FLOW-INDUCED STREAMWISE OSCILLATION OF SQUARE CYLINDERS

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ABSTRACT

Flow-induced streamwise oscillation of two tandem square cylinders was studied by means of free-oscillation testing in a wind tunnel. One cylinder was elastically supported so as to allow it to move in the streamwise direction; the other was fixed to the tunnel sidewalls. The oscillation was studied experimentally for small values of the reduced mass-damping parameter ($Cn \leq 1.63$). When the upstream cylinder is free to oscillate, there are two excitation regions: the first for reduced velocity, Vr, in the range $2.5 \leq Vr \leq 5.0$ and cylinder gap distance to reference-length ratio, s, between 0.3 and 2.0, is due to movement-induced excitation accompanied by symmetrical vortex shedding, while the second, for $0.75 \leq s \leq 2.0$ and $4.5 \leq Vr \leq 6.5$, is due to vortex excitation by alternate Karman vortex shedding, referred to here as unstable limit-cycle oscillation. For wide gap distances over 2.5, an excitation region of the upstream cylinder occurs for $3.5 \leq Vr \leq 4.6$, which is due to alternate Karman vortex shedding, and resembles the streamwise oscillation of a single cylinder. In contrast, when the downstream cylinder is free to oscillate with narrow gap distances of $0.3 \leq s \leq 0.75$, the response displays an excitation region due to alternate Karman vortex shedding from the two cylinders, connected by the dead water region between them, for $3.2 \leq Vr \leq 5.4$. When s is greater than 1.0, the downstream cylinder experiences buffeting influenced by wake fluctuation of the upstream cylinder.

1. INTRODUCTION

If the working fluid is a liquid such as water, oil or metal sodium at high temperature, structures with extremely small mass ratios may be easily induced to oscillate in the streamwise (in-line) direction at relatively low reduced velocities. For example, flow-induced oscillation in the streamwise direction caused damage to a thermometer well and sodium leakage at “Monju”, the Japan Nuclear Cycle Development Institute’s prototype fast breeder reactor, in 1995 (JSME 2001, Okajima et al. 2004).

Vortex shedding from an elastically supported cylinder can cause cylinders to oscillate in the cross-flow (transverse), and streamwise directions if there is little structural damping. In addition, since the value of the mass ratio M, defined by $M= m/\rho D^2$ where m is the mass per unit span length, ρ is the fluid density, and D is the reference-length of cylinders, is small in liquid flows, the streamwise oscillation of cylinders may easily occur at low reduced velocity, because the reduced mass-damping parameter Cn (=$2M\delta$, where δ is the logarithmic decrement of the structure damping parameter) is small.

Many studies have already been conducted on the streamwise oscillation of cylinders with a circular cross section. For example, King et al. (1973) carried out experiments on a flexible cantilevered circular cylinder beam in a water channel. Recently, many experimental studies have been carried out on the streamwise oscillation of structures in wind tunnels (Okajima et al. 2000) and water tunnels (Okajima et al. 2004). Furthermore, we reported the experimental results of the streamwise oscillation of two circular cylinders by means of free-oscillation testing in a wind tunnel (Okajima et al. 2006).

The drag coefficients of two stationary tandem cylinders with a square cross section were measured by Takano et al. (1981) and Ohya et al. (1989), and they reported that the critical value of the gap distance where the aerodynamic parameters, drag coefficients and Strouhal number change discontinuously with the gap distance, was determined to be about 2.6, similar to the case of circular cylinders.

The situation of multiple square cylinders placed one behind the other in a flow occurs in many areas of engineering (e.g. handrails, louvers, and fences of buildings in wind engineering, and platform structural members in offshore engineering) and is known to lead to flow-induced oscillations. Therefore, in this study, we examined the streamwise oscillation of an arrangement of two square cylinders, by means of free-oscillation testing in a wind tunnel.

