Experimental investigation on the flow field between two circular cylinders in tandem arrangement

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Particle image velocimetry (PIV) technique was applied to investigate the vibration response characteristics of two circular cylinders with same diameter in tandem arrangement and the flow field around them. The cylinders were mounted as cantilevers with low natural frequency (around 50Hz). The Reynolds number ranges from 4,000 to 20,000. The spacing between two cylinders was 20mm.

Key words: PIV, Flow Field, Two Circular Cylinders, Vibration, Fluctuation Transfer Velocity

1. Introduction

Flow-induced vibration is one of the main reasons to give rise to mechanical noise and fatigue failure. There are many cylindrical core internals in lower plenum of BWR. When the flows from recirculation pump run through these structures, fluid force could affect these cylindrical structures. Therefore, it is important to make sure the safety of these structures. In order to achieve this aim, it is necessary to clarify how the interaction among these cylinders affects each other. However, most of previous studies were focused on the condition that cylinders were fixed or had one-degree-of-freedom, the case that cylinders had two degree of freedom has received much less attention.

Therefore, the present study utilized PIV technique to measure the flow field around a pair of equal-sized circular cylinders which are free to oscillate both in stream-wise and transverse directions in order to understand the mechanism of flow induced vibration phenomena and estimate the safety of related applications.

2. Experimental Details

Fig.1 (a) shows a schematic view of experimental setup. The free-vibration tests were carried out in a closed-circuit square water channel with a test section of 50mm in width and 1,500mm in length. Fig.1 (b) shows the vertical view of two circular cylinders structure, each of them with the diameter of 10 mm and 40 mm in length, mounted as cantilevers. The spacing between two cylinders was 20 mm. Circular cylinders were made of Mexflon plastomer, one end of the cylinder was inserted by metal pin which was mounted on channel wall, and meanwhile the other end was free. The diameter of the metal pin was 1.5mm or 1.6mm and the gap between the free end and the wall is 10mm. The structural damping (C_n) and the natural frequency (f_0) of the cylinders can be altered by changing the material of metal pin.

The upstream side of the test section was connected to a large-capacity reservoir with no free surface, while the downstream side was connected to a large-capacity reservoir with a free surface. Water could drain through the test section into the downstream tank. The water level of the tank was kept almost constant and the movement of the free surface was damped. This ensured that no perturbations of the downstream side were transmitted to the test section. The water was supplied to the test section at a constant rate and the rectangular test section was equipped with a current plate in order to maintain a uniform initial flow. The circular cylinder was installed at approximately 24*D* downstream from the current plate, where *D* is the width of water channel. Measurement was carried out after the flow of water attained fully developed state.

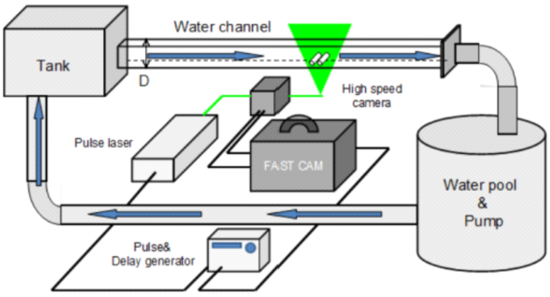
The experiments were carried out, by changing the current velocity from 0.40m/s to 1.75m/s with a stepwise increase of 0.05m/s increasing, at atmospheric pressure. And the Reynolds number of the experiments ranges from 4,000 to 17,500, varying the reduced velocity (Vru) up to about 3.4. The experimental parameters is shown in Table.1.

The oscillating frequencies of the cylinders and the surrounding flow were measured simultaneously using high temporal resolution PIV, which is non-intrusive with respect to the flow and has high spatial and temporal resolutions. Moreover, we obtain the positions of cylinders in images for each instant of time using image-pattern matching, and evaluate the oscillation of cylinders. In addition, experiments were carried out with in-line tandem cylinders in a water channel with two degree-of-freedom, varying the natural frequency ratio of upstream cylinder to downstream cylinder, $\eta=f_{ou}/f_{od}$. All the experimental results were normalized as non-dimensional type. The normalized frequency is defined as f/fu, where f is measured frequency, fu is the natural frequency of upstream cylinder. The normalized amplitude is defined as A/d, where A is the amplitude measured in experiments, d is the outer diameter of cylinder.

