Crosswind response analysis of high flexible structures with circular sections based on GVDP aerodynamic damping and ENLE technique

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SUMMARY:
For high flexible structures with high slenderness ratio and low damping, such as chimneys, power towers and high-rise buildings, accurate estimation of crosswind response is the key to ensure structural safety. Existing studies have shown that the large crosswind vibration of structures is mainly related to the aeroelastic effect between structure and flow field, and time-varying nonlinear aerodynamic damping is often used to characterize the coupling effect between flow field and structure. In this paper, based on the generalized van der Pol type (GVDP) nonlinear aerodynamic damping model and equivalent nonlinear equation (ENLE) technique(Chen,2013;Guo et al.,2021,2022), the closed-form solution of the probability density of the crosswind displacement response of highly flexible circular structures is obtained. In addition, the proposed method is applied to estimate the crosswind response of 16 steel chimneys, and the estimated values were in good agreement with the full-scale values, which confirmed the accuracy of the method.

Keywords: Crosswind response, Aerodynamic damping, High flexible structures

1. INTRODUCTION

Many mainstream international wind load codes use linear random vibration theory to calculate the crosswind response, in which the nonlinear aerodynamic damping is equivalent to the linear aerodynamic damping represented by the response second-order moment. However, a large number of wind tunnel experiments and measured results show that the crosswind response has obvious hardening non-Gaussian characteristics. The above approach ignores the nonlinear characteristics of the vortex-induced vibration system, which makes it impossible to ensure the estimation accuracy of higher order moments such as the extreme value of the response. This is also one of the main reasons why many mainstream international wind load codes cannot accurately estimate the extreme value of the crosswind response of structures (Lupi et al.,2017; Rahman et al.,,2020).

This paper is based on the generalized van der Pol-type (GVDP) nonlinear aerodynamic damping model and equivalent nonlinear equation (ENLE) technique (Chen,2013; Guo et al.,2021,2022), derived the closed-form solution of the probability density of the crosswind response of highly flexible structures with circular sections (see Section 2). Then, 16 steel chimneys with large vibrations were selected, and the crosswind response of the 16 chimneys was estimated by the above method to verify the accuracy of the proposed method, as shown in Section 3.

2. CLOSED-FORM SOLUTION OF NONLINEAR CROSSWIND RESPONSE BASED ON GVDP AERODYNAMIC DAMPING MODEL AND ENLE TECHNIQUE

The closed-form solution of the crosswind nonlinear motion equation based on GVDP aerodynamic damping model and ENLE technique can be expressed as (Guo et al.,2022)

$$p(A) = CAexp\left[-\frac{2\omega_s^2}{\pi^2 S_0}\cdot\sum_{j=0}^{n}\frac{b_j}{(\beta_j+2)}A^{\beta_j+2}\frac{\Gamma\left(\frac{3}{2}\right)\Gamma\left(\frac{\beta_j+1}{2}\right)}{\Gamma\left(\frac{\beta_j}{2}+2\right)}\right] \tag{1}$$

Where, $A=(\dot{y}^2/\omega_s^2+y^2)^{1/2}$ is the crosswind amplitude, y and $\dot{y}$ are the displacement and speed of structure respectively,ω_s is circular frequency; $p(A)$ is the PDF of crosswind amplitude; C is the standardization constant; b_j、β_j $(j=0,1,\cdots,n)$ are the parameters of time-varying nonlinear aerodynamic damping, $b_0=2\xi_s\omega_s-2(\rho D^2/m_e)K_{a0}\omega_s$, $b_1=2(\rho D^2/m_e)K_{a0}\varepsilon\omega_s$, $\beta_0=0$ and $\beta_1=\beta$, ξ_s、D、m_e are the structural damping、diameter and equivalent mass respectively, ρ is air density, K_{a0}、ε and β are the three parameters of GVDP aerodynamic damping model; $\Gamma(\cdot)$ is Gamma function; $S_0=\frac{9}{16\pi}\left(\frac{\rho D^2}{m_e}\right)^2\left(\frac{U}{U_{cr}}\right)^4\left(\frac{1}{S_t}\right)^4 f_s^4 S_M(f_s)$ is the spectral density constant related to the external excitation, U_{cr} is vortex-induced resonance critical wind velocity, S_t is Strouhal number, f_s is structural frequency, $S_M(f)$ is the PSD of the crosswind base bending moment coefficient with circular section. More details can be seen in Guo et al.,2021,2022.

