WAKE-INDUCED INSTABILITIES OF TWO PARALLEL CYLINDERS WITH SPIRAL PROTUBERANCES IN CLOSE STAGGERED ARRANGEMENT

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1. INTRODUCTION

While two parallel circular cylinders are common practices in bridge engineering, they are susceptible to wake-induced vibrations (WIV). WIV greatly depends on reduced wind velocity and the spacing between the two cylinders. Particularly, among two staggered parallel smooth cylinders nearby, the downstream cylinder experienced 2DOF wake-induced flutter (WIF) in the low reduced wind velocity regime and wake galloping in the high reduced wind velocity regime (Fukushima et al., 2021). Placing 12 spiral protuberances on the surface of both cylinders suppressed the wake galloping. 2DOF WIF was, however, extended over a wider range of reduced wind velocity (Do et al., 2021). Therefore, this study aims at clarifying the mechanism of the 2DOF WIF in the low reduced wind velocity regime and how the modified cylinders suppressed wake galloping in the high reduced wind velocity regime.

Fig. 1 Two parallel cylinders with spiral protuberances

2. AERODYNAMIC RESPONSE OF 2 PARALLEL CABLE WITH SPIRAL PROTUBERANCES

This study mainly focuses on the arrangement (*X/D*=3.0, *Y/D*=0.5), where *D* is the cylinder diameter; *X/D* and *Y/D* are the initial horizontal and vertical center-to-center distances. Two smooth cylinders in this arrangement produced a strong gap flow associated with wake galloping (Do et al., 2021). Fig. 2 shows the velocity-amplitude (VA) diagrams from 2DOF spring supported tests conducted on the downstream cylinder with a fixed upstream cylinder, where *W/D* and *S/D* are the horizontal and vertical equilibrium position of the oscillation considering static displacement; ξ and η indicate the horizontal and vertical displacements. Fukushima et al. (2021) attributed the 2DOF WIF in $U/fD\leq50$ to the coupling of ξ and η component, while the instability in $U/fD\geq100$ was wake galloping initiated by the static displacement as noted in Fig. 2. Similar testing conditions were applied to two cylinders with 12 spiral protuberances – spiral cylinders (Fig. 1). Fig. 3 shows the resultant VA diagrams, in which 2DOF WIF was enhanced and extended up to U/fD=100. In addition, no noticeable static displacement appeared. In $U/fD\geq100$, the two spiral cylinders did not experience wake galloping as seen in its counterpart.

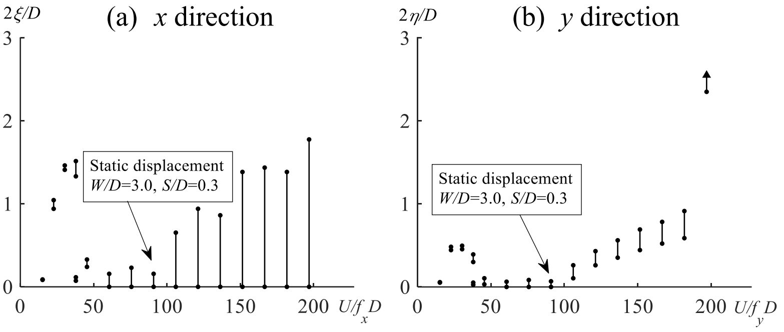

Fig. 2 VA diagrams of two smooth cylinders (*X/D*=3.0, *Y/D*=0.5) by Fukushima et al. (2021)

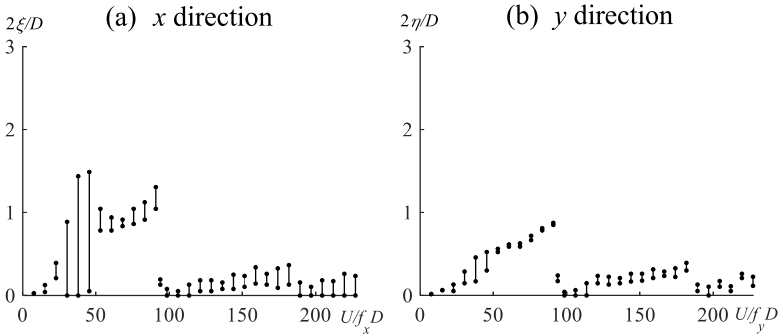

Fig. 3 VA diagrams of two spiral cylinders (*X/D*=3.0, *Y/D*=0.5)

3. WAKE-INDUCED 2DOF FLUTTER IN LOW REDUCED WIND VELOCITY

The 2DOF WIF observed in Fig. 3 is attributed to the Reynolds number dependency. A free stream U/fD=100 corresponded to $Re=2.5\times10^4$ considering the experimental conditions. However, given the close spacing between the two cylinders, the downstream cylinder was probably immersed in the wake of the upstream cylinder instantaneously during the oscillation. Therefore, the downstream spiral cylinder was subjected to a lower *Re*. Dao et al. (2021) reported that a single spiral cylinder with the same configuration underwent drag crisis at $1.3\times10^4\leq Re\leq2.3\times10^4$. Therefore, drag crisis and resultant

Table 1 Settings for forced vibration tests

	(I)	(II)
$2A_\eta=2A_\xi$	0.4	0.4
D [mm]	0.05	0.07
U [m/s]	0 - 12	12
f_{vib} [Hz]	1.32	0.67-2.60
Re	$0 – 4.9\times10^4$	6.9×10^4
U/fD	0 - 182	66 - 256

Keywords: wake-induced vibration, wake galloping, circular cylinder, spiral protuberances, parallel cylinders

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alteration in aerodynamic characteristics is probably associated with the extended 2DOF WIF in Fig. 3. To clarify this, forced vibration tests in respective 1DOF vertical and horizontal direction were conducted on the downstream spiral cylinder at ($W/D=3.0$, $S/D=0.5$) away from a fixed upstream cylinder. Table 1 shows the testing conditions. Fig. 4 shows the flutter analysis results using the collected flutter derivatives. The different color plots represent two solutions, also known as modes, of the flutter analysis. Negative logarithmic decrement δ indicates the negative damping, and thus, instability.

