CORRELATION OF FLUCTUATING VELOCITY IN THE WAKE OF AN OSCILLATING SQUARE CYLINDER WITH OPENINGS OR APPENDAGES

Seiji NAKATO*1

*1Associate Professor, Kanto-gakuin University, Yokohama, Japan

Correlation of wind velocity in the wake of stationary and oscillating square cylinders was studied in wind tunnel experiment. Models of square cylinders with openings or appendages for preventing vortex shedding were employed and oscillated with approximate triangle wave of two different periods. For normal square cylinder, component of vortex shedding frequency was dominant and oscillation did not affect spectra, correlation coefficient and coherence of fluctuating velocity. For square cylinder with openings, correlation increased with oscillation. On the contrary, both stationary and oscillated cylinders with appendages show low correlation. In general, vortex shedding was not strengthened or stabilized by forced oscillation without case that vortex shedding frequency is close to frequency of oscillation.

**Keyword**: square cylinder, fluctuating velocity, correlation coefficient, coherence.

1. INTRODUCTION

Wind-induced vibration tends to take place for cylinder-like structure, e.g. bridge, cable, chimney, member of structure. When its width to depth ratio (B/D) is small like square, vortex-induced vibration as well as galloping tends to occur. Important parameters to capture wind-induced vibration phenomena of cylinder like structure are fluctuating lift coefficient, the vortex shedding frequency and the correlation length. The correlation length represents three-dimensionality in the shedding flow. The measurement data of the correlation length is not enough compared to other parameters, and major focus of extensive research for investigating correlation length is circular cylinder. C. Norberg1) reviewed coefficients of spanwise correlation based on near-cylinder velocity fluctuations as well as fluctuating lift on a circular cylinder. A spanwise correlation length of about 30 cylinder diameters is indicated at the beginning of the subcritical regime (Re≈0.3×10³).

Vortex shedding from circular cylinder is relevant to many engineering application. For example, for application of marine riser with sheared flow, correlation length related to typical flexible circular cylinder was studied using a water flume2). When circular cylinder oscillates at or very near the shedding frequency, the correlation coefficient remains higher for larger separation. In contrast, when the cylinder oscillation frequency differs from the shedding frequency, correlation length drops off quickly toward the values for stationary cylinders.

Fluctuating lift and drag on a square cylinder in a smooth and in a turbulent stream was experimentally studied by B. J. Vickery3). This shows that fluctuating lift is greater than that for circular cylinder and spanwise correlation much stronger. P.W. Bearman and E.D. Obasaju4) describe measurements of pressure fluctuations on a stationary and oscillating square cylinder. Amplitudes of oscillation is up to 25% of the length of a side. Because of intermittent reattachment at side face, at lock-in the fluctuating lift and drag coefficient is reduced. Correlation of fluctuating velocity has also been discussed in buffeting response. Matsumoto et al5) evaluate spanwise coherence of rectangular cylinder of width-to-depth ratio B/D=5, focusing on the higher coherence of surface pressure than that of approaching flow in buffeting response.

Aerodynamic instability of cylinder-like structure is often described two-dimensional sections. But it has uncorrelated section along axis, which could stabilize instability. One method to suppress vortex-induced vibration is add-on devices helical strake, axial slats, splitter plate, spoiler plates and so on6). The author
investigated reduction of fluctuating lift force for square cylinder with changing cross section along axis with openings or appendages\(^7\). Experimental results of correlation of spanwise fluctuating velocity in the wake indicated that simultaneous vortex shedding was disturbed. However, if these cylinders are oscillated, vortex shedding may become well-organized again.

Therefore in this study, correlation of wind velocity in the wake of oscillating cylinders is studied in wind tunnel experiment. The models in the previous study were fixed\(^7\), so in this study the model is forced to oscillate transversely. For three models are employed; a prototype square cylinder, a square cylinder with openings, and a square cylinder with appendages. The objective of present study is evaluation of correlation due to the modification of cross section along axis. Motion of oscillation is triangle wave controlled by stepper motor.