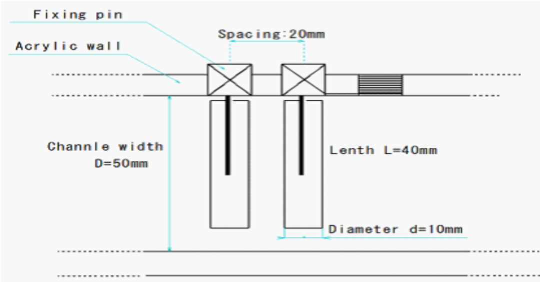
The reduced velocity V_r is defined:

$$V_r = V / f_0 d \qquad (1)$$

where V is the mean velocity of the test channel, f_0 is the natural frequency of the cylinder in the quiescent fluid, and d is the outer diameter of the cylinder.



(a) Schematic view



(b) Vertical view of two cylinders

Fig.1 Experimental setup

Table.1 Experimental condition

η(f0u/f0d)	specimen	f0	Cn	Vr	Re
0. 89	Brass2	47. 9	2. 16	0. 83-3. 12	4000-15000
	Stainless1	53. 7	1. 44		
1. 12	Stainless1	53. 7	1. 44	0. 74-2. 79	
	Brass2	47. 9	2. 15		
0. 83	Titanium4	38. 1	0. 71	1. 05-3. 94	4000-15500
	Stainless2	45. 9	1. 72		
1. 20	Stainless2	45. 9	1. 72	0. 87-3. 27	
	Titanium4	38. 1	0. 71		
1. 27	Stainless1	51. 8	1. 44	0. 77-2. 99	4000-17500
	Copper1	41	2. 14		

3. Experimental Results

3.1 Vibration characteristics of cylinders

Fig.2 and Fig.3 show the experimental results of normalized amplitude and normalized frequency of two cylinders, in the case of η=0.89.Fig.4 and Fig.5 show the results of η=1.12, and Fig.6 and Fig.7 show the results of η=1.28. In these figures, both results of upstream cylinder and downstream one are represented by reduced velocity of upstream cylinder *Vru* and normalized by natural frequency f_0 upstream cylinder, f_{0u}.

3.1.1 Frequency ratio η=0.89

With respect to the normalized amplitude, in the in-line direction, both cylinders had almost similar vibration characteristics. From V_{ru}>1.35, both cylinders were starting oscillating, amplitude of upstream was bigger than that of downstream. The maximum amplitude of upstream cylinder was 60% of the outer diameter. In the cross-flow direction, both cylinders had very slight vibration.

With respect to the vibration frequency, the frequency of downstream was close to the natural frequency of upstream cylinder. When V_{ru}<3.2, vibration frequency of both cylinders was locked in near to the natural frequency of upstream cylinder. In both directions, upstream cylinder had its oscillation peak at the frequency near S_t=0.4, also, downstream one had the same tendency.

Thus, in the case of η=0.89, it can be considered that upstream cylinder has strong influence on downstream cylinder, and the oscillation of upstream cylinder is dominant to that of downstream one.

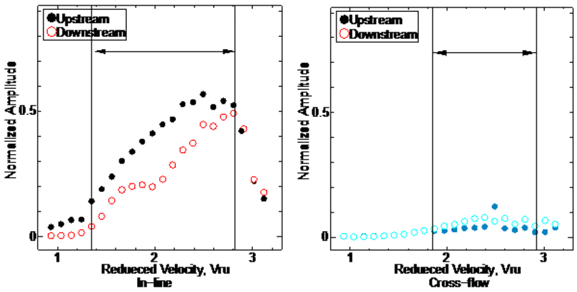


Fig.2 Normalized Amplitude (η=0.89)

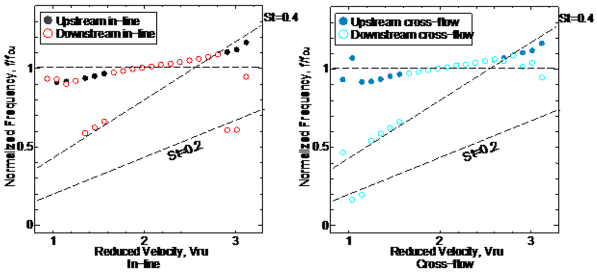


Fig.3 Normalized frequency (η=0.89)

3.1.2 Frequency ratio η=1.12

With respect to the normalized amplitude, in the in-line direction, both cylinders were exciting in 1.4< *Vru*<2.4, meanwhile, upstream one had larger amplitude. In cross-flow direction, the amplitude of upstream cylinder started increasing from *Vru*>2.4. Also, the amplitude of downstream cylinder started increasing from *Vru*>2.4, but it increased sharply, up to 50% of diameter.