The PDF of crosswind displacement response $p(y)$ and response statistical moment (such as response variance, kurtosis, etc.) can be expressed as (Chen,2013; Guo et al.,2022)

$$p(y) = \frac{1}{\pi}\int_{|y|}^{\infty}\frac{p(A)}{\sqrt{A^2-y^2}}dA \tag{2}$$

3. APPLICATION PRESENT METHOD TO ANALYSE 16 FULL-SCALE CHIMMNEYS CROSSWIND RESPONSE

In order to further verify the response prediction accuracy of the above method, 16 steel chimneys with large vortex-induced vibration were selected,as shown in Table 1 (Lupi et al.2017).

Table 1. 16 groups of measured parameters of chimney

No.	H	D	m_e	M_1	ξ_s	S_c	f_1	y_{max}/D	R_e
1	90	5.1	2090	37620	0.005	4.04	0.75	0.062	6.73×10^6
2	91.5	5.13	2010	36783	0.0045	3.42	0.68	0.057	6.17×10^6
3	83	4.1	1360	22576	0.006	4.88	1.15	0.063	6.67×10^6
4	60	1.58	233	2796	0.0024	2.24	0.5	0.25	4.31×10^5
5	55	2.14	323	3553	0.0024	1.69	1.12	0.18	1.77×10^6
6	50	2.2	945	9450	0.0022	4.37	0.919	0.016	1.53×10^6
7	45	1.1	258	2322	0.0054	11.6	0.629	0.025	2.63×10^5
8	54	2.2	834	9007	0.0094	16.27	0.61	0.012	1.02×10^6
9	60	2	340	4080	0.002	1.63	0.802	0.28	1.11×10^6
10	28	0.914	89	499	0.002	2.56	1.72	0.153	4.96×10^5
11	52	2	340	3532	0.002	1.63	0.75	0.25	1.04×10^6

12	120	4.9	2418	58024	0.003	2.9	0.49	0.122	4.06×10^6
13	99	4.25	3057	60538	0.002	3.25	0.425	0.089	2.65×10^6
14	140	6	1440	40320	0.005	1.92	0.51	0.2	6.33×10^6
15	76.2	2.62	535	8151	0.002	1.87	0.55	0.29	1.30×10^6
16	100	6	1639	32786	0.007	3.06	0.61	0.133	7.58×10^6

3.1. Parameter identification of GVDP aerodynamic damping model

Based on the cylinder aeroelastic model wind tunnel test, the parameters of GVDP aerodynamic damping model are obtained by using the MATLAB fitting toolbox, as shown in Table 2.

Table 2. GVDP aerodynamic damping model parameters

U/U_{cr}	K_{a0}	ε	β
0.92	0.3	3.2	0.121
0.99	0.5	5	0.585
1.05	3	1.19	0.111
1.11	3	1.12	0.101
1.18	3	1.13	0.103
1.21	2.5	1.11	0.1
1.24	0.61	2.93	0.819
1.276	0.79	1.30	0.281
1.31	0.425	1.33	0.589
1.34	0.405	2.57	0.678
1.37	0.279	2.56E-14	1
1.40	0.404	4.11	0.558
1.44	0.388	4.93	0.516
1.5	0.123	4.04	3.54E-10

It is worth noting that existing studies have shown the aerodynamic damping model parameters K_{a0} are very sensitive to Reynolds number (Guo et al.,2021). According to the provisions of Eurocode 1(2010), the values of aerodynamic damping model parameter K_{a0} of the 16 groups of chimneys listed in Table 1 are as follows: $K_{a0} = 0.8$ for group 1~3, 5~6, 8~14 and 16, $K_{a0} = 1.25$ for group 4, $K_{a0} = 1.5$ for group 7, and $K_{a0} = 1.1$ for group 15, other parameters remain unchanged.