The upstream cylinder of two tandem square cylinders is elastically supported so as to move in the streamwise direction, while the downstream cylinder is fixed; then, the downstream cylinder is allowed to oscillate, and the upstream cylinder is fixed, which is similar to the previous study of Okajima et al. (2006). For both configurations, the gap distance is varied, and the response amplitudes of the oscillating cylinder and the vortex-shedding frequency in the wake are measured. The smoke-wire method is used to visualize the flow around the cylinders.

2. EXPERIMENTAL ARRANGEMENT

Experiments were performed in a low-speed wind tunnel with a rectangular working section of 300mm × 1200mm. A schematic diagram of the test section is shown in Fig. 1. Two square cylinders, each with a square cross-sectional height, H, of 120 mm, and made of Styrofoam with smooth surfaces covered by aluminum foil, were used. The edges of the square cylinders were made as sharp as possible. The span length of each cylinder was 293 mm. Circular end plates, approximately 240 mm in diameter and 0.5 mm thick, were fixed to both sides of the oscillating cylinder, so as to reduce the influence of any end effects on the flow. The oscillating cylinder was supported by eight coil springs in order to allow it move in the streamwise direction only. The characteristic frequency, f_c, of the oscillating cylinder was found to be 3.6 Hz; this is used in the definition of the nondimensional value of the characteristic frequency of a cylinder, $St_c = f_cH/U$, where U is the wind speed. The reduced mass-damping parameter (Scruton number) is defined by $Cn = 2m\delta/\rho H^2$.

Three experimental configurations were considered. Figure 2(a) shows the case where the upstream cylinder, elastically supported to move in the streamwise direction, is free to oscillate, while the downstream cylinder is fixed to the tunnel side-walls, whereas Figure 2(b) shows the case where the downstream cylinder is free to oscillate, while the upstream cylinder is fixed. The cylinder gap width to height ratio, $s = S/H$, where S is the gap distance between the upstream and downstream cylinders, was varied between 0.3 and 3.0. Figure 2(c) shows an oscillating cylinder, behind which there is a splitter plate which suppresses the generation of alternate Karman vortex-shedding, as in the previous experiment (Okajima et al. 2006). The splitter plate was made of acrylic and was 0.3 m wide, 1.25 m long and 5 mm thick.

The response amplitude, x_{rms}, of the oscillating cylinder was measured using laser displacement detectors, and nondimensionalized with a square cross-section of height H, to give the dimensionless root-mean-square amplitude, X_{rms}.

Other parameters of importance are the reduced velocity, Vr, and the wake Strouhal number, St_w, defined respectively by $Vr = U/f_cH$, and $St_w = f_wH/U$, where f_w is the vortex-shedding frequency, measured by hot-wire probes located on the center line of the gap between two cylinders and in the wake, the positions of which are shown in Fig. 2. In addition, the flow around the cylinders was visualized by the smoke-wire method, using liquid paraffin smoke.

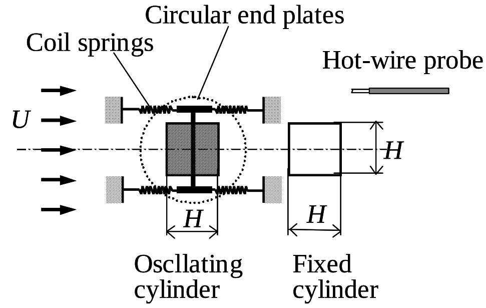
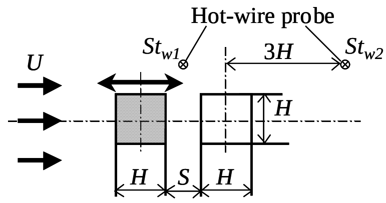
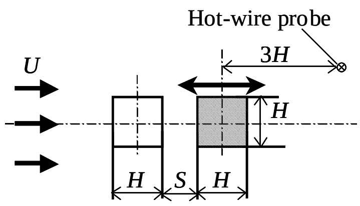


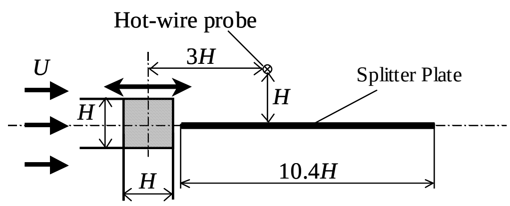
Figure 1: Schematic view of a test section for experiment; the upstream cylinder elastically supported to move in the streamwise direction, is free to oscillate, while the downstream cylinder is fixed.