With respect to the vibration frequency, in in-line direction, when 1< *Vru*<2.4, the oscillation frequencies of both cylinders were shifting close to the natural frequency of upstream cylinder, however, when V_{ru}>2.4, the frequency of downstream returned to its own natural frequency. In cross flow direction, when V_{ru}>2.4, frequencies of both cylinders were close to natural frequency of downstream one.

Therefore, in the case of η=1.12, it can be considered that the downstream cylinder which has larger amplitude is dominant to the upstream one.

According to table.1, since in η=1.12 and η=0.89, similar cylinders were utilized just sequence was different. Therefore the structural damping may have the dominant influence in these cases.

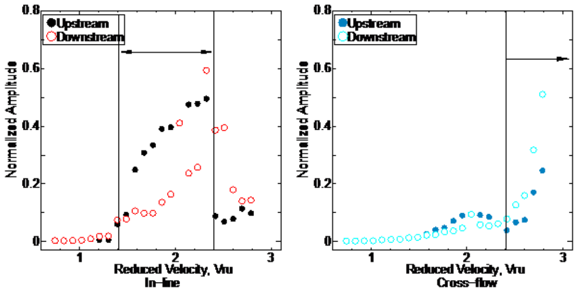


Fig.4 Normalized Amplitude (η=1.12)

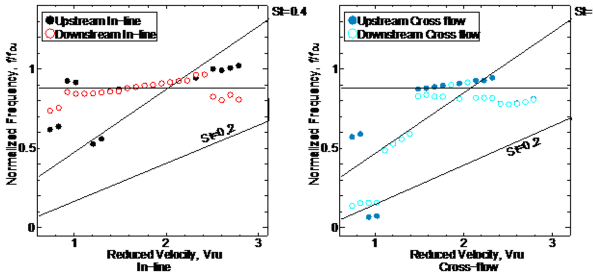


Fig.5 Normalized frequency (η=1.12)

3.1.3 Frequency ratio η=1.27

With respect to the normalized amplitude, vibration in the in-line direction, upstream cylinder excited when 1.5< V_{ru}<2.5. Also, downstream cylinder excited when 1.5< V_{ru}<2.8. Amplitude of upstream was bigger than that of downstream. The maximum amplitude of upstream cylinder was 30% of the outer diameter. In cross-flow direction, both cylinders started oscillating from Vru>2.45. Amplitude of downstream one grew rapidly, which reached 110% of cylinder diameter.

With respect to the vibration frequency, in the in-line direction, for 1.5< V_{ru}<2.5, both cylinders were locked in the natural frequency of upstream cylinder, while upstream cylinder had larger amplitude. In the cross flow direction, for V_{ru}>2.45, both cylinders were locked in the natural frequency of downstream one, meanwhile the amplitude of downstream cylinder was larger than that of upstream one.

Thus, in the case of 1.27, it can be considered that the cylinder which has larger amplitude is dominant to the other.

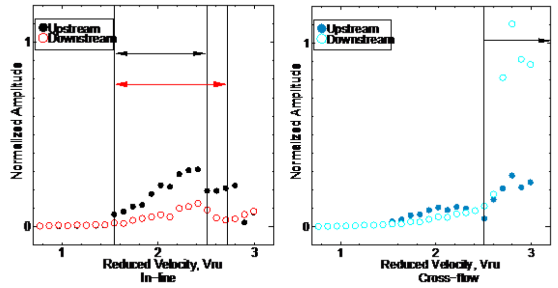


Fig.6 Normalized Amplitude (η=1.27)

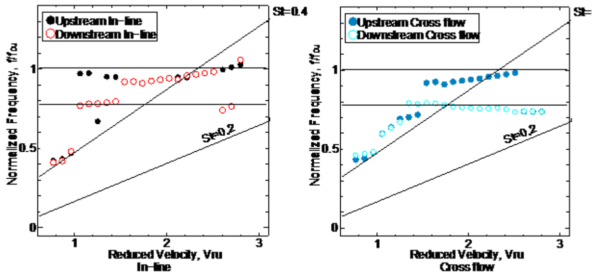


Fig.7 Normalized frequency (η=1.27)

3.2 Flow conditions and interference between upstream cylinder and downstream cylinder

3.2.1 Interference in vibration in the In-line direction

According to Fig.8, it is found that wake flow of upstream cylinder was shedding a pair of twin vortices. When calculating the frequency of flow field between two cylinders, in the in-line direction, upstream cylinder vibrated in the frequency which was close to S_t=0.4, downstream one vibrated in the frequency that was close to S_t=0.2. It is considered that this flow influences the vibration of downstream cylinder.