2. EXPERIMENTAL SETUP

The experimental tests are carried out in the Eiffel-type wind tunnel with nozzle section 400 mm × 400 mm. The model was placed 200 mm downward from the wind tunnel nozzle and 200 mm above the floor in open type test section.

In present study, three models are employed; one is a square cylinder (prism) with 15 mm × 15 mm (=D) square and 400 mm length (26.7D), another is a cylinder with openings, and the other is a cylinder with appendages (Fig. 1). Openings of the second model are 5 mm height by 10 mm width with space of 20 mm at center of square cylinder height. Appendages of the third model are 15 mm height, 20 mm width, and 5 mm length with space of 10 mm on the windward surface of square cylinder.

Aspect ratio of 26.7 is enough to neglect end disturbances. Since the blockage ratio is 3.75% for square cylinder, no blockage correction was adopted.

![Figure 1 Experimental Models](image)

Two hot wires with horizontal spacing \(s=35\) mm (2.33D) were placed at 37.5 mm (2.5D) leeward direction and 10 mm (0.67D) below from center of the model (Figure 2). Two hot wires were at the same relative position within a cross-sectional plane. End plates are mounted at both ends of models to keep a two-dimensional air flow (Figure 3). Each experimental run was 20 second long with the sampling rate of 1000 Hz.

![Figure 2 Arrangement of model and hot wire](image)

![Figure 3 Model with openings and hot wires](image)
The model was supported at one end like cantilever beam and forced to oscillate vertically by linear actuator with a stepper motor. Oscillating system was composed of stepping motor driver (Oriental Motor Co.: ARD-A), actuator (Oriental Motor Co.: EASM4RXE065ARAC) and linear slide. Two oscillation patterns, osc. (A) and osc. (B), were shown in Figure 4. Stepper motor was controlled by digital IO from AD board (National Instruments Co.: PCI-6259). Oscillation like triangular wave was employed due to the limitation imposed by the oscillation system. Harmonic oscillation by stepper motor has to be slow because of maximum speed limitation. Amplitude and frequency of vibration were maximized under the condition preventing a step-out of stepper motor. Although maximum speed is 220mm/s in specifications, approximately 400 mm/s is obtained. Oscillation time period was obtained from peak frequency of power spectrum of acceleration data.

Forced oscillating by stepper motor used in this experiment has advantage for non-sinusoidal motion, such as large amplitude motion of a cable with non-sinusoidal motion, long span bridge motion with some restriction of displacement and so on.

Figure 5 shows arrangement when the model was forced to oscillated. It is noted that hot wires were inside of separated shear layers in a certain arrangement.

The wind is uniform smooth flow and up to \( U = 5.9 \text{m/s} \) (Re=5.6×10^3). Wind speed is controlled by inverter frequency given by analog signal applied from AD/DA board on a computer.

<table>
<thead>
<tr>
<th></th>
<th>A (mm)</th>
<th>T (sec)</th>
<th>f (Hz)</th>
</tr>
</thead>
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<td>osc. (A)</td>
<td>25mm (1.67D)</td>
<td>0.256</td>
<td>3.9</td>
</tr>
<tr>
<td>osc. (B)</td>
<td>10mm (0.67D)</td>
<td>0.105</td>
<td>9.5</td>
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Figure 4 Oscillation pattern

3. EXPERIMENTAL RESULTS AND DISCUSSION

(1) Power spectral density and time series of fluctuating wind velocity

Power spectral density of fluctuating wind velocity is shown in Figure 6. Spectrum was averaged using 5000 points data with overlapped by 2500 points. Frequency resolution is 0.2Hz.

Top row is graph for square cylinder, center row for openings and bottom row for appendages; left column for fixed, center column for osc. (A), and right column for osc. (B). In graph, the horizontal axis shows frequency. The vertical axis is logarithmic scale, with power spectral density of wind velocity and its increments are \( 10^2 \text{(m/s)}^2/\text{Hz} \) of the values between each grid line. Each power spectral density at wind speed, 0.48, 1.07, 1.68, 2.28, 3.02, 3.67, 4.23, 4.75, 5.33, 5.88 m/s is plotted from bottom to top.