(a) Oscillating upstream cylinder



(b) Oscillating downstream cylinder



(c) Oscillating cylinder with splitter plate

Figure 2: Arrangement of two tandem square cylinders and a square cylinder with splitter plate

3. FLOW-INDUCED STREAMWISE OSCILLATIONS OF A SINGLE CYLINDER AND A SINGLE CYLINDER WITH A SPLITTER PLATE

Figure 3 shows results of the nondimensional response amplitude, X_{rms} for a single oscillating cylinder (Cn = 1.32) and an oscillating cylinder with a splitter plate (Cn = 1.41, abbreviated to S.P. in Fig. 3). The response curve of the single cylinder (indicated by a solid line with open circle) shows that its streamwise oscillation occurs in two regions at approximately half of the resonance velocity; the one at lower velocity, $3.0 \leq Vr \leq 3.5$ is termed the first excitation region, and the one at higher velocity, $3.6 \leq Vr \leq 4.4$ is termed the second excitation region, where a lock-in phenomenon occurs that the wake frequency (St_w) equals half of the nondimensional characteristic frequency of a cylinder ($St_c/2$). The response amplitudes of the streamwise oscillation of the cylinder with a splitter plate also are plotted (solid circles) in this figure. It should be noted that this oscillation begins to occur near Vr = 3.2, and X_{rms} increases with Vr up to the maximum value of 0.027 near Vr = 3.8, and then the oscillation gradually damps out to cease at Vr = 4.7. Since the splitter plate suppresses the generation of alternate Karman vortex-shedding, this excitation is apparently due to the movement-induced excitation, accompanied by symmetrical vortices.

4. FLOW-INDUCED STREAMWISE OSCILLATION OF THE UPSTREAM CYLINDER

The cylinder gap distance to cross-section height ratio, s, changed from 0.3 to 3, and the flow-induced streamwise oscillation of the upstream cylinder was examined. Here, we show typical results for s = 0.5 (narrow gap), 1.0 (middle gap), and 2.5 (wide gap).

4.1 s = 0.5 (narrow gap)

Figure 4 shows an example of the response curve of the streamwise oscillation of the upstream square cylinder for s = 0.5. This figure shows the response amplitude, X_{rms}, and the wake Strouhal number, St_w, plotted against reduced velocity, Vr, for Cn = 1.63. In this figure, streamwise oscillations begin to occur near Vr = 2.7, and X_{rms} changes along the curve of the cylinder with a splitter plate with increase of Vr, and then the value of X_{rms} suddenly increases at approximately half critical velocity, $Vr_{cr}/2$, up to a value of 0.074 at Vr = 4.7, followed by the damping of oscillation, with the cylinder completely ceasing to oscillate at Vr = 5. It should be noted that this response curve is quite different from that of the cylinder with a splitter plate for $3.8 \leq Vr \leq 5.0$. From this figure it can be seen that the lock-in phenomenon where the frequency of the gap flow (St_{w1}) equals St_c, occurs for $2.7 \leq Vr \leq 4.8$, and also the wake frequency (St_{w2}) behind the downstream cylinder is locking at St_c for $3.2 \leq Vr \leq 4.6$.

Figure 5 shows the visualized flow pattern when the upstream cylinder oscillates in the streamwise direction at Vr = 4.39. In observing the flow around the cylinder oscillating at Vr = 4.39, it can be seen that the upstream shear layers become reattached on the side surfaces of the downstream cylinder. It is evident that the streamwise oscillation is due to movement-induced excitation accompanied by symmetrical vortices.

