

Along-wind aerodynamic damping of high-rise buildings

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ABSTRACT: Along-wind aerodynamic damping ratios are identified from wind-induced responses of 46 aeroelastic models in simulated turbulent flow using the random decrement technique (RDT). Their validity is examined through comparison with previous research achievements and the results evaluated by quasi-steady theory. Based on the identified results, characteristics of along-wind aerodynamic damping of isolated high-rise buildings are studied. The effects of density ratio, generalized stiffness, structural damping ratio, aspect ratio, side ratio, roughness exposure, aerodynamically modified cross-sections and tapering on aerodynamic damping ratio of high-rise buildings are investigated. Results indicate that: aerodynamic damping ratio increases monotonically with reduced wind velocity; structural damping ratio, density ratio, side ratio, reduced wind velocity and aspect ratio are very important parameters for along-wind aerodynamic damping ratio, while no clear effect of generalized stiffness on aerodynamic damping ratio is observed. Aerodynamic damping ratio increases as corner-cut ratio or taper ratio increases; low corner-cut ratios significantly decrease aerodynamic damping; however, modifications of building corners and tapering are not always effective at reducing the aerodynamic damping of tall buildings. According to the database, an empirical aerodynamic damping function for high-rise buildings is proposed.

KEYWORDS: high-rise building; wind-induced vibration; aerodynamic damping; aeroelastic model; wind tunnel test; along-wind.

1 INTRODUCTION

Since structural damping ratio of high-rise building is always small and predominant frequency of aerodynamic force under strong wind is close to the natural frequency of structure, wind load would be one of the control loads in design of high-rise building for significant wind-induced response. In addition, coupling effect between incident turbulent flow and structure may generate negative aerodynamic damping, which would decrease total damping, and furthermore cause larger response. Generally, along-wind, across-wind and torsional structure motion all could induce aerodynamic damping. And aerodynamic damping in along-wind attracts researchers' attention most early.

Aerodynamic damping in along-wind can generally be estimated with satisfactory accuracy by adopting the quasi-steady theory. Based on it, Davenport (1979) [1] found $\zeta_a=0.0175$ with $V/(f_0B)=10$, $M/\rho_a B^2=182$ and $C_D\sim 2$. Holmes (1996, 2001) [2,3] estimated the aerodynamic damping in along-wind based on the assumption that the aerodynamic drag force is proportional to the square of the difference between the mean oncoming wind speed and the speed of the moving structure. Gabbai and Simiu (2010) [4] presented a methodology for estimating aerodynamic damping in which the relative wind speed with respect to the moving structure is modeled, more accurately, as the difference between the total oncoming wind speed and the speed of the moving structure. In addition, the structural motion is assumed to be proportional to the relative oncoming wind speed raised to powers larger than two. In theory, this methodology is more accurate than quasi-steady method and the method proposed by Holmes, but more complex.

There are also many researchers study along-wind aerodynamic damping of high-rise buildings through wind tunnel test. Marukawa (1996) [5] evaluated the aerodynamic damping of rectangular tall buildings from wind tunnel tests of aeroelastic model. Random decrement technique is used to analyze effects of side ratio, aspect ratio and structural damping ratio on along-wind aerodynamic damping. Cooper (1997) [6] studied the impact of motion amplitude on along-wind aerodynamic damping by forced vibration test. Besides, the aerodynamic damping obtained from aeroelastic response measurements was compared with those predicted by quasi-steady theory. The results indicated that aerodynamic damping ratios in this test are independent of motion amplitude. Quan (2002, 2004, 2005) [7,8,9] and Gu (2004) [10] proposed a formula for aerodynamic damping as a function of reduced velocity, roughness exposure and structural damping using RDT method. Zou (2003) [11] investigated the aerodynamic damping of an isolated rectangular high-rise building with side ratio of 2:1 at three reduced wind velocities. But up to now, existing researches only focus on one or a few influence factors and are far from systemization. Moreover, the research achievements are lack of comparison with each other and the theoretical results.

Generally, the use of aerodynamically modified cross-sections, such as slotted corners, chamfered corners and tapering, is an effective means to reduce the wind-induced response. However, modifications of building corners might not be entirely effective, as adverse effects may also occur (Kareem et al., 1999; Kim and Kawai, 1999) [12,13]. Kim and You (2002) [14] investigated the taper-ratio effect for reducing wind-induced excitations in along- and across-wind directions based on the force-balance test using rigid models with taper ratios of 5%, 10%, and 15%, and one basic model of a square cross-section without taper. They discovered that the tapering is more effective in reducing wind-induced excitations in the suburban flow environment than in the urban flow environment. They also showed that tapering reduces the across-wind responses more than the along-wind responses. And, compared with a basic model without a taper, the tapering is not always effective at reducing the wind-induced excitations of tall buildings. However, the literatures mentioned above could not systematically indicate the variation of wind-induced response of high buildings and aerodynamic damping. Huang (2003) [15] studied effects of modified cross-sections (corner-cut ratio of 10%) on along- and across-wind aerodynamic damping. Results showed that aerodynamic damping of high buildings with slotted corner and chamfered corner are much less than that of square high buildings, and in the view of engineering application, the aerodynamic damping in along- and across-wind all could be neglected for buildings with corner-cut ratio of 10%. However, up to the present, relevant researches all focus on rectangular building (Davenport, 1979; Marukawa, 1996; Quan, 2002, 2004, 2005; Gu, 2004; Zou, 2003 etc.). And whether theoretically or experimentally, quite limit studies are about the influence of corner-cut and tapering on aerodynamic damping. Therefore, further researches are needed to consider about these factors.