3.2. Results

Fig. 1 shows the variation of the RMS value and maximum value of the crosswind response extreme value of 16 groups of chimneys with Scruton number S_c . It can be seen that σ_y/D and y_{max}/D decreases with the increase of S_c , which is consistent with the variation rule of measured response.

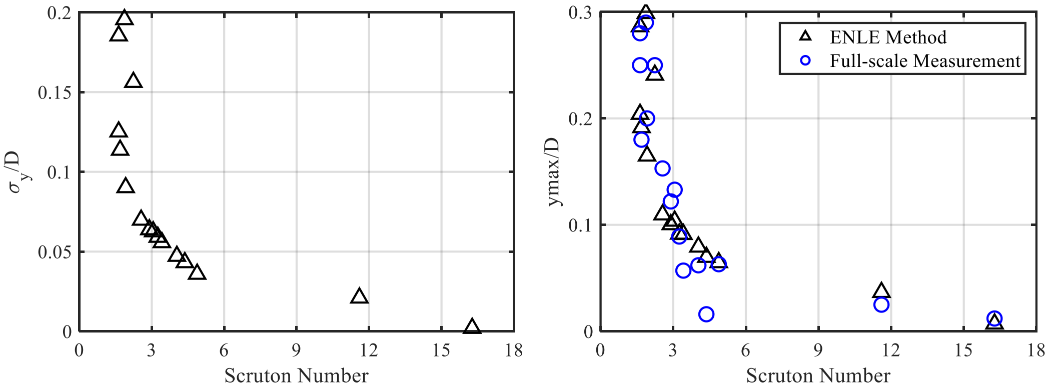

Figure 1. σ_y/D vs S_c and y_{max}/D vs S_c

Fig. 2 shows the change of peak factor of 16 chimneys with parameter $S_c/(4\pi K_{a0})$ and the comparison between the estimated and measured crosswind response extreme values of 16 groups chimneys.It can be seen that the error between the estimation value and full-scale measurement values is basically within 20%, which proves the accuracy of the above method.

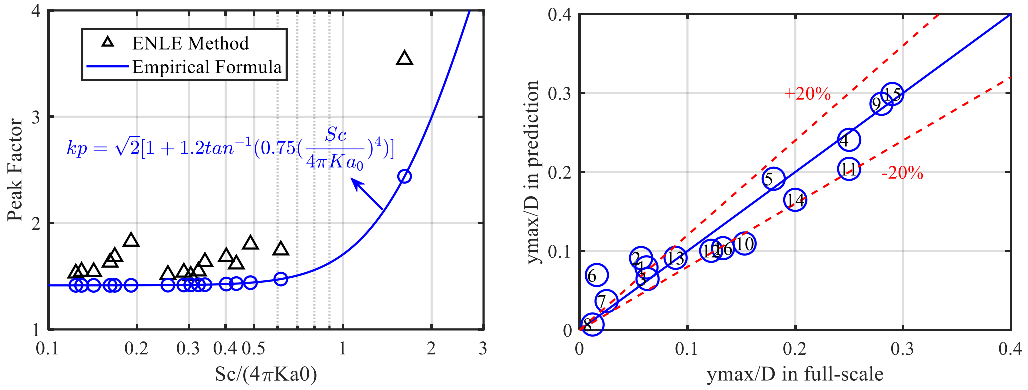

Figure 2. k_p vs $S_c/(4\pi K_{a0})$ and y_{max}/D in prediction vs y_{max}/D in full-scale

4. CONCLUSIONS

In this paper, an closed-form solution of the probability density function of the crosswind response of a highly flexible circular structure is proposed, and the crosswind response of 16 steel chimneys is estimated by using this method, which is in good agreement with the measured values and proves the accuracy of the method.

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