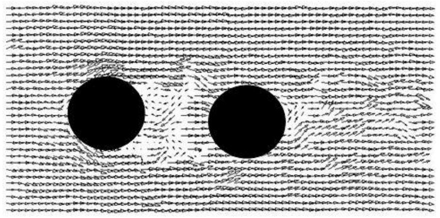


Fig.8 Flow field, V_{ru}=2.91 (η=0.89)

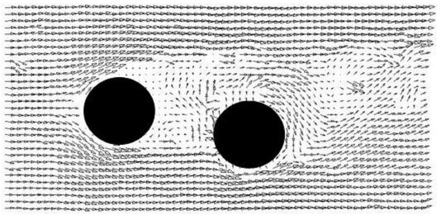


Fig.9 Flow field, V_{ru}=2.80 (η=1.27)

3.2.2 Interference in vibration in the Cross-flow direction

According to Fig.9, it is seen that wake flow of upstream cylinder shaped strong vortices, and the pairs of vortices were inducing the strong flow in vertical direction, furthermore, downstream cylinder had big oscillation amplitude in cross flow direction.

4. Discussion

4.1 Time delay and fluctuation transfer velocity

Due to the vortex forming, at different spatial locations where are on the vortex path, sudden velocity fluctuations are occurred with a time delay between two different spatial positions. The time delay value will increase when the distance between these two positions increases.

The measure of the degree of correlation between two velocity fluctuations in different spatial positions is defined as a function of space and time delay:

$$C(x,y,\tau)=\frac{\int_{-\infty}^{\infty}u(x_k,\ y_k,\ t)u(x,\ y,\ t+\tau)dt}{\sqrt{\int_{-\infty}^{\infty}u(x_k,\ y_k,\ t)^2dt}\sqrt{\int_{-\infty}^{\infty}u(x_k,\ y_k,\ t+\tau)^2dt}} \tag{2}$$

$C(x,y,\tau)_k$ is called the correlation value, k is the reference point index and $u(x,y,t)$ is the downstream component of the fluctuation velocity.

Theoretically, correlation value of every two spatial locations in the flow field could be calculated, then, time delay between two different spatial positions can be obtained, moreover, fluctuation transfer velocity at every position could be calculated by using the time delay result. The inverse of the slope of the delay curve, which is obtained by linear curve fitting method, gives the average transfer velocity of the fluctuations at this point due to equation [2]:

$$\frac{\partial\tau}{\partial x}=\frac{1}{u_{tr}} \tag{3}$$

Applying two-point velocity correlation method to not just single point, but for all points in the flow field, Fluctuation transfer velocity distribution which indicates the flow fluctuation transporting the flow field could be obtained. Then the two-dimensional fluctuation transfer velocity distribution is depicted in Fig.10, Fig.11, and Fig.12. All fluctuation transfer velocities are divided by the time averaged flow velocity. *Au* represents the amplitude of upstream cylinder. *Ad* indicates the amplitude of downstream one.

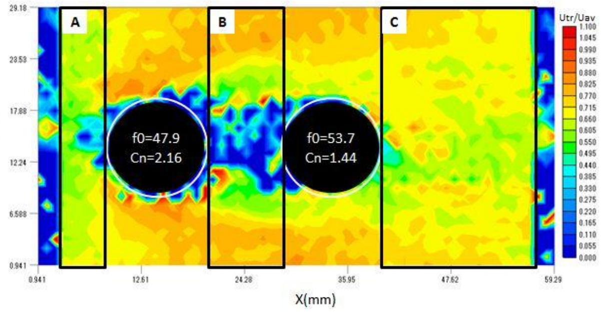


Fig.10 Normalized fluctuation transfer velocity distribution in Vru=1.04, Re=5,000 (η=0.89), Au=0.003d, Ad=0.002d