Along-wind aerodynamic damping ratios are identified from wind-induced response of 46 aeroelastic models in simulated turbulent flow. The effects of density ratio, generalized stiffness, structural damping ratio, aspect ratio, side ratio, roughness exposure and aerodynamically modified cross-sections and tapering on aerodynamic damping ratio of high-rise buildings are investigated. According to the database, an empirical aerodynamic damping function for high-rise buildings is proposed.

2 OUTLINE OF THE WIND TUNNEL TESTS

2.1 *Simulation of wind characteristics*

The test is carried out in TJ-1 Boundary Layer Wind Tunnel in Tongji University, whose working section is 1.8m in width, 1.8m in height and 18m in length, and the wind speed ranges from 3

to 32 m/s. Four kinds of wind conditions, corresponding to exposure category A, B, C and D in the Chinese code [16] are simulated in the wind tunnel at a length scale of 1/800. The exponents of the mean wind profiles for the exposure category A, B, C and D are 0.12, 0.16, 0.22 and 0.30, and the corresponding gradient heights are 300, 350, 400, 450m, respectively. The wind characteristics are achieved by a combination of turbulence generating spires, a barrier at the entrance of the wind tunnel, and roughness elements along the wind tunnel floor upstream of the model. The longitudinal turbulence intensities at the height of building (480m) are separately 9.23%, 9.36%, 9.52% and 9.78%, while the values at the height of roughness length are 18.52%, 22.11%, 27.07% and 27.50%. As profile of turbulence integral scale is difficult to be accurately simulated, the values at the 2/3 height of building for the exposure category A, B, C and D are respectively 229m, 231m, 285m, 274m. Figure 1 shows the simulated mean wind speed profiles and longitudinal component profiles of turbulence intensity, as wind speed profiles provided by Chinese code and turbulence intensity profile given by AIJ (2004) [17].

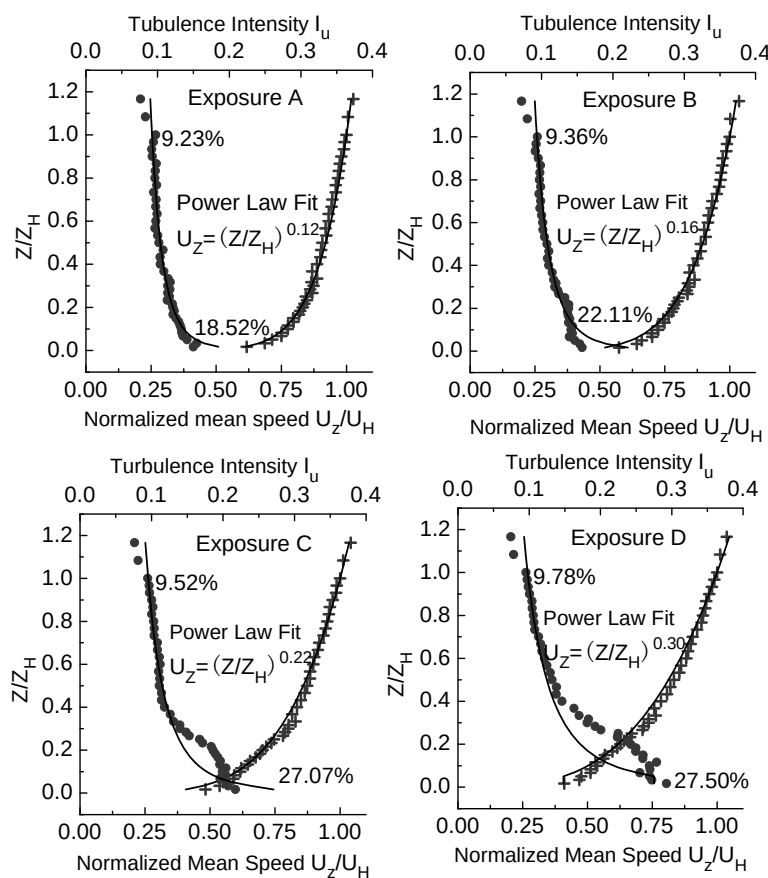


Figure 1 Profiles of wind velocity and longitudinal turbulence intensity

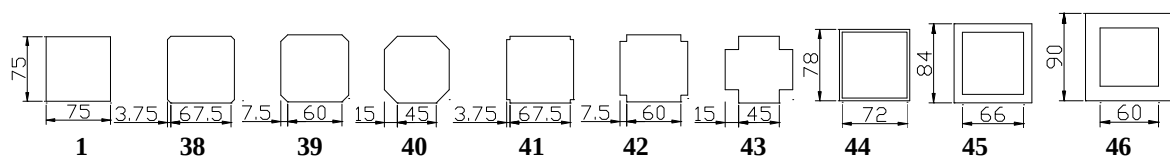


Figure 2 Model cross-sections (mm)

2.2 Building models

Length and velocity scale are separately 1/800 and 1/8. Dimensions of standard model are $0.075m \times 0.075m \times 0.6m$, with frequency of 13Hz, density of $213Kg/m^3$ and generalized mass of 0.24Kg. Corresponding to real structure, these parameters represent building with size of $60m \times 60m \times 480m$, natural frequency of 13 Hz, and density of $213Kg/m^3$. Generalized stiffness is selected to be $1600 Kg/s^2$ according to natural frequency. In addition, structural damping ratio of standard model is taken as 1%, while density of air is $1.227Kg/m^3$.

