Calculation of Across-wind Equivalent Static Wind Load on Typical Rectangular Tall Buildings

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Abstract. Due to the complexity of crosswind loads, only a few national codes/standards in the world provide calculation formulas. The high frequency force balance (HFFB) technique was used to get the across-wind base moment coefficients and power spectra by assessing the rigid models of 71 typical rectangular tall buildings under 4 different categories of terrain roughness. The effects of terrain roughness, side ratio and aspect ratio on the non-dimensional across-wind base moment spectra and RMS values of across-wind base moment coefficient are analyzed. The main parameters of non-dimensional across-wind base moment power spectra and RMS value of across-wind base moment coefficient are derived by using the nonlinear least squares method, and the error analysis of the fitted formula are studied. The accuracy and applicability of the formula are verified by comparison with wind tunnel test results and literature data. Using other parameters in the wind load codes/standards, the across-wind equivalent static wind load of typical rectangular tall buildings can be calculated by the empirical formula.

Keywords: HFFB; wind tunnel test; RMS of across-wind base moment coefficient; non-dimensional across-wind base moment spectra.

1 Introduction

The rapid expansion of urban space and population size has led to the "upward" development of the construction industry, with a large number of high-rise buildings over 100 meters built around the world. Earlier studies have shown that as building height increases, across-wind loads gradually exceed along-wind loads [1][2]. When the building exceeds 200m, the across-wind load gradually exceeds the seismic load, becoming the controlling horizontal load for structural design [3][4]. How to quickly and accurately estimate across-wind loads during the scheme design or preliminary design phase is an urgent problem to be solved in structural design [5][6][7]. For over 30 years, researchers have been focusing on this complex issue and have provided different methods for calculating equivalent static wind loads in the crosswind direction [8][9]. Some national standards have provided formulas for calculating equivalent static wind loads of typical

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high-rise buildings with rectangular cross-section. However, there is currently no widely accepted database for across-wind loads and calculation methods for equivalent static wind loads [10][11]. It was found that there are significant differences in the estimated across-wind loads of different standards, and the estimated results of the standards are overestimated compared to the wind tunnel test results of actual projects. The probable causes may be the scope of the formula can't satisfy the engineering application, as the scope of the AIJ 2004 standard is tall buildings below 200 meters and the scope of GB-2012 is tall buildings above 150 meters with a side length ratio of 0.5 to 2. In order to estimate the across-wind design wind load of rectangular cross-section high-rise buildings more accurately, it is necessary to conduct wind tunnel tests with more models, more terrain roughness categories and larger application scope.

71 typical cross-sectional high-rise building (actual height from 180m to 500m) models with different aspect ratios (4 to 7.5), side ratios (0.2 to 5) and 4 different terrain roughness (from open to city center) have been tested in the TJ-1 boundary layer wind tunnel of Tongji University to obtain the across-wind aerodynamic loads of these buildings. A new formula for the across-wind force spectrum and base moment coefficient has been provided. By comparing with wind tunnel test results and literature data, the reliability and accuracy of the crosswind aerodynamic force obtained in this experiment were further verified. Combined with other parameters in the standards, it can be further used for estimating equivalent static wind loads of across-wind.

2 Wind Tunnel Test

The experiment was conducted in TJ-1 Boundary Layer wind Tunnel with a test section of 1.8m wide and 1.8m high, and the wind speed ranges from 3 to 32m/s. According to the Chinese code GB 50009-2012, four kinds of wind fields were simulated in wind tunnels with length scales of 1/300 and 1/600, corresponding to terrain categories A, B, C and D, including all the real terrain roughness. Category A refers to the offshore sea surface and sea island, coast, lakeshore and desert areas; Category B refers to open country, village, underwood, hill, villages and towns with sparse houses; Category C refers to city proper with dense building complex; Category D refers to city proper with dense building complex and taller buildings. The exponents of the mean wind profiles for the terrain categories A, B, C and D are 0.12, 0.16, 0.22 and 0.30, and the corresponding gradient heights are 300, 350, 450 and 550m, respectively. The wind characteristics are achieved through 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. Fig. 1 shows the simulated mean wind speed profiles and the turbulence intensities for the terrain categories A, B, C and D. The cross-section shapes of the building models for the test are shown in table 1. The heights of most physical models are between 600mm and 833mm, the aspect ratio is between 4 and 7.5 and the side ratio is between 0.2-5.

