行政院國家科學委員會專題研究計畫成果報告

高層建築氣彈力行為之風洞試驗研究（一）
Wind Tunnel Investigations on The Aeroelastic Behavior of High-rise Buildings (I)

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主持人：鄭啟明　　淡江大學土木工程系

中文摘要

本文以高寬比 7 的正方斷面高層建築模型在開闊地形及都市地形的邊界層流場中，以 Scruton No. 為參數，進行一系列的氣彈力實驗，探討高層建築受風力作用的動態行為。實驗結果顯示都市地形流場對正方斷面高層建築而言，是一個氣動力穩定流場。在開闊地形則依其 Scruton No. 可分為氣動力穩定區（Scr ≥ 6.28），氣動力不穩定區（$2.76 \leq Scr \leq 5.82$）即氣動力發散區（Scr≤2.18）。文中並依據實驗數據得到氣動力阻尼經驗模式，可以正確的預測正方斷面高層建築受風作用的橫風向位移反應。

關鍵詞：高層建築、氣彈力、風洞實驗

Abstract

Systematic aeroelastic model tests were performed to study the dynamic responses of a square shape high-rise building with aspect ratio,H/D=7, in simulated atmospheric boundary later flows. During experiments, mass-damping coefficient (Scruton Number, Scr) was used as the primary controlling parameter. The experimental measurements are compared with response estimations based upon wind loads obtained from stationary pressure model. Results indicate that urban terrain flow field is aerodynamically stable for the square shape buildings. The response behavior of square shape buildings in open terrain is categorized into three regions based on buildings Scruton Number: (1)aerodynamic stable region, Scr≥6.28, (2)aerodynamic unstable region, $2.76 \leq Scr \leq 5.82$, (3)aerodynamic divergence regions, Scr≤2.18. Empirical models for aerodynamic damping are formed to augment the lack-of aeroelasticity in wind loads from stationary model test. The calculated acrosswind responses show good agreement with measurements.

Keywords: High-rise, Aeroelastic, Wind Tunnel Test

Introduction

Davenport & Novak (1) proposed a two-stage vibration model for vortex induced vibration, namely, random excitation and harmonic excitation stage. When building's tip amplitude, in random excitation, exceeds 2% of building width, harmonic excitation takes over. Kwok & Melbourne (2), based on the aeroelastic studies in boundary layer flow, indicated that, when wind velocity does not close to the critical velocity, acrosswind response is proportional to the -1/3 to -1/2 power of structural damping, proportional to -1 power of structural damping near critical velocity. This observation verifies Davenport & Novak's two-stage model. Kareem (3) constructed the acrosswind force spectra of a square shape building through pressure measurements. During the structural response calculation, it was found that introducing aerodynamic damping leads to better results.

Matsumoto (4) used data from aerodynamic and aeroelastic tests to show that, for rectangular cylinder with 4.0 aspect ratio and cross-sectional depth/width ratio of 0.6 and 1.0, acrosswind vibration exhibited instability in a α=0.2 flow field. Isyumov et. al. (5) conducted wind tunnel tests on a 85 stories, 390m tall high-rise building, showed that, in urban terrain, the aerodynamic damping is small but positive. Hayashida et. al. (6) also showed that , for a square cylinder with aspect ratio equals to 7.5, the acrosswind motion has positive aerodynamic damping in a α=0.25 flow field. Vickery & Steckley (7) showed that, with augment of aerodynamic damping, the acrosswind response can be accurately predicted for a aspect ratio, H/D=13.3, square cylinder in a α=0.112 flow field.

In this paper, author used duel axes aeroelastic model to study the acrosswind vibration behavior of a H/D=7 square cylinder in boundary layer flows. Aerodynamic damping was calculated through inverse response method.

Experimental Apparatus

The aeroelastic tests were conducted at Boundary Layer Wind Tunnel I, (BLWT-I), Structural Aerodynamic Laboratory, Tamkang University. BLWT-I has an $18.0m \times 2.0m \times 1.5m$ test section. Two sets of atmospheric boundary layer flows, BL1 and BL2, were generated to represent flows over open and urban terrain, respectively. Rigid body, base pivoted aeroelastic model system , shown in Fig. 1, was used in this study. A duel axes mechanism was used to allow the aeroelastic model have two sway mode vibrations. Square cylinder with aspect ratio, H/D, equals to 7 was chosen to be the geometry shape of high-rise building. Reynolds number was kept greater than 4×10^4 for most wind tunnel experiments.

Three structure densities, $\rho_s = 151 kg/m^3, 196 kg/m^3, 231 kg/m^3$, were used by adjusting the weight at model tip. Structural damping, varying from 0.4% to 6%, was provided by the liquid damper device at base of aeroelastic model. In order to avoid the complex crossing effects from mass and damping on building responses, the following form of mass-damping coefficient (Scruton number, Scr) was used as experimental controlling parameter,

$$Scr = \frac{\int_0^H m(z)\Phi^2(z)dz}{\int_0^H \Phi^2(z)} \frac{\xi}{\rho D^2}$$

Fifteen cases of Scruton number were used in this study. During experiments, the tip displacement of alongwind and acrosswind motion were measured.

