Numerical simulation of wall effects on flutter performance of the thin plate based on model width

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SUMMARY:
During wind tunnel tests, there are wall effects due to the size limitation of the wind tunnel. In addition to the blockage effects, the ratio of the model width to the test section height (*B/H*) will also affect the flutter test results. In this paper, the thin plate is taken as the subject and the variations of flutter performance and flutter derivatives with *B/H* are studied through CFD simulations. The free vibration simulation shows that the flutter critical velocity decreases with the increase of *B/H*. Then, flutter derivatives of the thin plate with different *B/H* are obtained by the forced vibration method. Results show that H_1^*, A_1^* which are associated with vertical velocity and H_3^*, A_3^* which are associated with torsional displacement are more sensitive to the change of *B/H*, which is not caused by the change of blockage rate. After that, calculations are conducted based on the closed-form solutions (CFS) and flutter derivatives. It is found that the flutter critical velocity decreases with increase of *B/H*, which is consistent with the conclusion drawn from the free vibration simulation. And the influence sensitiveness is related to the parameters like model width, mass, mass moment of inertia and bending-torsional frequency ratio.

Keywords: wall effect, flutter performance, ratio of model width to the height of the test section

1. INTRODUCTION

The wind tunnel test is one of the important means to study flutter performance of bridges. However, due to the size limitation of the wind tunnel, the experimental results will inevitably be affected by the wall of the wind tunnel. It is widely considered that the blockage effect can be ignored when the blockage ratio is less than 5% (Hunt 1982, Kubo et al. 1989). But Takeda and Kato (1992) believed that the influence of the blockage effect on the drag coefficient still existed when the blockage ratio was less than 5%. And the influence of the wind tunnel wall on the wind-induced vibration in section model wind tunnel tests was also affected by the width of the model. In addition to the recommended blockage ratio of less than 5%, CMT (2018) also suggests that *B/H* should less than 0.4 in the closed test section. With the progress of society and the development of transportation, the traffic volume is getting larger and larger. Then, the width of the main girder of the bridge is gradually required to increase. More and more girders with large aspect ratio (*B*/*D*) are applied to large span bridges, like the girder of the Lingdingyang Bridge of the Shenzhen–Zhongshan Link (*B*=49.7m, *D*=4m, *B/D*=12.425). For the section model wind tunnel test for these bridges, *B/H* is difficult to meet the recommended value when the blockage ratio just meets the requirement. Whether excessive *B/H* has an impact on the results of wind tunnel tests is still unclear.

The CFD numerical simulation is another important method to study flutter performance of bridges and it is convenient to change the distance of the wall. In order to weaken the influence of the blockage ratio, thin plates with large aspect ratio are selected in this paper. Firstly, the flutter performance of a 0.4m wide thin plate in wind tunnels with six different heights are tested through CFD simulations. Then, the flutter derivatives of the thin plates with three different widths in the 1.54m height wind tunnel are obtained by forced vibration method. Finally, the closed-form solutions are introduced to study how *B/H* affects the flutter critical velocity.

2. NUMERICAL SIMULATION AND MODEL SETUP

The section of the thin plate is shown in Fig. 1. In this paper, the CFD software FLUENT was employed to obtain the motion and the aerodynamic force. The computational domain is shown in Fig. 2. The Y+ value around the thin plate and the tunnel wall are less than 1 and 5 respectively. The SST k-ω turbulence model is applied.

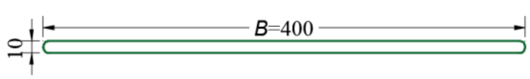

Figure 1. Section of the thin plate (unit: mm).

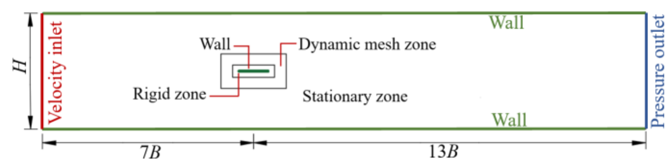

Figure 2. Computational domain.