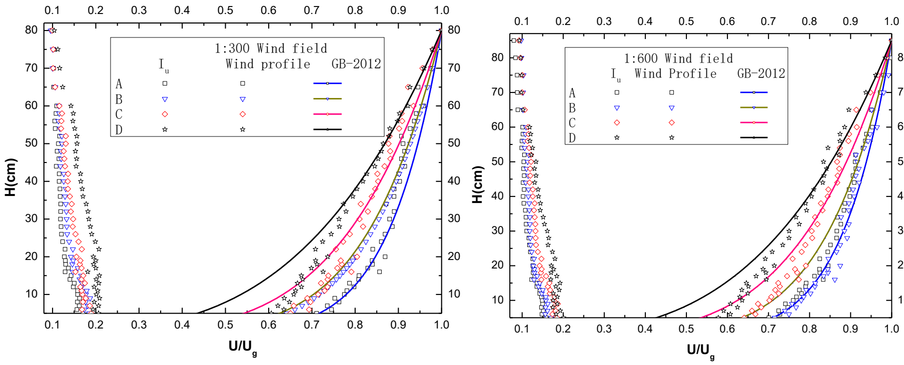

Fig. 1. Simulated wind parameters of the terrain categories

To make the frequencies of the model-balance systems high enough for testing, the weight of physical models should be exceptionally light, so all models are built with aluminum core as the cores and light foamed plastics as their ‘‘clothes’’. A six-component force balance is used for the test. The lowest frequency among these model-balance systems is about 60 Hz, which is more than 2.5 times the actual frequency of tall buildings. The testing wind speeds are selected to be 6 and 8m/s.

Table 1. Models for the test

Aspect ratio	Terrain categories	Model scale	Model height(mm)	Side ratio (D/B)
$H/\sqrt{BD}=4$	A,B,C,D	1:300	600	0.2, 0.25, 0.33, 0.5, 1, 2, 3, 4, 5,
$H/\sqrt{BD}=5$	A,B,C,D	1:300	600	1/4.7, 0.25, 0.33, 0.4, 0.5, 1/1.75, 0.67, 0.75, 0.8, 1, 1.25, 1.33, 1.5, 1.75, 2, 2.5, 3, 4, 4.7
$H/\sqrt{BD}=5.7$	A,B,C,D	1:300	800	0.2, 0.25, 0.33, 1/2.4, 0.5, 1/1.75, 0.67, 0.75, 0.8, 1, 1.25, 1.33, 1.5, 1.75, 2, 2.4, 3, 4, 5
$H/\sqrt{BD}=6.5$	A,B,C,D	1:600	650	0.5, 1/1.75, 0.67, 0.75, 0.8, 1, 1.25, 1.33, 1.5, 1.75, 2
$H/\sqrt{BD}=7.5$	A,B,C,D	1:600	833	0.5, 0.67, 0.75, 0.8, 1, 1.25, 1.33, 1.5, 2
$H/\sqrt{BD}=4.9$	B,C,D	1:250	720	1/1.5, 1.5/1
$H/\sqrt{BD}=4.9$	A,B,C,D	1:300	600	1/1.5, 1.5/1
$H/\sqrt{BD}=5.77$	A,B,C,D	1:300	800	1/3, 3/1
$H/\sqrt{BD}=11.4$	B,C,D	1:300	570	1/1
$H/\sqrt{BD}=14.24$	B,D	1:300	712	1/1

3 Empirical Formula of Across-wind Aerodynamic Forces

3.1 Coefficients of Across-wind Base Moment

The RMS coefficient of the base moment and the base shear force are defined, respectively, as:

$$\tilde{C}_{ML} = \sigma_{M_L}/\bar{M}' \tag{1}$$

In which, σ_{M_L} is the RMS values of the base moment coefficients in the across-wind; $\bar{M}' = 0.5\rho U_H^2 BH^2$ is the reference moment; B is building width normal to the oncoming wind, D is the depth of the building, and H is the height of the building; ρ is the air density, U_H is the mean wind speed at building height H.

