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Across-wind response of tall circular chimneys to vortex shedding

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ABSTRACT

A semi-empirical method for predicting across-wind response of a circular chimney due to vortex shedding during lock-in region was earlier presented by the author. This involved use of only structural damping, with suitable modification of spectrum of modal lift force through a parameter 'fact', having a value of 0.45. When applied to three typical chimneys, the predicted across-wind base bending moment values showed good comparison with ACI code ACI-307-2008. In this paper, by considering additional experimental data from Wootton, a non-linear relation between the parameter 'fact' and the normalized rms tip deflection, $\left(\frac{\sigma y}{De}\right)$ is presented. The relationship is also verified using full-scale chimney data by Galemann and Ruscheweyh, Waldeck, and Melbourne. The suggested method is simple and useful for design offices and appears equally applicable both for steel and concrete chimneys.

1. Introduction

Wind is one of the dominant load criteria in the design of tall circular chimneys which are important power plant structures. Vortex induced oscillations significantly influence the across-wind load and response of a chimney. Several researchers have significantly contributed to this important problem and these include studies by Wootton (1969), Vickery and Basu (1983), Ruscheweyh (1989), ESDU (1996), and Flaga, Lipecki (2010). In a recent paper, Niemann et al. (2014) have observed that available design models for vortex resonance, especially at relatively low Scruton numbers often provide considerable scatter in their results. Currently, the methods by Vickery and Basu, and by Ruscheweyh are widely being recommended in many international codes of practice. A salient feature of the method proposed by Vickery and Basu is the concept of a negative aero-dynamic damping, using which the enhanced response due to vortex shedding in lock-in region is computed. While this might be a useful concept, Kijewski and Kareem (2000) reported that simply attributing all motion-induced effects to aerodynamic damping may be an excessive simplification, since the motion of a structure also modifies the flow field around it and particularly enhances the span-wise pressure correlation, which may lead to increased forces. Based on research carried out at CSIR – Structural Engineering Research Centre (SERC), Chennai, India, a semi-empirical method has been earlier suggested by the authors for predicting across-wind response of a circular chimney, due to vortex shedding both for non-lock-in and lock-in regions (Arunachalam and Lakshmanan, 2009). In this method it is proposed that once the spectrum of generalized lift force is computed, the spectrum of across-wind response can be obtained using the principle of conventional structural dynamics with the use of only structural damping. By suitably modifying the spectrum of generalized lift force, through a non-dimensional parameter, 'fact', and by using only the structural damping, the increased response in lock-in region is predicted. A closed form solution for the normalized across-wind tip deflection is developed (Arunachalam (2011, 2014) and Arunachalam et al., 2013). The suggested method has been verified by applying to three typical concrete chimneys and by comparing the across-wind base bending moments with corresponding values as obtained through ACI Code 307-2008 (ACI-307, 2008), which showed a very good agreement. In this method, a value of 0.45 for the parameter 'fact' has been earlier suggested, although it was realized that 'fact' is expected to vary as a function of the normalized response. In the present paper, by including additional experimental data reported by Wootton (1969) on circular stack models, a non-linear relationship between the parameter, 'fact' and the normalized response, $\left(\frac{\sigma y}{De}\right)$, is established. The above relationship is subsequently verified by considering additional full-scale data on steel and concrete chimneys reported by Ruscheweyh and Galemann (1996), by Waldeck (1992) and by Melbourne et al. (1985). A good agreement is seen between the predicted and full-scale experimental values and the results are encouraging. Thus, the method appears equally applicable both for concrete and steel chimneys.

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Notation

B	spectral band width parameter
$\bar{C}_D$	mean drag coefficient
$C_{\acute{L}}$	rms total lift coefficient
$C_{\acute{L},turb}$	rms lift coefficient due to lateral turbulence
$C_{\acute{L},vs}$	rms lift coefficient due to vortex shedding
$C_{\acute{L},V}$	modified value of $C_{\acute{L},vs}$
D_e	effective diameter (average diameter of top one third height of chimney)
D_Z	diameter at z,
f	frequency
f_0	fundamental natural frequency
'fact'	non-dimensional parameter used to account for enhanced response during lock-in region
f_{sh}	shedding frequency
$fS_{F_z}(f)$	spectrum of lift force
$F_z(t)$	local lift force per unit height
g	peak factor (=4)
H	height of the chimney
$I_{5/6H}$	turbulence intensity value expressed in percentage at reference height, (5H/6)
I_z	turbulence intensity value expressed in percentage at height, z
k	generalized stiffness
L_c	correlation length
$m(z)$	mass per unit length
m_{ei}	equivalent mass
S	Strouhal number
$\bar{V}_Z$	mean velocity at the height z
$(\bar{V}_z/f_0 D_e)$	reduced velocity
V_{cr}	critical velocity
y	across- wind tip deflection
Ω_z	non-dimensional correlation length ($\Omega_z = L/D_e$)
α	power law coefficient for mean velocity
β	power law coefficient for first mode shape
η	structural damping as a fraction of critical damping
σ_y	rms value of across-wind tip deflection
$\left(\frac{\sigma_y}{D_e}\right)$	normalized across-wind tip deflection
φ	first mode shape
ρ	mass density of air