Wind-induced responses of 46 high-rise buildings are measured from aeroelastic model wind tunnel test. The structure characteristic parameters are shown as Table 1. As to the other cases, the heights of models keep the same, and cross sections are changed according to aspect ratios and side ratios. The maximum block ratio of model to test section of wind tunnel is 2.22%. Case 38 to 46, cross sections are changed in accordance with corner-cut and taper ratios, considering one type of aerodynamically modification each case, as shown in Figure 2. The base is used to model the elastic parameters of buildings, as structural damping ratios are simulated by width of damping plates and their depth dipped into oil, while springs are used to achieve stiffness. In order to avoid energy transmission in the two orthogonal directions, one degree of freedom in horizontal direction is fixed. All of the models are built with base plates, hollow aluminum alloy as the cores, foamed plastics, light wood plates of 1mm thickness as their “clothes” and balancing weight. Two piezoelectric accelerometers with sampling frequency of 1000Hz are placed at the two ends inside windward surface, as sampling time set as 7 minutes.

Table 1 Wind tunnel test cases for high-rise buildings

Case	Model Height $H(mm)$	Roughness Exposure	Side Ratio B/D	Aspect Ratio $H/(BD)^{0.5}$	Structural Damping $\zeta_s (\%)$	Structure Density $\rho_s (Kg/m^3)$	Generalized Stiffness $K (Kg/s^2)$	Corner-cut or Taper Ratio
1-4	600	A,B,C,D	1	8	1	213	1600	0
5-12	600	B,D	1/3,3, 1/2,2	8	1	213	1600	0
13-18	600	B,D	1	5,10,12	1	213	1600	0
19-25	600	B,D	1	8	0.5,0.9,1.1,1.7 5,2.3,2.3,2.8	213	1600	0
26-31	600	B,D	1	8	1	360,255,160	1600	0
32-37	600	B,D	1	8	1	213	947,2130,3027	0
38-40	600	C	1	8	1	213	1592,1568,1472	5%-20%
41-43	600	C	1	8	1	213	1584,1536,1344	5%-20%
44-46	600	C	1	8	1	213	1600	1%-5%

3 TEST RESULTS

The generalized formula with four variables proposed by Tamura et al (1996) [18] is used to estimate damping from random acceleration responses.

$$a(\tau) = Ae^{-\zeta\omega\tau} \left(\cos \sqrt{1-\zeta^2} \omega_0 \tau + B \sin \sqrt{1-\zeta^2} \omega_0 \tau \right) \quad (1)$$

Firstly, amplitude dependent structural damping ratio is derived from free acceleration response. Then, RMS of wind-induced acceleration response after band-pass filtering is taken as the initial amplitude of RDT to calculate total damping ratio. Afterwards, structural damping ratio corresponding to this amplitude is derived through interpolation. The aerodynamic damping ratio ζ_a is

calculated by subtracting the value of structural damping ratio ζ_s from the value of total damping ratio ζ , i.e. $\zeta_a = \zeta - \zeta_s$. Following research mainly focuses on the study of aerodynamic damping variation with density ratio, generalized stiffness, structural damping, aspect ratio, side ratio, roughness exposure, aerodynamically modified cross-sections and tapering.

3.1 Verification of result

Marukawa (1996) studied the effects of side ratio in the range of 0.33-3, aspect ratio from 4 to 6, and structural damping ratio of 0.5% to 2% on along-wind aerodynamic damping, and compared the results with that evaluated by quasi-steady theory. Here, the drag coefficient was derived from the mean displacement assuming that the wind force is distributed in proportion to the velocity pressure. Quan (2002, 2004) discussed impacts of exposure category (A、B、C、D) and structural damping on along-wind aerodynamic damping, and made comparison with Marukawa (1996). The validity of research results in this paper is examined through comparison with previous research achievements and the results evaluated by quasi-steady theory as shown in Figure 3, corresponding structure characters shown in Table 2.

As shown in Table 2 and Figure 3, there are certain differences between research results with different roughness exposures and model parameters. But in general, the results show a good agreement with previous research achievements and that derived by quasi-steady theory, especially with the result evaluated by quasi-steady theory.