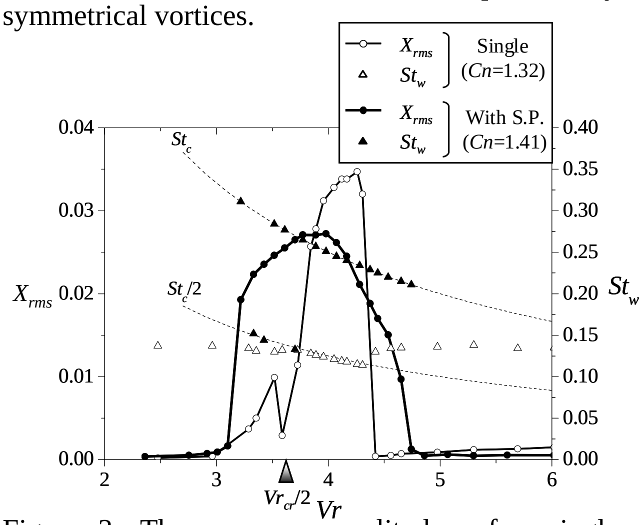


Figure 3: The response amplitudes of a single cylinder (Cn = 1.32) and a square cylinder with splitter plate (Cn = 1.63), and Strouhal number versus Vr.

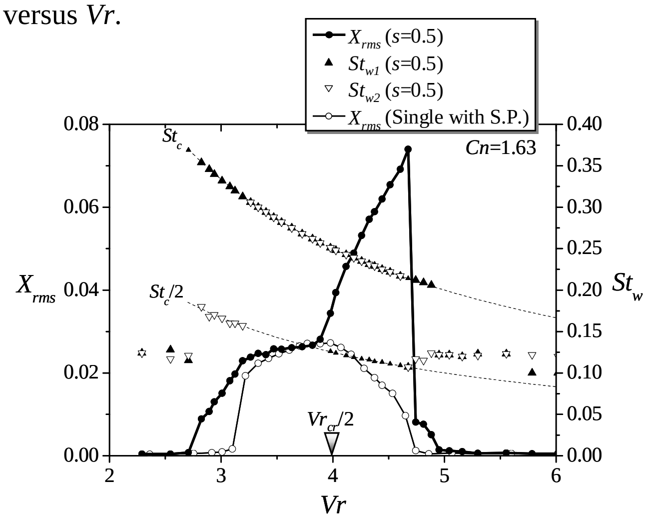


Figure 4: The response amplitude of the upstream cylinder and Strouhal number versus Vr for Cn = 1.63 and s = 0.5.

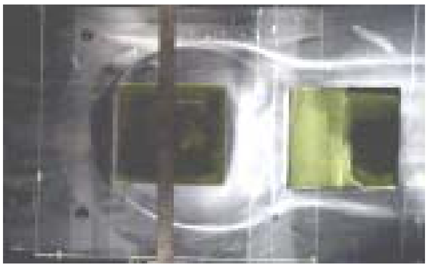


Figure 5: Visualized flow patterns at Vr = 4.39 for Cn = 1.63 and s = 0.5.

4.2 s = 1.0 (middle gap)

Figure 6 shows the results (Cn = 1.44) of the streamwise oscillation of the upstream cylinder for s = 1.0. Two excitation regions appear: the response characteristic for $3.0 \le Vr \le 4.7$ is similar to those of the cylinder with a splitter plate, the Strouhal frequency of which equals St_c, and the excitation for $5.1 \le Vr \le 6.3$ can be characterized as an unstable limit cycle oscillation with $St_c/2$ which increases to X_{rms}= 0.06 at Vr = 6.3 when the initial displacement provided is over to X_{rms} = 0.02, while the oscillation is suppressed for $4.7 \le Vr \le 5.1$.

Figure 7 shows the visualized flow patterns when the upstream cylinder oscillates in the streamwise direction at Vr = 4.17 and 5.25. In these figures, it is apparent that a pair of symmetrical vortices forms in the gap between the cylinders with St_c, at Vr = 4.17, and that an unstable limit cycle oscillation with large amplitude is induced by the alternate Karman vortex-shedding formed with $St_c/2$ in the gap between the two cylinders, at Vr = 5.25. Giving an initial oscillating displacement to the cylinder promotes the formation of alternate vortex shedding in the gap between two cylinders, which results in the unstable limit-cycle oscillation.