3. FREE VIBRATION SIMULATIONS

Free vibration was firstly employed through FLUENT and user-defined functions to obtain the motion of the plate. Then the flutter critical velocities of the plates in tunnels with six different heights were determined. A set of parameters in Wu (2020) are selected as the main parameters in this section, as shown in Table 1. Table 2 shows the setting of the simulation cases, and the results are shown in Fig. 3. It can be seen that the flutter critical wind speed decreases with the *B/H* increases. The simulation results here are fit well with the test result in Wu (2020) and the theoretical result. Therefore, it can be considered that the simulation results in this research are reliable.

Table 1. Main parameters of the free vibration simulation.

Properties	Model
Equivalent mass per unit length (m/kg/m)	5.85
Equivalent mass moment of inertia per unit length (I/kg·m^2/m)	0.16
Height (D/m)	0.01
Width (B/m)	0.40
Vertical frequency (f_h/Hz)	2.34
Torsional frequency (f_α/Hz)	3.26
Vertical damping ratio (ξ_{s1}/%)	0.3
Torsional damping ratio (ξ_{s2}/%)	0.3

Table 2. Cases for free vibrations.

case	Upper and lower boundary type	*H(m)*	*B/H*	blockage ratio (%)
1	Symmetry	/	0	/
2	Wall	2.00	0.20	0.50
3	Wall	1.54	0.26	0.65
4	Wall	1.33	0.30	0.75
5	Wall	1.00	0.40	1.00
6	Wall	0.80	0.50	1.25
7	Wall	0.67	0.60	1.50

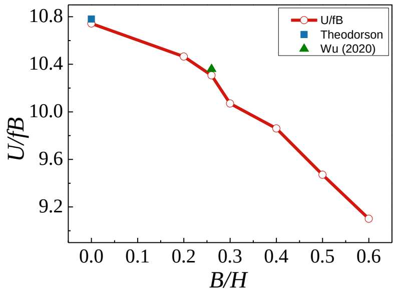

Figure 3. The flutter critical velocity variation with B/H.

Table 3. Cases for forced vibrations

case	Upper and lower boundary type	*B(m)*	*H(m)*	*B/H*	blockage ratio (%)
F1	Symmetry	0.4	/	/	/
F2	Wall	0.4	1.54	0.26	0.65
F3	Symmetry	0.6	/	/	/
F4	Wall	0.6	1.54	0.40	0.65
F5	Symmetry	0.8	/	/	/
F6	Wall	0.8	1.54	0.52	0.65

4. FORCED VIBRATION SIMULATIONS

In order to further study the correlation between the flutter performance of the thin plate and *B/H*, the forced vibration method was employed to obtain the flutter derivatives. Simulation cases are shown in Table 3, and the results are shown in Fig. 4. The blockage ratio of case F2, F4 and F6 are 0.65%.