Table 2 Structure parameters for tests

	Aspect Ratio $H/(BD)^{0.5}$	Side Ratio B/D	Roughness Exposure (α , I_h)	Model Height H (mm)	Length Scale	Structural Damping ζ_s	Structure Density ρ_s (Kg/m^3)
Standard Model	8	1	A、B、C、D	600	1/800	0.88%	213
Marukawa (1996)	6	1	$\alpha=0.167$, $I_h=10.7\%$	480	1/500	1%	200
Quan (2002)	6	1	A	600	1/500	0.6%	180
$\zeta_a = \frac{1}{4\pi} \frac{\rho_a B^2}{M} \frac{V_H}{f_0 B} C_D$, as reduced velocity defined as $V_H/f_0(BD)^{0.5}$, derives							
Quasi-steady Theory	$\zeta_a = \frac{1}{4\pi} \frac{\rho_a B}{\rho_s D} \frac{V_H}{f_0 \sqrt{BD}} C_D$ (According to Marukawa (1996), for $B/D=1$, $C_D=1.05$; as to the Chinese code, for $B/D=1$, $C_D=1.3$)						

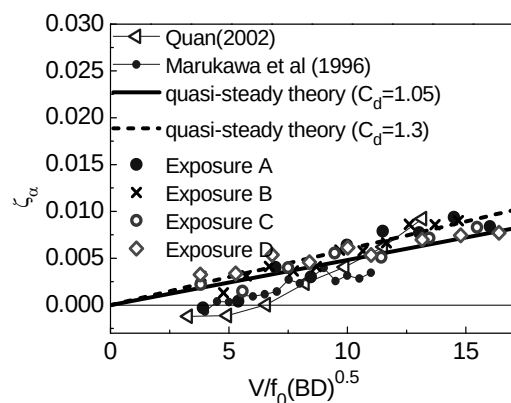


Figure 3 Comparison with research achievements and theoretical result

3.2 Characteristics of aerodynamic damping

3.2.1 Effect of roughness exposure

Figure 3 indicates the variation of aerodynamic damping ratio with reduced velocity $V_H/f_0(BD)^{0.5}$ in simulated turbulence wind environments A、B、C、D. The aerodynamic damping ratio in the along-wind in Figure 3 represents positive damping at reduced velocities of 4 or more, and it increases monotonically with reduced wind velocity. At low reduced wind velocities, aerodynamic damping ratios in exposure D are bigger than that in exposure category A. Furthermore, at reduced wind velocities of more than 10, aerodynamic damping ratios are apparently bigger than other cases. That is, aerodynamic damping ratio gradually increases slower with reduced velocity for exposure category A、B、C、D. But overall, wind environment has no clear effect on along-wind aerodynamic damping, as discrepancies are within 0.003. It may be caused by the similar profiles of wind velocity (Chinese code) and turbulence intensity (AIJ2004) for this height of building. So, the influence of roughness exposure still needs further research.

3.2.2 Effect of side ratio B/D

Figure 4 shows the variation of aerodynamic damping ratio with reduced velocity, as aspect ratio $H/(BD)^{0.5}=8$, structural damping ratio $\zeta_s=1\%$, side ratio B/D ranges from 0.33 to 3. The corresponding values obtained by quasi-steady theory are also provided in this Figure. Here, the drag coefficients adopt the values given in Marukawa (1996). Figure 4 indicates that side ratio is an important parameter for aerodynamic damping, as aerodynamic damping increases with side ratio, exclude the case with $B/D=0.33$. In most cases, aerodynamic damping increases monotonically with reduced wind velocity, except that it starts to decrease at reduced velocity of 8-10 for the case with $B/D=0.33$. For side ratios $B/D \geq 1$, aerodynamic damping increases with side ratio; for side ratios $B/D \leq 1$, there is no clear variation in aerodynamic damping ratio with side ratio. As to side ratios $B/D > 1$, aerodynamic damping ratios derived from experiment are bigger than that evaluated by quasi-steady theory in exposure category B; and opposite phenomena can be observed in exposure category D. As to side ratios $B/D=1, 0.5$, aerodynamic damping ratios derived from experiment are a little bigger than that evaluated by quasi-steady theory, as discrepancies are within 0.002 in exposure category B and much less in exposure category D. Generally, there's no big difference between each other, so along-wind aerodynamic damping can be well predicted by quasi-steady theory for these cases. But as to the case of $B/D=0.33$, experimental values are much bigger than theoretical values. All in all, there is a much better agreement between aerodynamic damping evaluated from wind tunnel test and the theoretical value than that obtained by Marukawa (1996). This is because, reduced velocity adopted by Marukawa (1996) is $V_H/f_0(BD)^{0.5}$, while the one used for quasi-steady theory is $V_H/f_0 B$.