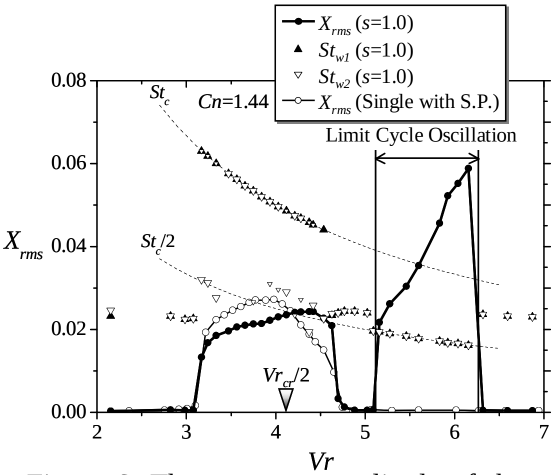
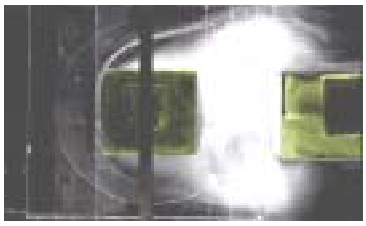


Figure 6: The response amplitude of the upstream cylinder and Strouhal number versus Vr for Cn = 1.44 and s = 1.0.

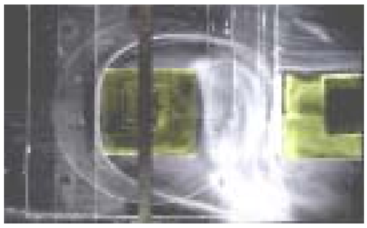
4.3 s = 2.5 (wide gap)

Figure 8 shows the results of the streamwise oscillation of the upstream cylinder for Cn = 1.36 when s becomes relatively large, i.e., s = 2.5. Only one excitation region appears for $3.5 \le Vr \le 4.6$; these responses have a maximum amplitude of X_{rms}= 0.035 around $Vr_{cr}/2$ = 4.3 and St_{w2} behind the downstream cylinder locks with $St_c/2$ for $4.2 \le Vr \le 4.5$. These results are similar to those of a single cylinder.

Figure 9 shows the visualized flow pattern when the upstream cylinder oscillates in the streamwise direction at Vr = 4.28. In this figure, it is apparent that alternate Karman vortex-shedding is formed in the gap between the cylinders with $St_c/2$.



(a)Vr=4.17



(b)Vr=5.25

Figure 7: Visualized flow patterns at (a)Vr= 4.17 and (b)5.25 for Cn = 0.99 and s = 1.0.

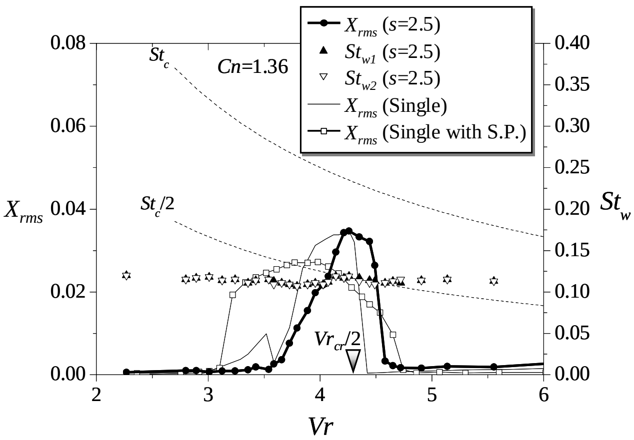


Figure 8: The response amplitude of the upstream cylinder and Strouhal number versus Vr for Cn = 1.36 and s = 2.5.