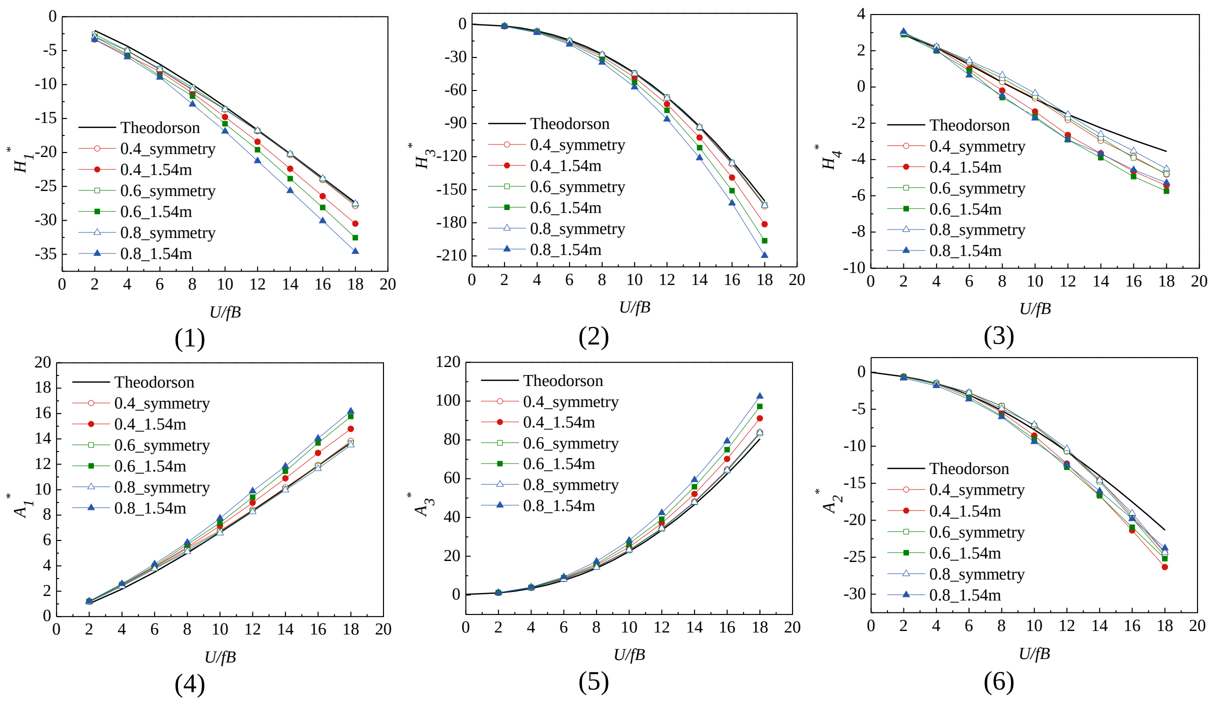

Figure 4. Some flutter derivatives: (1) H_1^*, (2) H_3^*, (3) H_4^*, (4) A_1^*, (5) A_3^*, (6) A_2^*.

It is found that H_1^*, A_1^* which are associated with vertical velocity and H_3^*, A_3^* which are associated with torsional displacement regularly change with the increase of *B/H*, and this change is independent of the blockage ratio. The modal damping ratio in torsion was simplified by Chen (2007) as

$$\xi_2 = \xi_{s2}\ (1 + \ vA_3^*)^{1/2} - 0.5vA_2^* + 0.5\mu v D^2 H_3^* A_1^* / [1 - \frac{\omega_{s1}}{\omega_{s2}} (\frac{1 + vA_3^*}{1 + \mu H_4^*})^{1/2}] \quad (1)$$

where ξ_2 is the modal damping ratio in torsion; ξ_{s2} is the structure damping ratio; $v = \rho b^4/I$; $\mu = \rho b^2/m$; ρ is the air density; b=B/2; I and m are equivalent mass and mass moment of inertia per unit length, respectively; ω_{s1} and ω_{s2} are frequencies of vertical and torsional modes, respectively. It can be seen from Fig. 5 that when *B/H* changes, the change of the modal damping ratio is mainly caused by the change of the coupled damping ratio.

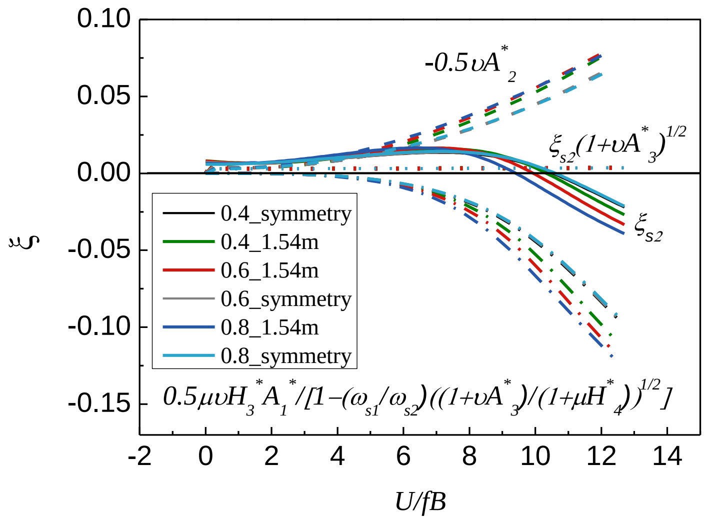

Figure 5. The flutter critical wind speed variation with *B/H*.

5. CONCLUSIONS

(1) The flutter critical velocity decreases with the *B/H* increases. It should be noted that *B/H* should not be too large when wind tunnels tests are conducted.

(2) Keeping the blockage ratio constant, H_1^*, A_1^* which are associated with vertical velocity and H_3^*, A_3^* which are associated with torsional displacement regularly change with the increase of *B/H*.

(3) When *B/H* changes, the change of the modal damping ratio is mainly caused by the change of the coupled damping ratio. This is how *B/H* affects the flutter critical velocity.

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