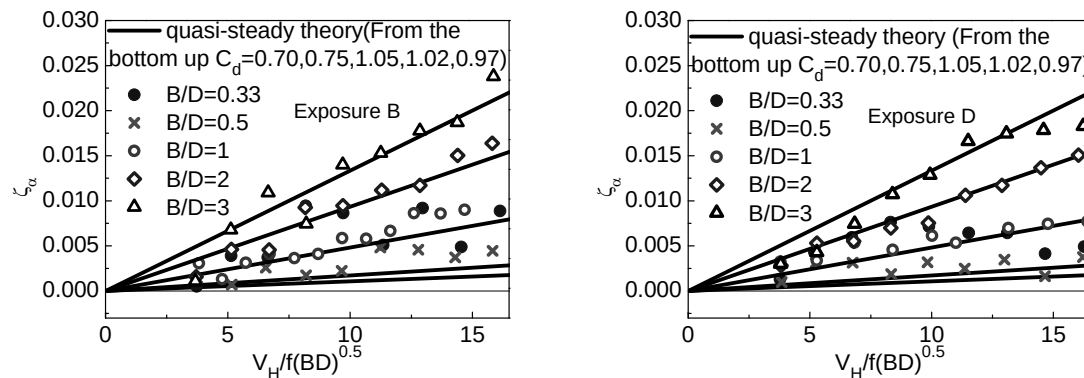


Figure 4 Effect of side ratio B/D ($H/(BD)^{0.5}=8$, $\zeta_s=1\%$)

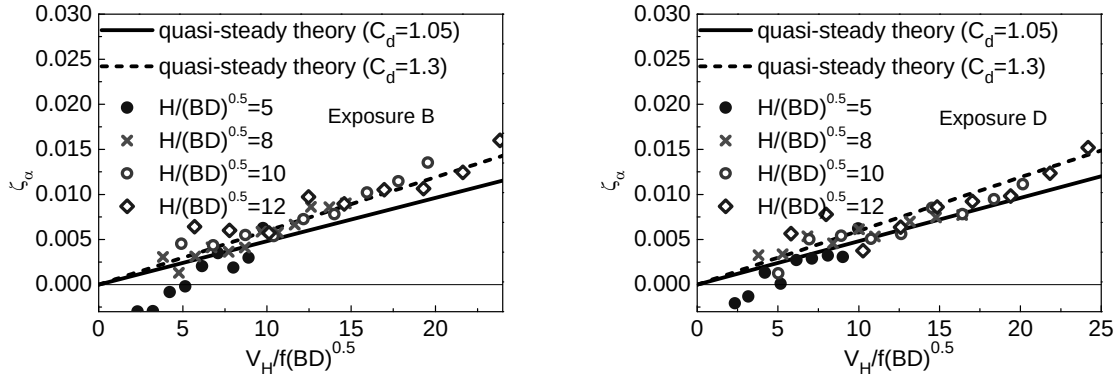


Figure 5 Effect of aspect ratio $H/(BD)^{0.5}$ ($B/D=1$, $\zeta_s=1\%$)

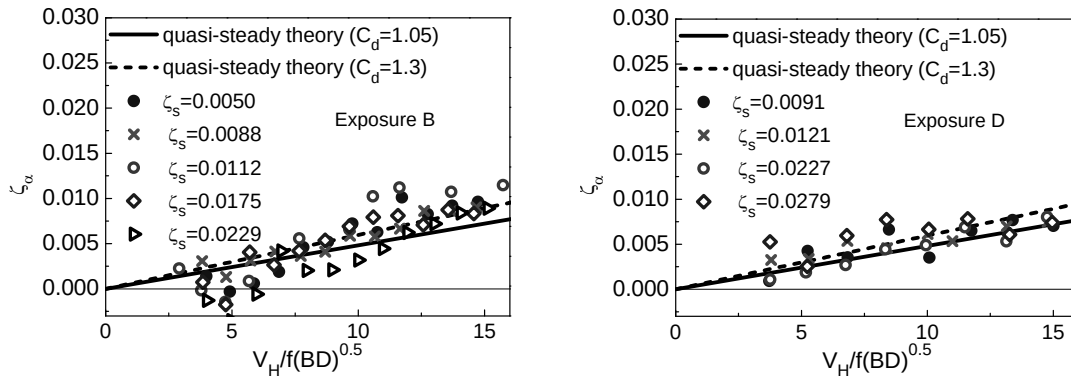


Figure 6 Effect of structural damping ζ_s ($B/D=1$, $H/(BD)^{0.5}=8$)

3.2.3 Effect of aspect ratio $H/(BD)^{0.5}$

Figure 5 shows the variation of aerodynamic damping ratio with reduced velocity, as side ratio $B/D=1$, structural damping ratio $\zeta_s=1\%$, aspect ratio $H/(BD)^{0.5}$ ranges from 5 to 12. Figure 5 indicates that aerodynamic damping ratio gradually increases slower with wind velocity as aspect ratio increases. At reduced wind velocity lower than 10, aerodynamic damping ratio increases as aspect ratio increases; while opposite trend is observed at reduced wind velocity higher than 10. Above all, the effect of aspect ratio is not so obvious, with difference not more than 0.003, and they can be relatively accurate evaluated by quasi-steady theory.

3.2.4 Effect of structural damping ζ_s

Figure 6 shows the variation of aerodynamic damping ratio with reduced velocity, as side ratio $B/D=1$, aspect ratio $H/(BD)^{0.5}=8$, structural damping ratios ζ_s ranges from 0.005 to 0.0279. At the same reduced velocity, difference of aerodynamic damping is about 0.005, which states unlectable effect of structural damping on aerodynamic damping. At low reduced wind velocity, aerodynamic damping generally decreases with structural damping; while the smaller the structural damping, the bigger the aerodynamic damping at high reduced wind velocity. The smallest aerodynamic damping ratio is observed when the structural damping ratio is 0.023. In addition, variations of aerodynamic damping for $\zeta_s=0.0091$, 0.0121, 0.0227 in exposure category D are similar with cases of $\zeta_s=0.0088$, 0.0112, 0.0229 in exposure category B.