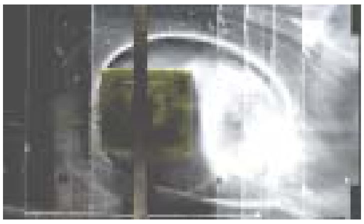


Figure 9: Visualized flow pattern at Vr= 4.28 for Cn = 1.36 and s = 2.5.

4.4 The excitation regions of the upstream cylinder

Figure 10 shows the excitation regions of the upstream cylinder as functions of s and Vr. There are several excitation regions, each created by different oscillation mechanisms: movement-induced excitation accompanied by symmetrical vortex shedding, alternate Karman vortex excitation, and unstable limit cycle oscillation.

Movement-induced excitation is accompanied by the formation of symmetrical vortices in the gap in front of the downstream cylinder, for $Vr \geq 2.7$ for $0.3 \leq s \leq 2.0$. For $0.75 \leq s \leq 2.0$, the response characteristics of the upstream cylinder have two excitation regions; these are associated with symmetrical vortex shedding and alternate Karman vortex shedding. Unstable limit cycle oscillation is due to alternate vortex-shedding for $0.75 \leq s \leq 2.0$ and $4.5 \leq Vr \leq 6.5$, which occurs when an initial displacement over X_{rms}= 0.02 is given to the oscillating cylinder.

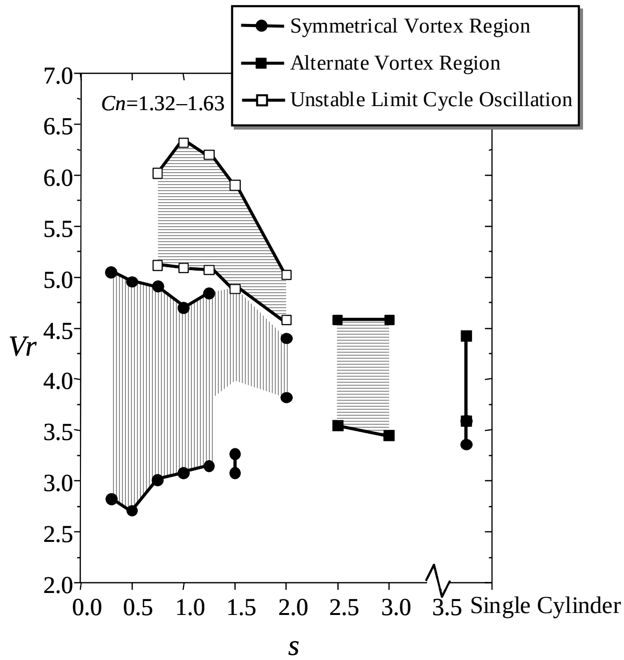


Figure 10: The excitation regions of the upstream cylinder as functions of s and Vr for Cn = 1.32–1.63.

5. STREAMWISE OSCILLATION OF THE DOWNSTREAM CYLINDER

Here, we show typical results for the streamwise oscillation of the downstream cylinder, when it is free to oscillate in the streamwise direction and the upstream cylinder is fixed. Results are presented for the gap distance ratios: s = 0.3, for example.

5.1 s = 0.3 (narrow gap)

Figure 11 shows the response curve and Strouhal numbers for the downstream cylinder for s = 0.3 and Cn = 1.63, together with the results for a single oscillating cylinder. The response curve of only one excitation region with half the characteristic frequency, $St_c/2$, is quite different from those of a single cylinder with two excitation regions. In this case, the downstream cylinder oscillates with frequency $St_c/2$, locking into a pattern of alternate Karman vortex-shedding from the two cylinders, and it is as if the cylinders and the dead water region between them form a single body from which vortex shedding occurs.

5.2 The excitation regions of the downstream cylinder

Figure 12 shows the excitation regions of the downstream cylinder as a function of s and Vr. The excitation region for the narrow gap distances of $0.3 \leq s \leq 0.75$ is induced by the alternate Karman vortex shedding from the two tandem cylinders, connected by the dead water region formed in the gap between them. When s is greater than 1.0, the downstream cylinder experiences buffeting oscillation.