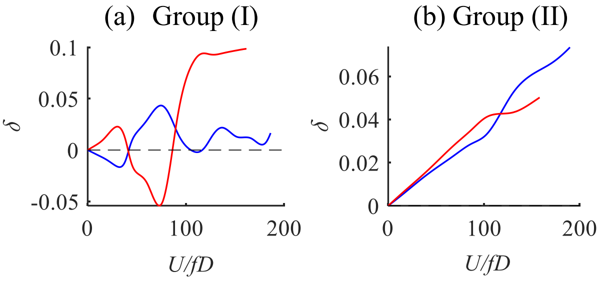

Fig. 4 Resultant δ from flutter analysis

Group (I) corresponded to the settings of the VAs in Fig. 3. In Fig. 4 (a), group (I) showed negative δ in both solutions in $U/fD\leq100$. The 2DOF WIF here appeared to be 2DOF coupling flutter, similar to the case of two smooth cylinders in $U/fD\leq50$. Conversely, by fixing freestream velocity U=12m/s, group (II) was assumed to be well beyond the drag crisis of a spiral cylinder. There was no trace of 2DOF coupling flutter in Fig. 4 (b). Apparently, 2DOF WIF in $U/fD\leq100$ was exclusive to $Re\leq2.3\times10^4$ and should not appear in high Re. Therefore, even though 2DOF WIF occurred in the experiments, it should be of no concern in bridge engineering practices.

4. SUPRESSION OF WAKE GALLOPING IN HIGH REDUCED WIND VELOCITY

Do et al. (2021) reported that flow switching between gap flow and outer flow was attributed to wake galloping in 2 parallel smooth cylinders nearby. In fact, flow switching alone was not sufficient but it must be accompanied by a phase delay between lift force and vertical displacement of $\psi_{L\eta} \geq \pi/2$.

Fig. 5 shows the hysteresis loop of instantaneous dimensionless lift $C_L(t)$ against $\eta(t)$ during 1 ensemble-averaged cycle when the downstream smooth cylinder harmonically oscillated around ($W/D=3.0$, $S/D=0.3$) (after static displacement occurred) at $U/fD=171$. The clockwise direction of the bounded region indicates that the cylinder would extract energy from the flow, and thus, the excitation of wake galloping, and vice versa. The negative peaks of $C_L(t)$ at $\eta(t)=0$ and $\eta(t)=0.1$ came from the occurrences of gap flow. At these two instances, the downstream cylinder was vertically $0.3D$ and $0.4D$ away from the upstream cylinder. Do et al. (2021) reported that a strong gap flow was produced between two stationary smooth cylinders in ($W/D=3.0$, $S/D=0.3$) at $U/fD=183$. Therefore, the hysteresis of gap flow occurrence in Fig. 5 was motion-induced and was unfavorable.

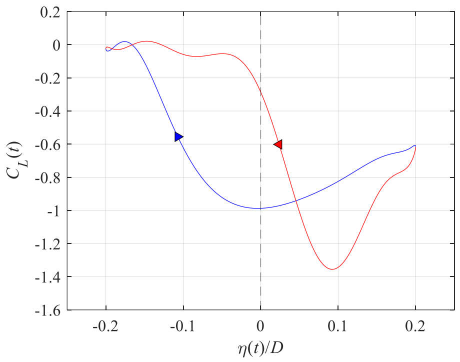

Fig. 5 Hysteresis loop of $C_L(t)$ for two smooth cylinders ($W/D=3.0$, $S/D=0.3$) at $U/fD=171$

Fig. 6 shows similar information as in Fig. 5 but applied to two parallel spiral cylinders at $U/fD=183$. In sharp contrast to Fig. 5, no distinguishable $C_L(t)$ peak is observed and thus no hysteresis. Although energy exchange existed, it was trivial and the flow damped away any motion of the cylinder. This solidified the finding by Do et al. (2021) that the suppression of gap flow acted to stabilize the cylinder agaisnt wake galloping.

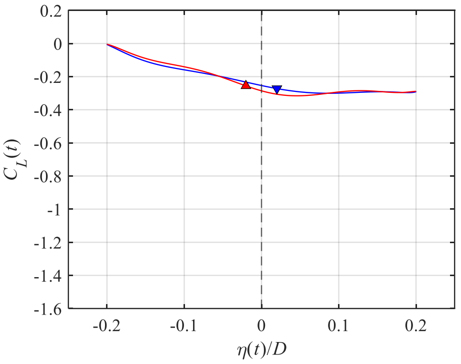

Fig. 6 Hysteresis loop of $C_L(t)$ for two spiral cylinders ($W/D=3.0$, $S/D=0.5$) at $U/fD=183$

5. CONCLUSIONS

- Two parallel cylinders attached with 12 spiral protuberances were subject to 2DOF flutter in $Re\leq2.3\times10^4$. Conversely, at $Re>2.3\times10^4$, the structure was stable, which is a practical advantage as the Reynolds number in engineering practices are often well beyond this threshold.
- Cylinders with 12 spiral protuberances can successfully suppress wake galloping occurred in ($X/D=3.0$, $Y/D=0.5$) at high reduced wind velocity by suppressing gap flow and eliminating hysteresis.

ACKNOWLEDGEMENT

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