3.2.5 Effect of density ratio ρ_s/ρ_a

Figure 7 shows the variation of aerodynamic damping ratio with reduced velocity when density ratio varies from 294 to 131. Density ratio has a clear effect on aerodynamic damping, with difference between 0.003 and 0.005 at the same reduced wind velocity. Aerodynamic damping ratio increases monotonically with density ratio. Moreover, the value derived in exposure category D is a little smaller than that in exposure category B.

3.2.6 Effect of generalized stiffness K

Figure 8 shows the variation of aerodynamic damping ratio with reduced velocity when generalized stiffness varies from 947 to 3027. As shown in Figure 8, no clear effect of generalized stiffness on aerodynamic damping is observed in the along-wind direction, with difference not more than 0.002. Likewise, aerodynamic damping ratio in exposure category D gradually increases slower with reduced velocity than in exposure category B. The values estimated in exposure category D are much closer to the values derived by quasi-steady theory, while much more discrepancies are observed in exposure category B.

3.2.7 Effect of slot rate

Figure 9 shows the variation of aerodynamic damping ratio with reduced velocity, as aspect ratios $H/(BD)^{0.5}=8$, structural damping ratio $\zeta_s=1\%$, side ratio $B/D=1$, slot rate ranges from 0% to 20%. The corresponding values obtained by quasi-steady theory are also provided in this Figure. Here, the drag coefficients adopt the value given in Marukawa (1996). Figure 9 indicates 5% and 10% slot rates significantly decrease aerodynamic damping, and this trend is more obvious at