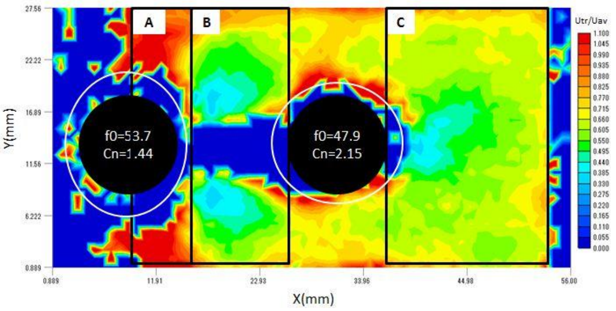


Fig.11 Normalized fluctuation transfer velocity distribution in V_{ru}=2.42, Re=13,000 (η=1.12), Au=0.2d, Ad=0.1d

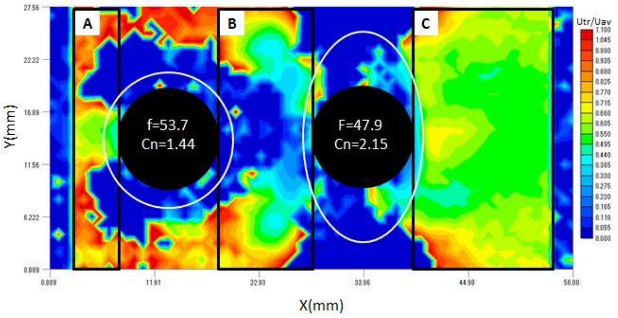


Fig.12 Normalized fluctuation transfer velocity distribution in V_{ru}=2.89, Re=15,000 (η=1.27), Au=0.2d, Ad=0.9d

Fig.10, Fig.12 were obtained while the speed of camera was set to be 1,000 fps, Fig.11 was obtained with the speed of camera at 5,000 fps. Under higher flow velocity, as shown in Fig.11 and Fig.12, even Fig.12 could indicate the fluctuation transfer approximately; it can be found that Fig.11 has better accuracy. In these figures, the extents of cylinders oscillation are schematically shown in white circle. Blue (V_{tr}=0) region is noise or error where the precise value could not be obtained due to lack of experimental data. Green regions are considered to be vortex locations in the flow field.

With respect to Fig.10, the in-line and cross-flow amplitude of cylinders were small, less than 0.1d. In the B region, two vortexes were shed from upstream cylinder. It can be observed that there were two obscure green areas which mean the vortex locations behind the upstream cylinder. In the C region where is the wake of downstream cylinder, turbulence was created. Similarly, it is considered that the green region in the wake of the downstream cylinder was caused by the turbulence.

With respect to Fig.11, in the A area, it can be observed that stable flow came from upstream and the velocity of this region was about 1.30m/s. Then sharp boundary could be found in the rear area of the upstream cylinder. It means the fluctuation transfer velocity changed suddenly. In the B region where is in middle of two cylinders, two vortexes (green spots) were created by upstream oscillation, and in the C area, one green spot which caused by downstream oscillation could be found. Moreover, even two cylinders have different natural frequencies, they were oscillating near the natural frequency of upstream one. Therefore, it can be considered the downstream cylinder was forced to oscillate by the upstream cylinder oscillation.

According to Fig.12, where the ratio of natural frequency is 1.27 and the flow velocity was 1.50m/s. in the cross-flow direction, the amplitude of downstream cylinder increased dramatically, reached up to 0.9d. Since the downstream amplitude was larger, fluctuations (green region) in C area was enlarged, however, because of downstream oscillation influence, available fluctuation transfer velocities are less than other cases. Therefore, the green spot in B area shrunk. Since both cylinders were locked in the natural frequency of downstream one, it can be thought that there is strong interaction between two cylinders. The downstream cylinder which has larger amplitude was dominant to upstream cylinder. The upstream cylinder was shedding vortexes to downstream one, however, the downstream cylinder had strong feedback to the upstream one.

5. Conclusions

This study investigated the flow-induced vibration interference between two tandem circular cylinders. Cylinders were locked in its own or the other's natural frequency. In the cases of η=0.89 and η=1.12, there was strong interaction between two cylinders. Furthermore, when two cylinders have close natural frequencies, the cylinder which has larger structural damping was dominant to the other.

Generally, higher flow velocity and larger amplitude of cylinder oscillation would create more fluctuation. Two vortexes would be shed from the rear region of upstream cylinder. In the wake of downstream cylinder, one street of vortices is able to be observed. Furthermore, fluctuation velocity distribution indicates the fluctuation energy transferring. In the vortex shedding path, the vortex fluctuation has the dominant fluctuation energy to affect the downstream regions. However, in order to capture more details, the camera speed should be increased largely.

6. References

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