For stationary square cylinder, a spectral peak is observed and its frequency is proportional to wind speed. So this peak is related to vortex shedding. When square cylinder is oscillated, spectra are almost same
behavior as that of stationary cylinder. Peak at oscillation frequency is weak for osc. (A) and not clear for osc. (B). This results reflect the fact that motion-correlated separating flow from the leading edge declines in dominant Karman vortex shedding.

For model with openings, a weak spectral peak of vortex shedding is indicated. When model is forced to oscillate, there is a peak at oscillation frequency, 3.9 Hz and 9.5 Hz respectively in contrast to square cylinder. For model with appendages, a peak of vortex shedding is weak than model with openings as well as a peak of oscillation frequency. It is indicated that motion-correlated vortex shedding is not organized because motion-directional projection shape is irregular.

From the viewpoint of amplitude of fluctuation velocity in the wake, appendage is effective for reduction of each periodic fluctuation.

Figure 6 Power spectral density of fluctuating wind velocity.

- top: square cylinder, center: openings, bottom: appendages, left: fixed, center: osc. (A), right: osc.(B)

Please note the 20 dB shift between successive cases.

Figure 7 shows example of fluctuating velocity time series, from 5 to 5.4 second, at U=3.0m/s corresponding to 5th graph from bottom in each graph of Figure 6. For stationary square cylinder, periodic wave is observed which looks like triangle wave rather than sinusoidal wave. For oscillating square cylinder, spiky noise overlap periodic wave. The time series for cylinder with openings or appendages are dominated by random fluctuations of the velocity. For stationary model, velocity is lower than others because position of hot wire is in the wake affected by openings or appendages.
Peak frequencies of vortex shedding is the Strouhal number (St) is defined as

$$St = \frac{f_s B}{U}$$  \hspace{1cm} (1)

where $f_s$ is the vortex shedding peak frequency, $B$ is characteristic length (here is $d=15\text{mm}$), and $U$ is wind speed.

The Strouhal number of square cylinder is shown in Figure 8. The Strouhal number of stationary square cylinder is slightly depends on wind speed and less than the past reported data $St=0.13$. These results are probably due to open type test section of the wind tunnel. The Strouhal number of oscillation square cylinder is greater than that of stationary cylinder at $U=1.7, 2.3 \text{ m/s}$, implying that separation flow reattaches intermittently at side face. For $U > 3.7 \text{ m/s}$, flow around cylinder is supposed to become fully separated flow again.

There is a spectral peak at 17Hz for fixed cylinder with appendages at $U=2.28\text{m/s}$ in left and bottom graph in Figure 6, from which Strouhal number is 0.11 corresponding to increase of side ratio, $B/D=1.33$, at section with appendages.
(2) Coherence and Correlation coefficient of fluctuating wind velocities

Spanwise correlation is depends on the three-dimensionality in the vortex shedding. At small separation coherence is almost 1, while at large separations coherence is expected to close to 0.

The root-coherence function of two wake velocity is defined as follows:

\[
coh(f, r) = \frac{|P(j, j+s, f)|}{\sqrt{P(j, f) \cdot P(j+s, f)}} \tag{3}
\]

where \(P(j, j+s, f)\) is the cross-spectral density function, \(P(j, f)\) and \(P(j+s, f)\) are power spectra, and \(s\) is the spanwise separation. If two signals of hot-wire correspond to each other with a constant phase difference at a given frequency, the magnitude of coherence is 1. Even if ensemble average times is increased, peak of coherence does not become clear, since the coherence does not have power.

Figure 9 shows coherence for each wind speed. Coherence (square of eq. (3)) in spite of root coherence (eq. (3)) is shown in these figures because of making peak clear. Each coherence at wind speed is plotted from bottom to top like Figure 6. The vertical axis is from 0 to 1 between each grid line.