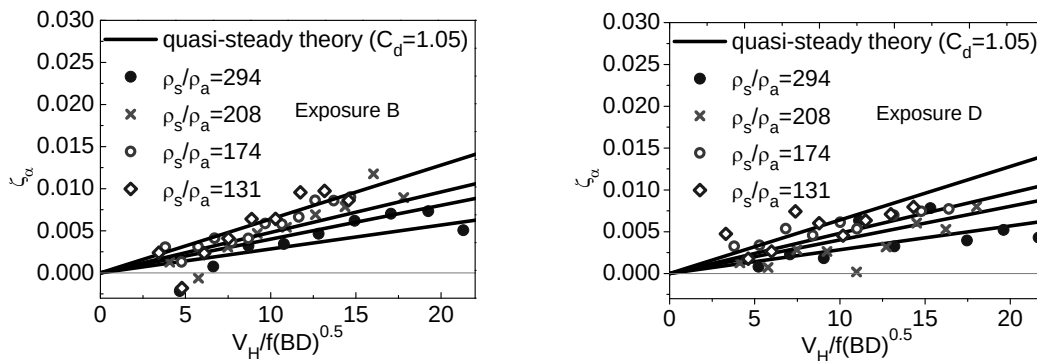


Figure 7 Effect of density ratio ρ_s/ρ_a

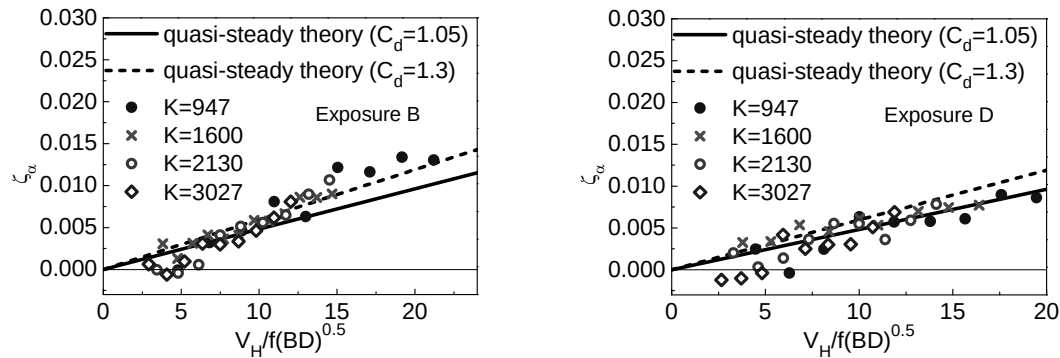


Figure 8 Effect of generalized stiffness K

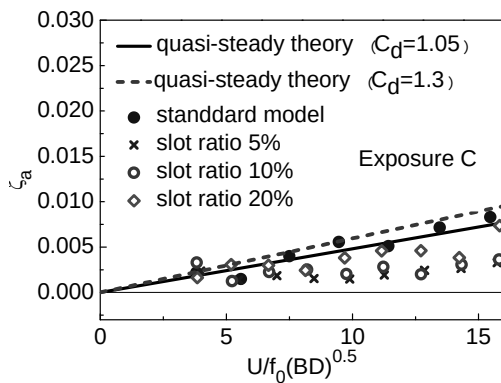


Figure 9 Effect of slot rate

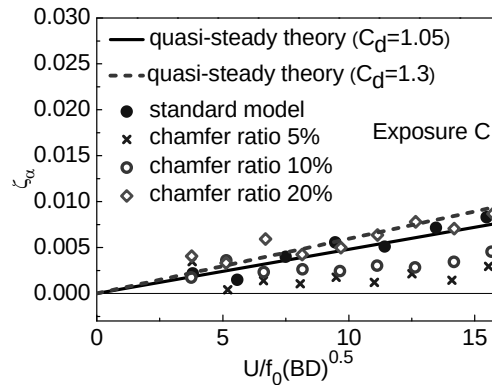


Figure 10 Effect of chamfer rate

higher reduced wind velocity. For slot rate of 20%, although it decreases in certain extend, but difference is not significant, i.e. larger slot does not lead to more decrease. Also in this case, decrease effect of aerodynamic damping strengthens as reduced wind velocity increases. In general, slot rates in certain range significantly decrease aerodynamic damping, especially for the case with slot rate of 5%.

3.2.8 Effect of chamfer rate

Figure 10 shows the variation of aerodynamic damping ratio with reduced velocity, as aspect ratios $H/(BD)^{0.5}=8$, structural damping ratio $\zeta_s=1\%$, side ratio $B/D=1$, chamfer rate ranges from 0% to 20%. The corresponding values obtained by quasi-steady theory are also provided in this Figure. As shown in Figure 10, 5% and 10% chamfer rates significantly decrease aerodynamic damping, and this trend is more obvious at higher reduced wind velocity. For chamfer rate of 20%, although it decreases in certain extend, but difference is not significant, which means larger chamfer is not always effective at reducing the aerodynamic damping of tall buildings. When chamfer rate varies from 5% to 20%, aerodynamic damping ratio increases as chamfer rate increases. As compared with cases with slotted corner, aerodynamic damping ratios of building with 5% chamfer rate are smaller than that with 5% slot rate, the opposite phenomena can be observed for chamfer rate 10% and 20%. Overall, the effects of slotted corner and chamfered corner on aerodynamic damping ratio are similar; for low corner-cut ratios, aerodynamic damping ratios are bigger with slotted corner, while for high corner-cut ratios, they are bigger with chamfered corner.

3.2.9 Effect of tapering

Figure 11 shows the variation of aerodynamic damping ratio with reduced velocity, as aspect ratios $H/(BD)^{0.5}=8$, structural damping ratio $\zeta_s=1\%$, side ratio $B/D=1$, taper rate ranges from 0% to 20%. The corresponding values obtained by quasi-steady theory are also provided in this Figure. As shown in Figure 11, taper rate of 1% reduces aerodynamic damping, but taper rate of 3% and 5% increase aerodynamic damping. When taper rate varies from 1% to 5%, aerodynamic damping ratio increases as taper rate increases. Therefore, tapering is not always effective at reducing the aerodynamic damping of tall buildings, as lower rates of tapering reduce aerodynamic damping and it will increase when taper rate exceeds 3%.

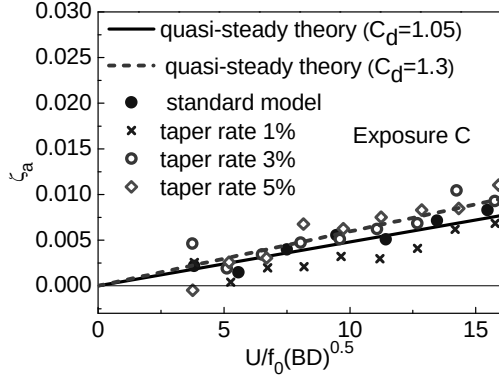


Figure 11 Effect of tapering

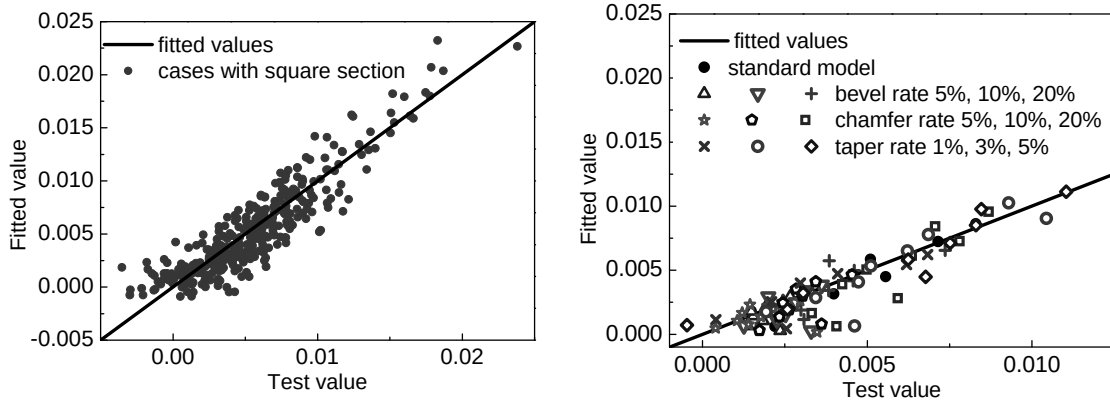


Figure 12 Comparison between fitted values and tested values for aerodynamic damping