Based on literatues analysis (see table 2) and parameters analysis of terrain roughness, side ratio and depth ratio, side ratio D/B is the key parameter. It's derived by curve-fitting technique as:

$$C'_{ML} = -0.431 + 0.35\frac{D}{B} + 0.28\frac{B}{D} - 0.39\left(\ln\frac{D}{B}\right)^2 \tag{2}$$

In order to facilitate the engineering application, error rate facilitating quantitative analysis is defined as follows:

$$\text{Error ratio= (Fitted result - Testing result)/Testing result} \times 100\% \tag{3}$$

Table 2. Summary of RMS empirical formulas of across-wind base moment coefficient

Main literatures	RMS empirical formulas of across-wind base moment coefficient
Marukawa	$C'_{ML} = 0.0141(\frac{D}{B})^3 - 0.129(\frac{D}{B})^2 + 0.325(\frac{D}{B}) - 0.0757 + \left(-0.0737(\frac{D}{B})^3 + 0.688(\frac{D}{B})^2 - 1.20(\frac{D}{B}) + 0.566\right)I_H$
AIJ-2004	$C'_{ML} = 0.0082(\frac{D}{B})^3 - 0.071(\frac{D}{B})^2 + 0.22(\frac{D}{B})$
Gu and Quan	$C'_{ML} = (0.002\alpha_w^2 - 0.017\alpha_w - 1.4) \times (0.056(\frac{D}{B})^2 - 0.16\frac{D}{B} + 0.03) \times (\alpha_{ht}^2 - 0.622\alpha_{ht} + 4.357)$, α_w is wind field parameter, $\alpha_{ht} = H/T$, $T = \min(B, D)$

Fig.2 shows the comparison between the fitting formula and other research results. The average error rate of the formula is 0.07%, and the standard deviation is 6.73%, which means the fitting formula has good consistency with the above calculation formula. The calculated results not only match the original data, but also have good consistency with experimental results from other literature, showing that the fitting formula in this paper has high accuracy and credibility.

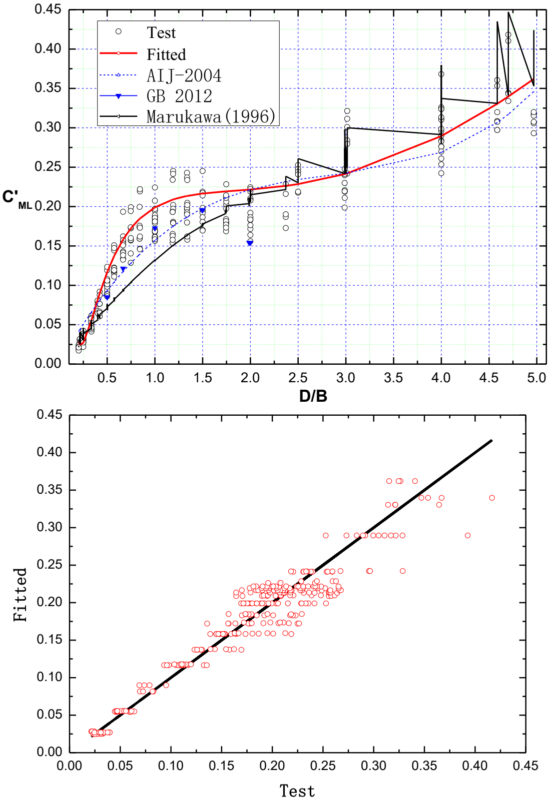

Fig. 2. Comparisons of empirical formulas of the RMS values of the across-wind base moment coefficient and error analysis

3.2 Power Spectra of Across-wind Forces

Based on earlier research, the composition of the across-wind bending moment spectrum includes inflow excitation and wake vortex shedding, and analytical formulas are mainly expressed in Gaussian and polynomial styles. Considering that the energy of the across-wind aerodynamic spectrum is mainly controlled by the wake vortex shedding, the polynomial form is more suitable. Based on the parameter analysis, side ratio, aspect ratio and turbulence intensity at 2H/3 are the key parameters on basement power spectra. Using the nonlinear least squares method, after a lengthy derivation, a proper format of the formula is selected for the curve fitting of the non-dimensional base power spectra of the across-wind loads:

$$\frac{fS_{ML}(f)}{\left(0.5\rho U_H^2 DH^2\right)^2}=\sum_{i=1}^{m}\frac{S_{pi}\beta_i\left(n_L/f_{pi}\right)^{\gamma_i}}{\left[1-\left(n_L/f_{pi}\right)^2\right]^2+\beta_i\left(n_L/f_{pi}\right)^2} \tag{4}$$