2. Background

2.1. Spectrum of lift force due to vortex shedding alone : non-lock-in region

(i) While it is recognized that the rms total lift coefficient $C_{\acute{L}}$, contains contributions from two sources; one due to lateral turbulence, $C_{\acute{L},turb}$ and the other due to vortex shedding, $C_{\acute{L},vs}$, in most of the experiments in the literature, only the results on the single parameter, $C_{\acute{L}}$ is reported.

(ii) Generally, the value of $C_{\acute{L},vs}$ is not universally constant since it depends on individual test conditions. However, by applying a correction factor to the correlation length, the authors have shown that (Arunachalam et al., 2001) the modified value of $C_{\acute{L},vs}$ denoted as $C_{\acute{L},V}$ takes a mean value of 0.089 (with cove = 18%) corresponding to a turbulence intensity level of 7.5%. The above hypothesis is validated using the wind tunnel test data measured at CSIR-SERC and also the published test results in the literature, which includes both wind tunnel and full-scale experiments. Although the *Re* number typically differs by 2 or 3 orders of magnitude between the WT and full scale experiments, the above finding of $C_{\acute{L},V}$ attaining a near constant value of 0.089, irrespective of WT or full scale experiments *may be viewed as independent of Re number regime*. It may be stated that the above finding is based on analysis of empirical data alone from several wind tunnel and full-scale experiments published in literature. The reasons why this is so is not clear at this time and require further studies.

(iii) Under the situation that there is a practical constraint to achieve exact Reynolds number similarity in a boundary layer wind tunnel, which affects the across-wind prediction for full-scale chimneys, it is believed that the above finding of $C_{\acute{L}V}$ attaining a near constant of 0.089 independent of Reynolds number regime, enables in overcoming this difficulty to the extent of the role played by the Reynolds number.

(iv) The turbulence intensity in the approach flow affects both the rms total lift coefficient, $C_{\acute{L}}$ and the correlation length, L_c. The higher the turbulence intensity, the higher is the $C_{\acute{L}}$ (Kareem et al., 1989; Sanada et al., 1992). An improved empirical variation was suggested by Vickery between $C_{\acute{L}}$ and modified turbulence intensity, I_z^* (Vickery 1994).

(v) The correlation length due to vortex shedding decreases with increasing rougher terrain. Based on the wind tunnel results on a chimney tested in two different terrain categories by Kareem et al. (1989), the following relationship between the non-dimensional correlation length, Ω_z($\Omega_z = L/D_e$) and turbulence intensity was proposed by the authors,

$$\Omega_z = 3.4 - 0.12\ (I_z - 7.5) \tag{1}$$

where I_z is the turbulence intensity value expressed in percentage, L is the local correlation length and D_e *is* the effective diameter. Eq. (1) can be considered reasonably adequate to relate the correlation length and turbulence intensity. From (iv) and (v) above, it is deduced that $C_{\acute{L}}$ is inversely proportional to the correlation length. Hence, the following empirical expression Eq. (2) for the parameter $C`_{L,vs}(z)$ is suggested by the authors:

$$C_{L,VS}(z) = \frac{(0.089)\ (3.4)}{[3.4 - 0.12\ (I_z - 7.5)]} \tag{2}$$

As discussed elsewhere (Arunachalam and Lakshmanan, 2009), Eq. (2) provides results which are in good agreement with full-scale measured data by Waldeck (1992) and Sanada et al. (1992). Hence, Eq. (2) is used in the proposed method by the authors for the evaluation of spectrum of generalized lift force, only due to vortex shedding.

(vi) The following well-known bell-shaped function for narrow banded spectrum of vortex shedding as given by Vickery and Clark (1972) is assumed in the present study.

$$\frac{fS_{CL,Z}(f)}{C`_{L,z}{}^2} = \frac{1}{B\sqrt{\pi}}\left[\frac{f}{f_{sh,z}}\right] exp\left[-\left\{\frac{1-\frac{f}{f_{sh,z}}}{B}\right\}^2\right] \tag{3}$$

$$f_{sh} = S\bar{V}_z/D_z \tag{4}$$