at the neighborhood of *Vr* = 4.4-5.3. Focusing on the square cylinder at the downstream side in Fig.8 (b), the response is developed from a reduced wind speed of approximately *Vr* = 4.2 later than the square cylinder on the upstream side. It is probably because the response amplitude in the first excited region of the square cylinder on the upstream side is comparatively small, and its effect on the response of the square cylinder downstream side is small. It was found that the larger the aspect ratios of square cylinders on the upstream and downstream sides become, the larger the maximum amplitudes tend to become. The relation between aspect ratio and response amplitude shows a similar tendency to the result of the test using a single circular cylinder in the previous research [5]. The change in response in the first excitation region of the square cylinder on the upstream side due to the changes of aspect ratio is rarely observed; however, the responses of the second excitation regions of square cylinders on the upstream and downstream sides tend to become larger with an increase in aspect ratio. Because the in-line oscillations in the first excitation region and the second excitation region are those accompanied by the expression of symmetric vortices or alternate vortices, as a result of testing, it was confirmed that aspect ratio has a greater effect on alternate vortices than symmetric vortices for *S/D*=3.0. In the case of aspect ratio *L/D*=4.44, in particular, the response characteristics of a square cylinder on the upstream side and downstream side are similar to those of a single square cylinder shown in Fig.5.



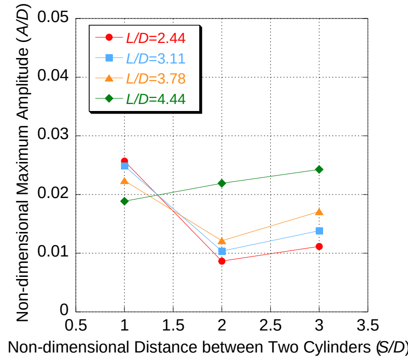

(a) Upstream Square Cylinder



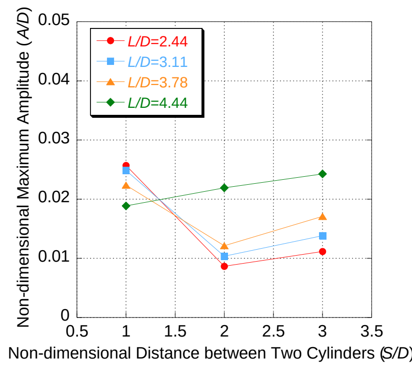

(b) Downstream Square Cylinder

**FIGURE 8:** RESULTS OF SPRING-SUPPORTED TEST (*S/D*=3.0)

The relation between non-dimensional distance *S/D* and the maximum response amplitude at the time when aspect ratio was changed is shown in Fig.9. The maximum response amplitude at the time when *S/D* = 2.0 became the minimum for the aspects ratios other than aspect ratio *L/D* = 4.44 where limit cycle generated in both square cylinders on the upstream and downstream sides. Therefore, it was found that non-dimensional distance *S/D* = 2.0 is the most favorable state for the structure of two square cylinders in a tandem arrangement for the purpose of reducing the response amplitude.




(a) Upstream Square Cylinder




(b) Downstream Square Cylinder

**FIGURE 9:** RELATION BETWEEN NON-DIMENSIONAL DISTANCE AND MAXIMUM RESPONSE AMPLITUDE

## Smoke flow visualization

The results of visualization experiments of almost the same wind speeds by each non-dimensional distance *S/D* were compared, and the difference of flow field caused by non-dimensional distances *S/D* were discussed. The results of visualization experiments of the flow fields are shown by each non-dimensional distance *S/D* in Figs. 10, 11 and 12. The result of visualization experiments of these flow fields showed the two-dimensional flow, so that the effect of aspect ratio cannot be considered.

In the case of non-dimensional distance *S/D* = 1.0, when reduced wind speed was *Vr*= 4.7, alternate vortices getting into between the two square cylinders were confirmed as shown in Fig.10. The reason why the response of the square cylinder on the downstream side was expressed more than that of the upstream side is that a shear layer separated from the leading edge of the square cylinder on the upstream side gets in between the two square cylinders, vortices were frequently formed in the space between the two cylinders, and they hit the square cylinder on the downstream side. It was found that as a result, the fluctuating base pressure of the square cylinder at downstream side became large and the response also increased.

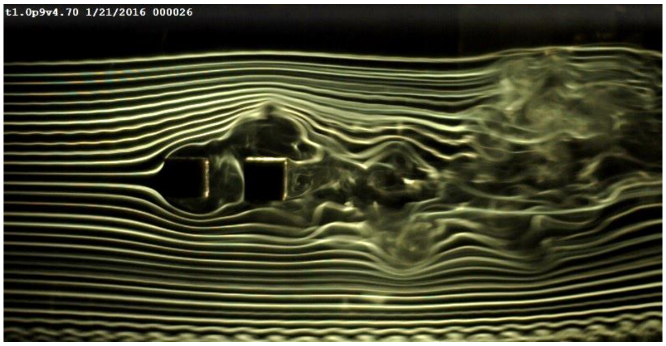



**FIGURE 10:** RESULTS OF FLOW VISUALIZATION AROUND TWO SQUARE CYLINDERS (*S/D*=1.0)

In the case of non-dimensional distance *S/D* = 2.0, it was confirmed in Fig.11 that the flow separation from the square cylinder on the upstream side was relatively small and much less flow separation got in between the square cylinders. It can be considered as the reason why the response was on a declining trend at the spring-supported test in the case of *S/D*=2.0.

