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Investigation on wind-induced instabilities of a H-shaped cylinder by a novel 3DOF mechanical system

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SUMMARY:
Taking the H-shaped hangers of a truss stiffen continuous bridge as the engineering background, aerodynamic instabilities of a small side-ratio (width to depth ratio 1.9) were investigated through elastically supported section model tests. A novel mechanical system was developed to model the 3 degrees of freedom (DOF) structural stiffnesses, i.e., torsional, strong-axis bending and weak-axis bending, to allow 3DOF coupled vibration, which is frequently observed on site during slender hanger vibration. The results indicate that the model exhibited nonlinear flutter under initial attack angle 0°, 10°, 30° and 40°, VIV around attack angle 0°. The observed VIV demonstrate obvious heave-sway coupling effect, whereas the coupling effect during nonlinear flutter is slight. When the coupling of sway DOF is constrained as in conventional spring-suspended system, noticeable discrepancy will be introduced into the stable amplitude of VIV. Free-stream turbulence tends to mitigate VIV peak response under attack angle 0°, but enlarges the stable amplitude when reduced velocity is larger than the peak response. The VIV response is found to be sensitive to turbulence intensity and insensitive to turbulence integral length scale.

Keywords: Vortex-induced vibration, nonlinear flutter, free-stream turbulence

1. INTRODUCTION

H-shaped cylinder is a common form of slender members in civil engineering, such as hanger, pillar, bridge deck, et al. Due to their unfavorable aerodynamic configuration, H-shaped members are prone to various wind-induced instabilities (Chen et al., 2012). The aerodynamic performance of a relatively large side ratio (around 4.8) has been extensively investigated in the survey of the collapse of old Tacoma Bridge. However, little is still known about the relatively small side ratio H-shaped cylinders. In the present study, the long hangers of a truss stiffen continuous bridge was taken as an engineering background, which was found to demonstrate aerodynamic instabilities. As a typical thin-walled section, a H-shaped member has a rather small torsion-heave and heave-sway frequency ratio, as a result, its torsional instability might be a critical issue and the possibility DOF coupling might be high. To accurately model the 3DOF stiffness, a novel mechanical system was firstly introduced allowing 3DOF coupled vibration. The effects of attack angles and freestream turbulence on wind-induced instabilities were then experimentally investigated.

2. WIND TUNNEL TEST

Elastically supported section model tests were carried out in CA-1 wind tunnel with a test section 2.5m(height)×3.0m(width). The experimental setup is shown in Fig.1(a). The dimension of the section model is 1.5m (length), 0.18m (width) and 0.094m(depth) as shown in Fig.1(b). A novel elastically supporting system in Fig.1(c) was employed to model the torsional, weak-axis bending and strong-axis bending stiffnesses of the prototype structure, where the heaving and swaying stiffness were modeled by plate springs and torsional stiffness by rhomboid helical springs. Wind angle of attack was adjusted continuously by turning the circular rings in Fig.1(c). To mitigate the end effect, two airfoil-shaped end plates were installed as shown in Fig.1(a) and (d), where the shape was designed using irrotational fluid theory to guarantee that the stream lines between the end plates are proportional to the cross section and flow separation around model ends is suppressed. The supporting system, displacement sensors and magnetic dampers were installed between the curved parts of the end plates to avoid interference. The dynamic parameters are listed in Table 1. Turbulence was generated through passive grids placed upstream. Turbulence intensity and integral length scales listed in Table 2 were adjusted by changing the relative distance and width of grid bars.