Buildings' Dynamic Responses

(1) Buildings in Open Terrain, BL1

(a) Region I: Scr$\geq$6.28, Aerodynamic Stable

In this region, the acrosswind response displays maximum value at critical velocity, $U_{r,cr} \approx 11.0$. At critical velocity, acrosswind response, σ_y / D, increases slightly from 2.3% to 3.2% when Scruton number decreases from 10.02 to 6.28. Comparisons between measurements of aeroelastic model and predictions based on acrosswind force spectrum show that σ_y / D =3% is a critical value. When building's response smaller than it, vortex shedding process dominate acrosswind motion. Exceeding it, motion induced force becoming significant, response prediction based solely on stationary force spectrum is no longer conservative.

(b) Region II: 5.82$\geq$Scr$\geq$2.76, Aerodynamic Unstable

Structural response in this region displays peak value due to structural resonance at critical velocity. The comparison between experimental observations and predictions shows that, for reduced velocity less than 8.0, these two agree well. In other words, motion induced force insignificant, vortex shedding still controls. When U_r > 8.0, motion induced force starts to show, measured values become greater. At critical velocity, the difference can be as large as 40% for model CD (Scr=5.82) up to 80% for model AC (Scr=2.76). This negative aerodynamic damping effect near critical velocity becomes stronger as Scruton number decrease. In most literature, this phenomenon is called 'lock-in'. However, 'lock-in'—vortex shedding frequency locked on structural frequency for a certain range of wind speed, which should be reflected by a plateau of maximum response—does not occur, even in the case of model AC which has R.M.S. acrosswind response exceeding 0.1D.

(c) Region III: Scr$\leq$2.18,
Aerodynamic Divergent

In this Scruton number region, high-rise buildings exhibit different response characteristics from the other two regions. Acrosswind response amplitude in this region is about an order greater than the previous two. For reduced velocity less than 10, vortex shedding prevails. Measurements from aeroelastic tests equal or less than predictions from stationary force spectrum. When $U_r \geq 10$, significant aeroelastic phenomenon occurs. For model CB, Scr=2.18, it happens between Ur= 10 to 14. For model BB, whose Scruton number is lower to 1.54, this velocity range becomes Ur= 10 to 17. In these velocity range, Structural response does not remain constant, but increases with wind speed. In other words, this aeroelastic behavior is likely initiated by vortex shedding resonance at critical velocity but not sustained by vortex shedding or 'lock-in' in the latter stage as structural response kept on increase with wind velocity. When wind velocity exceeding the aforementioned range, vortex shedding regains control of the acrosswind vibration. Again, measurements agree with predictions. If buildings' Scruton number further decrease, galloping occurs. Building's acrosswind response diverges as wind speed increases.

(2) Building in BL2 flow field

Building has different pattern of acrosswind response in BL2 (city) flow field. The response measurements indicate that, regardless building's Scruton number, acrosswind response has no peak value or resonance-then-galloping phenomenon at critical velocity, Ur,cr. Disappearance of maximum response at critical velocity is caused by following reasons: (1) large mean velocity gradient and high free stream turbulence in BL2 make vortex induced force more scattered in frequency domain, which will weaken structural resonance, (2) when acrosswind response greater than the aeroelastic threshold, σ_y/D>3%, presence of high turbulence would damp the aeroelastic effect, i.e., negative aerodynamic damping will not occur in BL2 flow field.

Aerodynamic damping

For the aerodynamic damping analysis, inverse response methods was chosen to calculate the small quantity of aerodynamic damping for its reliability. During aeroelastic tests, total damping of the vibration system consists of structural damping and aerodynamic damping:

$$\xi_T\,(\mathit{total}) = \xi_S\,(\mathit{structure}) + \xi_a\,(\mathit{aerodynamic})$$

First, the structural damping of aeroelastic model was determined. Then system's total damping during vibration was determined by matching the calculated response, based on stationary wind force spectrum, to the measurement. Obtaining aerodynamic damping for all model tests, three empirical models were established through regression analysis.

(1) BL1 flow field, Scr≥6.28

$$\xi_a = 0.06\left[1 - \exp(-0.2(U_r - 11)^2)\right]$$

(2) BL1 flow field, 2.76≤Scr≤5.82

$$\xi_a = -0.015\exp\left[-\frac{Scr - 1.6}{10}(U_r - 11)^2\right]$$

(3) BL2 flow field

$$\xi_a = 0.15U_r^{-3}$$

Buildings' acrosswind responses were then calculated by using measured wind force spectrum coupled with these aerodynamic damping model and compared with direct measurements. The response calculation agrees with experimental data well.

Conclusions

Systematic wind tunnel aeroelastic tests were performed on single square shape high-rise building with aspect ratio equals to 7. Results indicate that building's acrosswind behavior is strongly influenced by building's Scruton number and flow field characteristics. Some of the conclusions are:

1. The acrosswind aeroelastic behaviors of square shape high-rise building in open terrain flow field can be classified into three regions according to building's Scruton numbers: aerodynamic stable region (Scr ≥ 6.28), aerodynamic unstable region (2.76 ≤Scr≤5.82) and aerodynamic divergent region (Scr≤2.18).
2. In open terrain flow field, the aeroelastic threshold is 3% of building's width, R.M.S. response exceeding it will induce negative aerodynamic damping effect.
3. For a square cylinder in turbulent boundary layer flows, acrosswind galloping will not occur spontaneously, it has to be leaded by vortex resonance.
4. Urban terrain flow field is aerodynamic stable for square cylinder, only positive aerodynamic damping will occur in this flow field.
5. Empirical models of aerodynamic damping are established based on experimental data. Coupled with acrosswind force spectrum from stationary model, building's acrosswind response can be accurately predicted.

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