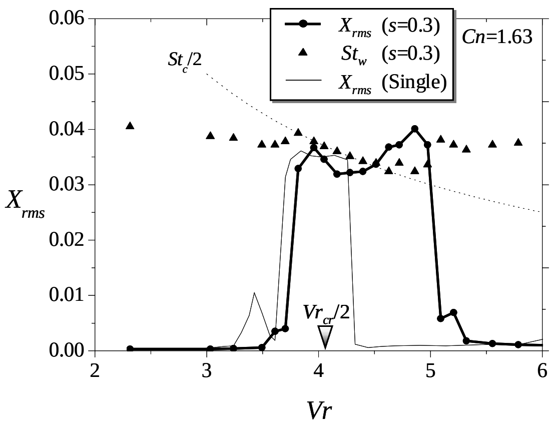


Figure 11: The response amplitude of the downstream cylinder and Strouhal number in terms of Vr for Cn = 1.63 and s = 0.3.

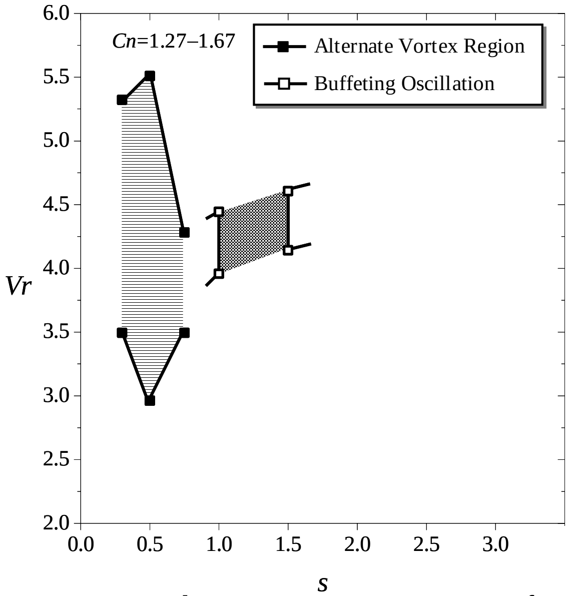


Figure 12: The excitation regions of the downstream cylinder as functions of s and *Vr* for *Cn* = 1.27–1.67.

6. CONCLUSIONS

Flow-induced streamwise oscillation of two tandem square cylinders was experimentally studied by free-oscillation testing in a wind tunnel for small values of the reduced mass-damping parameter (*Cn* ≤ 1.63). One of the cylinders was elastically supported so that it could move easily in the streamwise direction, whereas the other was fixed. The gap between them was varied from 0.3 to 3.0 cross-section heights. The response amplitudes of the oscillating cylinder in streamwise oscillation and the vortex-shedding frequency in the wake were measured, and the flow around the cylinders was visualized by the smoke-wire method.

When the upstream cylinder is free to oscillate, there are two excitation regions: the first for reduced velocity, *Vr*, in the range 2.5 ≤ *Vr* ≤ 5.0 and cylinder gap distance to reference-length ratio, *s*, between 0.3 and 2.0, is due to movement-induced excitation accompanied by symmetrical vortex shedding, while the second, for 0.75 ≤ *s* ≤ 2.0 and 4.5 ≤ *Vr* ≤ 6.5, is due to vortex excitation by alternate Karman vortex shedding, referred to as unstable limit-cycle oscillation. For wide gap distances over 2.5, an excitation region of the upstream cylinder occurs for 3.5 ≤ *Vr* ≤ 4.6, which is due to alternate Karman vortex shedding, and resembles the streamwise oscillation of a single cylinder. On the other hand, when the downstream cylinder is free to oscillate for narrow gap distances of 0.3 ≤ *s* ≤ 0.75, the response shows an excitation region due to alternate Karman vortex shedding from the two cylinders, connected by dead water region between them, for 3.2 ≤ *Vr* ≤ 5.4. When *s* is greater than 1.0, the downstream cylinder experiences buffeting due to wake fluctuation of the upstream cylinder.

7. REFERENCES

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