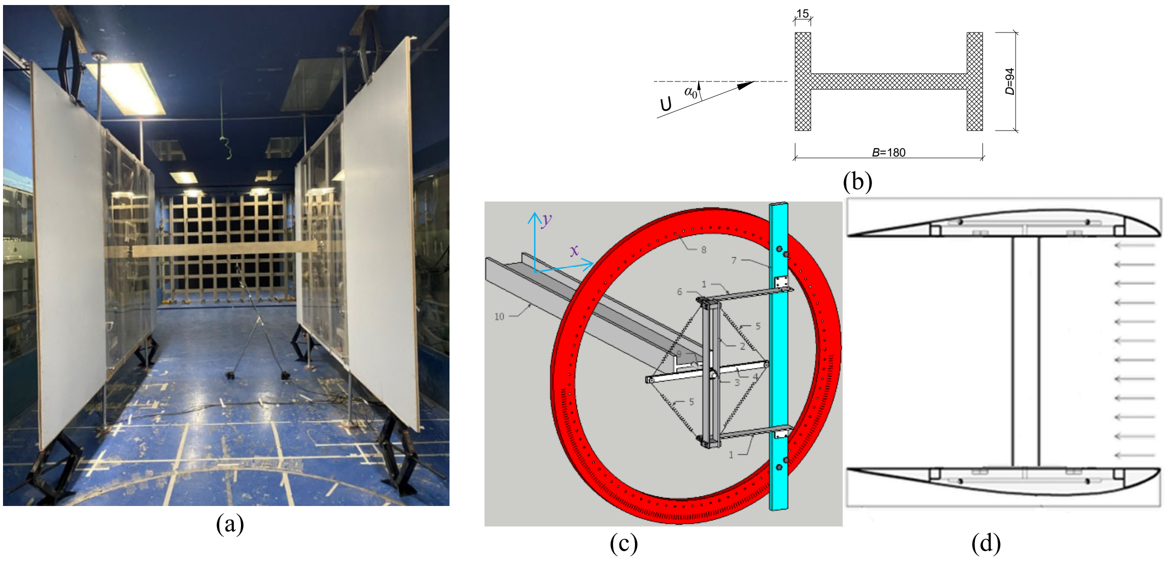


Figure 1. Experimental setup of the elastically supported section model test. (a) Setup in CA-1 wind tunnel, (b) Cross of section model (Unit: mm), (c) 3DOF elastically supported system allowing heave-sway-torsion coupled vibration, where *y* is strong axis and *x* is weak axis, (d) Schematic diagram of the airfoil-shaped end plates.

3. RESULTS AND DISCUSSSION

The observed stable amplitudes during aerodynamic instabilities are displayed in Fig 2. One can find from Fig.2(a) that the model exhibited nonlinear flutter in the torsional DOF under attack angle 0°, 10°, 30° and 40°. The coupling of weak-axis and strong-axis DOFs during nonlinear flutter was rather weak. As indicated in Fig.2(b)~(c), the model also underwent a large-amplitude VIV under attack angle 0° with an obvious heave-sway coupling effect.

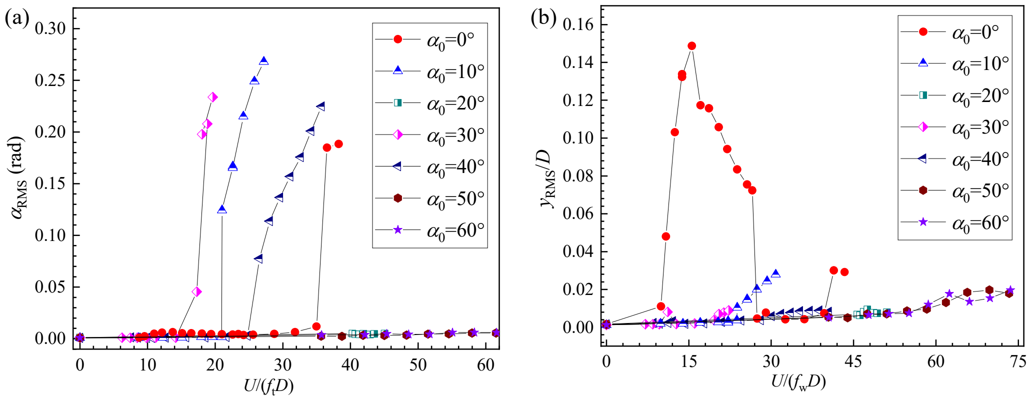
Fig.3 compares the VIV responses from the proposed 3DOF elastically supported system and the conventional 2DOF technique, wherein the swaying DOF, i.e., bending around strong-axis, is restrained and wind attack angle is adjusted by directly rotating the model by keeping the elastically supporting system unchanged. One can find that conventional technique generally leads to significant discrepancy in VIV responses at large attack angle, even when the attack angle is around 5°.

Table 1. Parameters of sectional model tests, where *B*, *D* and *L* are width, height, and length of the model. *M* is the total effective mass. f_{t0}, f_{w0} and f_{s0} are torsional, weak-axis and strong-axis bending frequency in still air.

Side ratio *B*/*D*	*B*/m	*D*/m	*L*/m	*M*/kg	f_{t0}/Hz	f_{w0}/Hz	f_{s0}/Hz	ξ/%
1.9	0.18	0.094	1.5	11.61	3.320	2.929	10.551	0.2~0.3

Table 2. Parameters of the turbulence flow field generated by passive grids in upstream. I_u, I_v and I_w are turbulence intensities in along-wind, vertical and transverse directions. L_{ux}, L_{vx} and L_{wx} are turbulence integral length scales.