Where $S_{ML}(f)$ is the first generalized across-wind force spectrum; f is the frequency; $n = fB/U_H$ is reduced frequency; U_H is the mean wind speed at the top of the building; D is the depth of the building and H is the height of the building; f_{pi}、 S_{pi}、 β_i、 γ_i are the location parameter, deciding the peak frequency of the spectrum, the band width parameter, the amplitude parameter and the deflection parameter while i=1 means single peak value and i=2 means there are two peak values in the spectrum. All the four parameters, which are the functions of the aspect ratio, height ratio and wind field condition (turbulence intensity at 2/3 height), can be identified by curve fitting technique with nonlinear least squares method, which are shown as follows:

$$f_{p1} = 0.15 - 0.046\alpha_{DB} + 0.005\alpha_{DB}^2 - 0.16I_{2H/3}, 0.2 \le \alpha_{DB} \le 5 \tag{5}$$

$$f_{p2} = 1.26 - 0.81\alpha_{DB} + 0.202\alpha_{DB}^2 - 0.017\alpha^3_{DB} - 0.16I_{2H/3}, 2.5 \le \alpha_{DB} \le 5 \tag{6}$$

$$S_{p1} = \begin{cases} \dfrac{0.6}{\left[1 + 19\left(\alpha_{DB} - 0.64\right)^2\right]\left[1 + 625\left(I_{2H/3} - 0.07\right)^2\right]} + 0.0009\alpha_{HR}, & 0.2 \le \alpha_{DB} \le 1.5 \\ 0.0031 + 3.4 \times 10^{-5}\left(\alpha_{DB} I_{2H/3}\right)^{-3.6}, & 1.5 < \alpha_{DB} \le 5 \end{cases} \tag{7}$$

$$\begin{aligned} S_{p2} = {} & 0.0038 + 0.00017\alpha_{DB} - 2.9 \times 10^{-5}\alpha_{DB}^2 - 0.049I_{2H/3}\text{ , } 2.5 \le \alpha_{DB} \le 5 \\ & + 0.175I_{2H/3}^2 - 6.14 \times 10^{-5}\alpha_{HR} \end{aligned} \tag{8}$$

$$\beta_1 = \begin{cases} \dfrac{10^{-3}\left(1.15 - 6\alpha_{DB} + 7.5\alpha_{DB}^2 + 6I_{2H/3}\right)}{1 + 0.007\alpha_{DB} - 21I_{2H/3} + 150I_{2H/3}^2 - 360I_{2H/3}^3}, 0.2 \le \alpha_{DB} \le 1.5 \\ \dfrac{0.068 + 0.0096\alpha_{DB} - 1.2I_{2H/3} + 4.46I_{2H/3}^2}{1 + 0.003\alpha_{DB} - 20.9I_{2H/3} + 145I_{2H/3}^2 - 333I_{2H/3}^3}, 1.5 < \alpha_{DB} \le 5 \end{cases} \tag{9}$$

$$\beta_2 = -0.082 + 0.1\alpha_{DB}^{0.74} I_{2H/3}^{0.27} \tag{10}$$

$$\gamma_1 = \begin{cases} 3.15 - 2.4\alpha_{DB} + 0.65\alpha_{DB}^2 - 1.37I_{2H/3}, & 0.2 \le \alpha_{DB} \le 1 \\ \dfrac{1.37 + 0.007\alpha_{DB} - 20.2I_{2H/3} + 75I_{2H/3}^2}{1 + 0.002\alpha_{DB} - 14.6I_{2H/3} + 54I_{2H/3}^2}, & 1 < \alpha_{DB} \le 5 \end{cases} \tag{11}$$

$$\gamma_2 = 1.5, 2.5 \le \alpha_{DB} \le 5 \tag{12}$$

Where, α_{DB} is the side ratio; α_{HR} is the aspect ratio; $I_{2H/3}$ is the turbulence intensity at height.

Fig.3 and Fig.4 shows the comparison between the fitting formula and other research result, which means the fitting formula has good consistency with the above calculation formula. The calculated results not only match the original data, but also have good consistency with experimental results from other literature, showing that the fitting formula in this paper has high accuracy and credibility.