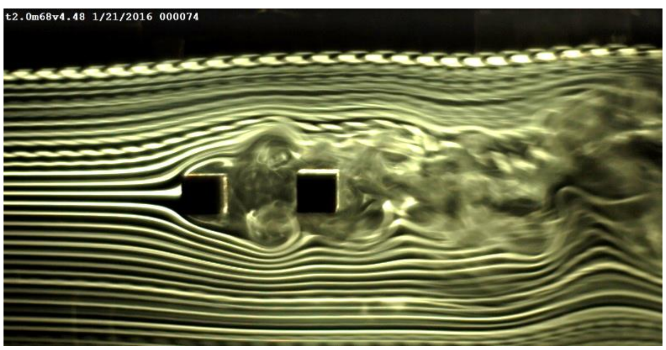



**FIGURE 11:** RESULTS OF FLOW VISUALIZATION AROUND TWO SQUARE CYLINDERS (*S/D*=2.0)

The alternate vortices greatly getting into between the square cylinders at the neighborhood of reduced wind speed *Vr* = 4.5 were confirmed when non-dimensional distance was *S/D* = 3.0. Comparing the results of previous research [6], the comparison between the case of forced vibration of the square cylinders on the upstream and downstream sides in the same phase and the case of forced vibration of the square cylinder only on the upstream side shows that there was almost no difference in the formation status of alternate vortices in this research. The reason why the response characteristics of the spring-supported test of square cylinders on the upstream side and downstream side are similar to those of single square cylinder is considered that because non-dimensional distance expanded to *S/D* = 3.0, the response characteristics of square cylinders on the upstream and downstream sides came close to those of a single square cylinder.

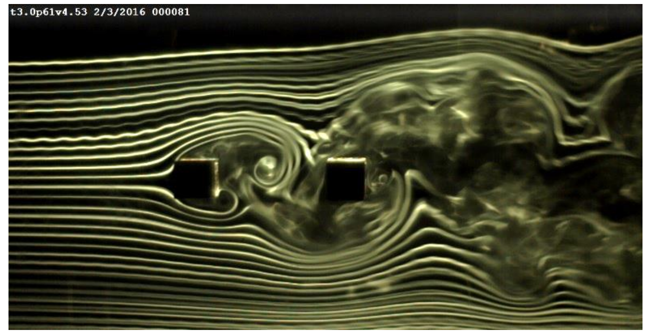



**FIGURE 12:** RESULTS OF FLOW VISUALIZATION AROUND TWO SQUARE CYLINDERS (*S/D*=3.0)

## CONCLUSIONS

Wind tunnel tests were carried out in order to find out the effects of aspect ratio *L/D* and non-dimensional distance *S/D* between two square cylinders in a tandem arrangement on in-line oscillation characteristics. The findings obtained from this research are as follows:

1. The in-line oscillation characteristics of two square cylinders in a tandem arrangement depends on the aspect ratio *L*/*D* to a certain extent as the same as that of single cylinder.
2. The maximum response amplitudes of two square cylinders in a tandem arrangement also depend on non-dimensional distance *S/D*. The maximum response amplitudes when *S/D* = 2.0 became the minimum for the aspects ratios other than aspect ratio *L/D* = 4.44.

## REFERENCES


[1] The Japan Society of Mechanical Engineers, 1998, Guideline for evaluation of flow-induced vibration of a cylindrical structure in a pipe, Standard JSME S012-1998. (in Japanese)

[2] K. Matsuda, K. Kato, I. Aratsu, Y. Tashiro, 2016, "In-Line Oscillation Characteristics of Two Square Cylinders in a Tandem Arrangement in Flow Hysteresis", *Electronic Proceedings of 11th International Conference on Flow-Induced Vibrations.*

[3] A. Okajima, S. Yasui, Y. Mori, S. Kimura and T. Kiwata, 2007, "Flow-Induced In-Line Oscillation of Two Square Cylinders in Tandem Arrangement", *Journal of the Japan Society of Mechanical Engineers*, ***73***, ***725***, pp.76-84. (in Japanese)

[4] A. Okajima, S. Ohtsuyama, T. Nagamori, T. Nakano and T. Kiwata, 1999, "In-Line Oscillation of Structure with a Circular or Rectangular Section", *Journal of the Japan Society of Mechanical Engineers*, ***65***, ***635***, pp.10-17. (in Japanese)

[5] K. Matsuda, H.Uejima and T. Sugimoto, 2001, "Wind Tunnel Tests on In-line Oscillation of a 2-Dimensional Circulular Cylinder, *Proceedings of the Fifth Asia-Pacific Conference on Wind Engineering (APCWE 5).*

[6] K. Matsuda, K. Kato, K. Suda and Y. Nakamura, 2017, "In-Line Oscillation Characteristics of Two Square Cylinders in a Tandem Arrangement", *Electronic Proceedings of 7th European-African Conference on Wind Engineering.*