	I_u(%)	I_v(%)	I_w(%)	L_{ux}(m)	L_{vx}(m)	L_{wx}(m)
A#	4.991	4.586	4.856	0.162	0.077	0.093
B#	14.426	13.444	12.977	0.176	0.079	0.073
C#	8.639	8.129	7.987	0.189	0.082	0.102
D#	8.143	7.502	7.057	0.299	0.145	0.149



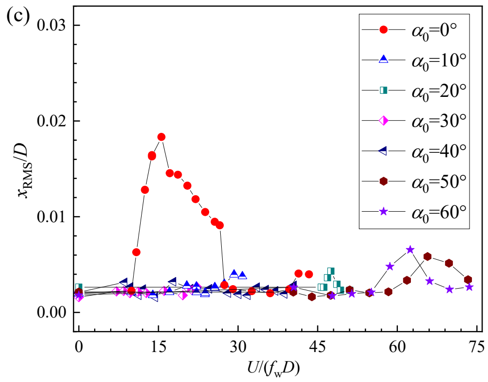


Figure 2. Stable amplitudes under various attack angles in smooth flow field. (a) Torsional DOF, (b) in strong-axis direction, (c) in weak-axis direction.

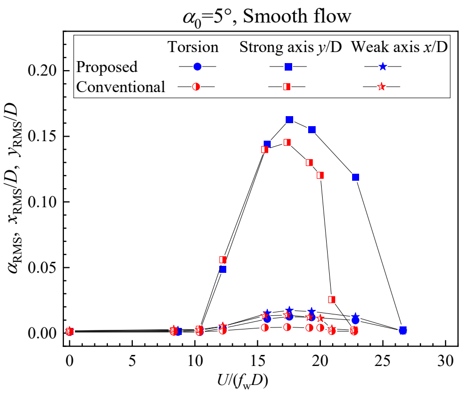


Figure 3. Comparison of tested VIV results by the proposed 3DOF coupled elastically supporting system and the conventional 2DOF coupled system.

The influence of free stream turbulence is shown in Fig.4. It is found that increasing turbulence intensity generally mitigates VIV peak response but leads to larger fluctuation when reduced velocity is larger than that at peak amplitude. VIV response is insensitive to the turbulence integral length scale, which is consistent with the results of Kobayashi et al.(1992) and Kobayashi et al.(1993,1999).

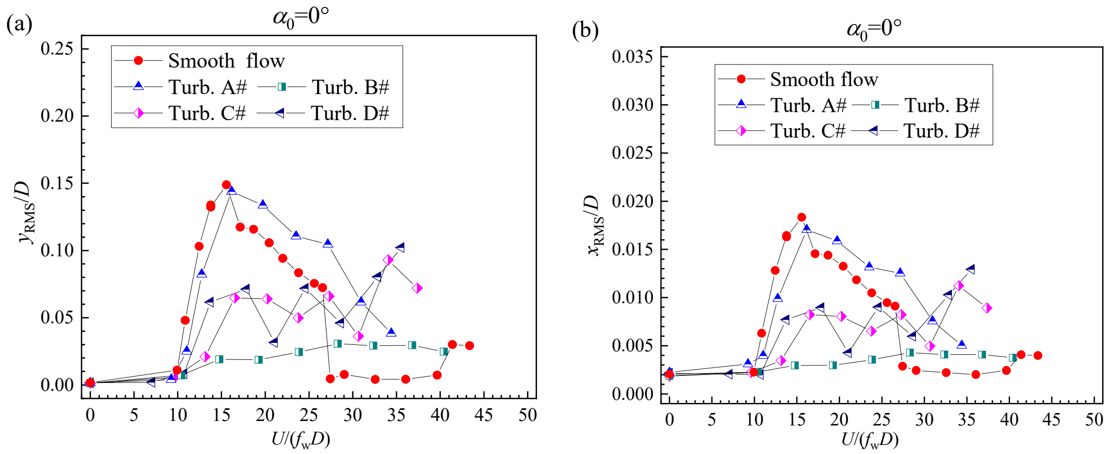


Figure 4. Influence of free stream turbulence on VIV amplitude. (a) Along strong-axis direction, (b) along weak-axis direction.

4. CONCLUSIONS

A novel elastically supporting system was proposed to model the torsion-heave-sway coupled vibration of H-shaped hangers. The aerodynamic instabilities of a typical H-shaped hangers with a side ratio 1.9 was measured using the proposed mechanical system. The model was found to exhibit nonlinear flutter and VIV under different attack angles. Weak-axis VIV has an obvious heave-sway coupling effect, whereas the coupling during nonlinear flutter is relatively slight. Turbulence intensity tends to mitigate the peak response of weak-axis VIV but enlarges the response at larger reduced velocity. The observed VIV response is insensitive to turbulence integral length scale.

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