3.3 Formula fitting of aerodynamic damping ratio

As described above, the aerodynamic damping ratios of high-rise building increase monotonically with reduced wind velocity. In most cases, they can be relatively accurately evaluated by quasi-steady theory. Research shows that structural damping ζ_s , density ratio ρ_s/ρ_a , side ratio B/D , reduced velocity $V_H/f_0(BD)^{0.5}$, aspect ratio $H/(BD)^{0.5}$, aerodynamically modified cross-sections and tapering are important effects for aerodynamic damping ratio in along-wind, while the influence of generalized stiffness and roughness exposure are not so significant. As quasi-steady theory only takes density ratio, side ratio, reduced velocity and drag coefficient into consideration, an empirical aerodynamic damping function for high-rise buildings, written as formula (2), is proposed according to the database after many times comparison. The conformity between aerodynamic damping ratios derived from wind tunnel test and by fitting is shown in Figure 12. Standard error for this for this empirical formula is

$$\delta_{\zeta_a} = \sqrt{\frac{1}{N} \sum_{i=1}^N (\zeta_{a-calc}(i) - \zeta_{a-test}(i))^2} = 0.0018$$

Where, N is the number of case (415 for here); ζ_{a-calc} and ζ_{a-test} are separately the fitted values and tested values for aerodynamic damping.

$$\zeta_a = \lambda \left(\frac{1}{4\pi} \frac{\rho_a}{\rho_s} \frac{B}{D} \frac{\bar{U}}{f_0 \sqrt{BD}} \right) \zeta_s^{0.15} \left(\frac{H}{B} \right)^{0.5} C_D - 0.002 \quad (2)$$

Here, drag coefficient C_D adopts 1.05; λ is modification coefficient of cross section, as $\lambda=1.0$ for square building, with λ for other cases and corresponding standard error shown in Table 3.

Table 3 Fitting parameter of aerodynamic damping for corner-cut and tapering high-rise buildings

	Slot rate 5%	Slot rate 10%	Slot rate 20%	Chamfer rate 5%	Chamfer rate 10%	Chamfer rate 20%	Taper rate 1%	Taper rate 3%	Taper rate 5%
λ	0.38	0.44	0.75	0.30	0.53	1.10	0.71	1.17	1.26
$\delta_{\zeta ai}$	0.8×10^{-3}	1.2×10^{-3}	1.1×10^{-3}	1.2×10^{-3}	1.2×10^{-3}	1.7×10^{-3}	0.9×10^{-3}	1.5×10^{-3}	1.0×10^{-3}

4 CONCLUSION

46 aeroelastic model tests are conducted to study the effects of important factors on along-wind aerodynamic damping ratios using RDT method with four parameters. The influences of density ratio, generalized stiffness, structural damping ratio, aspect ratio, side ratio, roughness exposure, aerodynamically modified cross-sections and tapering on aerodynamic damping are investigated. All parameters of high-rise building, which could affect aerodynamic damping, are systematically taken into consideration. The following conclusion can be drawn:

- 1 Aerodynamic damping ratio gradually increases slower with reduced velocity in exposure category A, B, C, D. But overall, wind environment has no clear effect on along-wind aerodynamic damping, which may be caused by the similar profiles of wind velocity (Chinese code) and turbulence intensity (AIJ2004) for this height of building. So, the influence of roughness exposure still needs further research.
- 2 For side ratios $B/D \geq 1$, aerodynamic damping ratio increases with side ratio; for side ratios $B/D \leq 1$, there is no clear variation in aerodynamic damping ratio with side ratio. In addition, along-wind aerodynamic damping can be well predicted by quasi-steady theory.
- 3 Structural damping ratio and aspect ratio has great influence on aerodynamic damping. Aerodynamic damping ratio gradually increases slower with wind velocity as aspect ratio increases. At reduced wind velocity lower than 10, aerodynamic damping ratio increases as aspect ratio increases; while at reduced wind velocity higher than 10, opposite trend is observed.
- 4 Although density ratio and generalized stiffness all reflect in change of structural damping, the impact of density ratio is relatively significant while no clear effect of generalized stiffness can be observed.
- 5 The effects of slotted corner and chamfered corner on aerodynamic damping ratio are similar; aerodynamic damping ratio increases with corner-cut ratio, as corner-cut ratio of 5% and 10% significantly decrease aerodynamic damping, while there's little difference between square building and cases with corner-cut ratio of 20%.
- 6 Aerodynamic damping ratio increases as taper rate increases; taper rate of 1% reduces aerodynamic damping, but taper rate of 3% and 5% increase aerodynamic damping.
- 7 Modifications of building corners and tapering are not always effective at reducing the aerodynamic damping of tall buildings.

Structural damping ζ_s , density ratio ρ_s/ρ_a , side ratio B/D , reduced velocity $V_H/f_0(BD)^{0.5}$, aspect ratio $H/(BD)^{0.5}$, aerodynamically modified cross-sections and tapering are important effects for aerodynamic damping ratio in along-wind, while the influence of generalized stiffness is not

so significant. Through fitting of estimated aerodynamic damping ratios, an empirical aerodynamic damping function for high-rise buildings is proposed with taking effects of structural damping, aspect ratio and modification of cross section into quasi-steady theory.

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