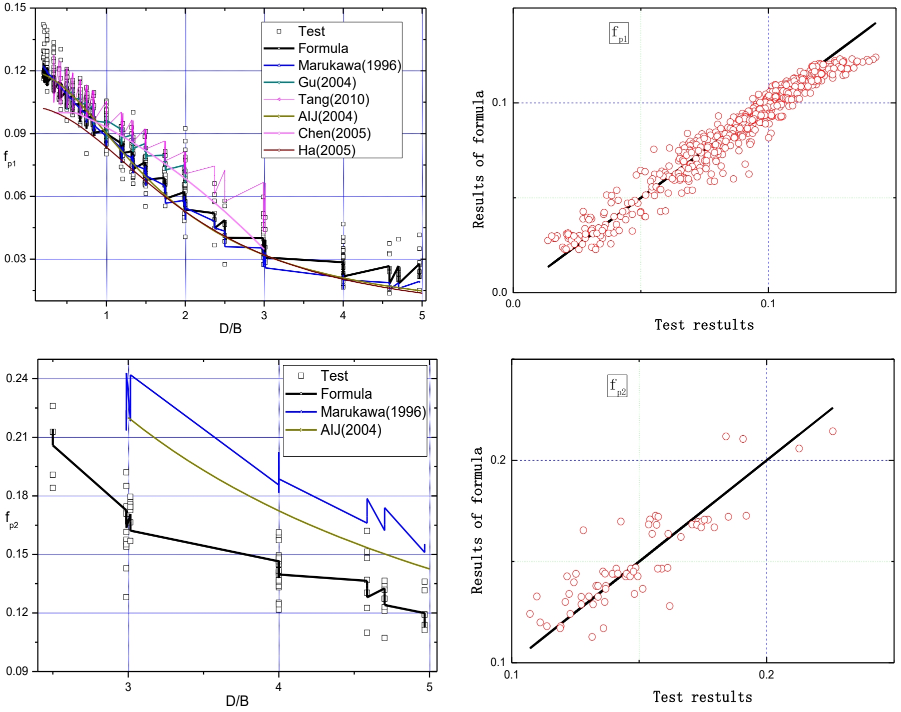

Fig. 3. Comparisons of empirical formulas of f_p and error analysis

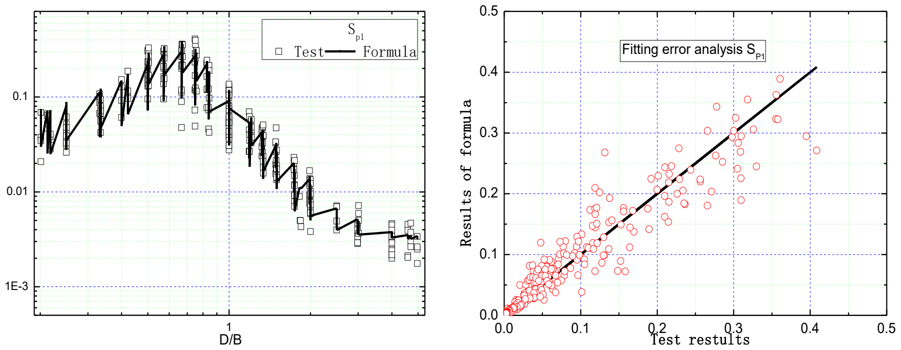

Fig. 4. Comparisons of empirical formulas of S_{p1} and error analysis

3.3 Comparisons with Earlier Works

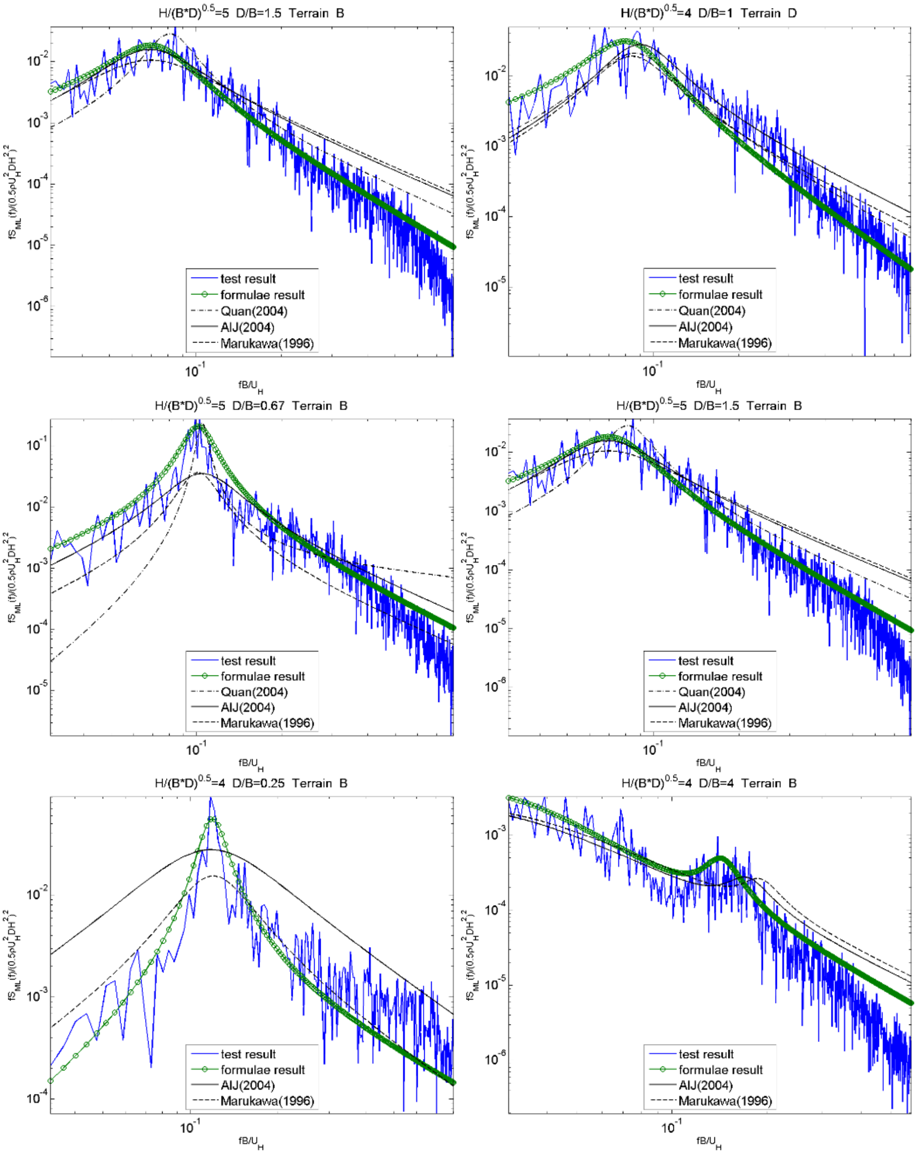

Fig. 5. Comparisons of empirical formulas of power spectrum and those from other literatures

Fig. 5 shows comparisons of the present results with the corresponding results from the AIJ-2004, Gu and Quan (2004) and Marukawa (1996). It is seen from Fig. 5 that the non-dimensional spectra of the across-wind loads of the square building with aspect ratio of 4 with different side ratios in the terrain category B and D from various sources agree well. It shows that the fitted formula not only match the original data, which can reduce the overestimate at the high frequency area and can estimate the across-wind load more accurately.

4 Calculation of Across-wind Equivalent Static Wind Load

The characteristic value of across-wind equivalent static wind load of tall buildings with rectangular section can be calculated according to the following formula:

$$w_{ac} = g w_0 \mu_z (2 + 2\alpha) C'_{ML} \sqrt{1 + R_L^2} \tag{13}$$

$$R_L = \frac{1.4}{(\alpha+0.95)} \left(\frac{z}{H}\right)^{-2\alpha+0.9} \sqrt{\frac{\pi S_{FL}}{4\zeta C'^{2}_{ML}}} \tag{14}$$

Where, $w_{ac}$is the characteristic value of equivalent wind load for across-wind vibration (kN/m^2) ; g is the peak factor, taking 2.5; w_0 is the reference wind pressure (kN/m^2); μ_z is the exposure factor for wind pressure; α is the wind speed profile power index, taking 0.12, 0.15, 