For stationary square cylinders, there is peak coherence at vortex shedding frequency. While peak at vortex shedding frequency is also observed for oscillating cylinder, peak at oscillation frequency is not clear. For model with openings, a weak and broad coherence peak of vortex shedding is indicated. When model is forced to oscillate, there is a peak at oscillation frequency, 3.9 Hz and 9.5 Hz respectively. For fixed model with appendages, no distinct peak was observed in the coherence. A weaker peak at vortex shedding frequency is indicated than model with openings.

In this measurement, hot-wire probes were fixed in position, and therefore wake due to cylinder motion could reduce coherence. However, higher coherence level at vortex shedding frequency is obtained for oscillating square cylinder, and also higher coherence level at oscillation frequency is obtained for cylinder with openings, which implying that evaluation of both spanwise correlation of vortex shedding and separating flow with force oscillation can be detected with position of hot wire in this experiment.

![Figure 9 Coherence of fluctuating wind velocity](image)
Figure 10 shows correlation coefficients $R$ and coherence level of each experimental case.

For the square cylinder, $R$ is approximately at 0.5 in all range of wind speed, and forced oscillation did not affect correlation. In most cases, $R$ had peak at 0.43m/s and 1.1m/s for osc. (A) and (B) respectively where oscillation frequency was almost same as vortex shedding frequency. Coherence level at oscillation frequency 3.9 Hz of osc. (A) is greater than stationary model. However, coherence level at oscillation frequency 9.4 Hz of osc. (B) is slightly greater than stationary model. This implies that oscillation of osc. (B) with small amplitude and high frequency produces smaller-scale vortex shedding. In this study, value of coherence at 3.8 Hz and 9.4 Hz are used since frequency resolution is 0.2 Hz in spectral analysis.

For fixed model with openings, $R$ is almost zero which means fluctuating velocities were not correlated in the wake. For both oscillating cases, $R$ increased but was still less than that of square cylinder, while coherence level at oscillation frequency is same as or a little greater than it.

For fixed model with appendages, small or negative correlation was observed. Coherence level at vortex shedding frequency shows similar behavior to cylinder with openings except at oscillation frequency coincides with Strouhal frequency. Coherence level at oscillation frequency 3.8 Hz of osc. (A) is high. However, coherence level at 3.6 Hz is higher than it. This tendency is clear for osc. (B), so that coherence level at 9.0 Hz is higher than oscillation frequency 9.4 Hz in all wind speed. Reason for this need further study.

Figure 10 Correlation coefficient and coherence

top: square cylinder, center: openings, bottom: appendages
left: correlation coefficient, center: coherence at frequency of Strouhal component, right: coherence at oscillation frequency
Here, it is worthwhile to roughly apply the results of present study to bridge application. Supposing that cylinder discussed here is bridge-handrail beam with 50mm × 50mm square section attached to long span bridge. When the cylinder is forced to oscillate with 0.2 Hz of heaving natural frequency of the bridge, vortex shedding frequency coincides with 0.2 Hz at wind speed $U=0.08$m/s. In the range of wind speed where aerodynamic instability could be problem, frequency of vortex shedding from cylinder is larger than that of bridge natural frequency. In this condition, it can be indicated from the present result that periodic flow in the wake of cylinder (handrail beam) was not affected by motion of the bridge. In addition, countermeasure on the cylinder such as openings or appendages to suppress vortex shedding is also effective even in forced oscillation.

4. CONCLUSIONS

Correlation of wind velocity in the near wake of stationary and forced oscillating cylinder was studied through the wind-tunnel experiments.

It has been found that for the square cylinder, oscillation did not affect correlation and component of vortex shedding frequency was dominant. For square cylinder with openings, correlation increased with oscillation. On the contrary, both stationary and oscillated cylinders with appendages show low correlation. In general, vortex shedding was not strengthened or stabilized by forced oscillation without case that vortex shedding frequency is close to frequency of oscillation.

The next procedure is to change the hot-wire space parametrically and to evaluate correlation length.

REFERENCES

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