0.22 and 0.30 corresponding to Category A, B , C and D terrain roughness in Chinese code GB 50009-2012 respectively; C'_{ML} is the Coefficients of across-wind base moment in formula (2); $\zeta$is the sum of structural damping ratio of the first order vibration mode and the aerodynamic damping ratio of the across-wind first order vibration mode; S_{FL} is non-dimensional base power spectra of the across-wind loads in formula (4).

5 Conclusions

Based on HFFB test data, the influences of terrain roughness, side ratio and aspect ratio on the non-dimensional across-wind base moment spectra and RMS values of across-wind base moment coefficient are analyzed. The following meaningful conclusions are obtained:

1) Based on parameters analysis of terrain roughness, side ratio and depth ratio, side ratio D/B is the key parameter for RMS values of across-wind base moment coefficient, while the effects on the non-dimensional across-wind base moment spectra are different in different situation.

2) The empirical formula presented in this article considers the effects of side ratio, aspect ratio, and incoming turbulence intensity on RMS coefficient and non-dimensional across-wind base moment spectra of rectangular cross-section high-rise buildings. The empirical formula is simple in form and has high accuracy and credibility, which can provide reference for practical applications and code revisions.

3) Using other parameters in the wind load codes/standards, the across-wind equivalent static wind load of typical rectangular tall buildings can be calculated by the empirical formula.

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