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AN ONLINE ANALYSIS SYSTEM FOR WIND-INDUCED RESPONSE OF HIGH-RISE BUILDINGS

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The wind-resistant design of high-rise buildings is generally based on wind loading codes, wind tunnel test or computational fluid dynamics (CFD) method. With the accumulation of wind tunnel test data and the development of internet, database of aerodynamic loads, which can provide wind-induced response and equivalent static wind load of high-rise buildings to structural designer, will become a more convenient method. In present study, an online analysis system for wind-induced responses of high-rise buildings with different parameters, such as side ratio, aspect ratio, terrain category, mass, free vibration frequency, structural damping, etc, is established with random vibration analysis based on the high-frequency base balance (HFBB) tests of several rigid models. The system can estimate base shears, base moments and torque at several wind angles, which include mean values and extreme values considering background component and resonant components. The system can estimate acceleration of both translational direction, torsional acceleration at corners and their combined values. The equivalent static wind load for strength and stiffness checking in all three directions can be obtained as well. The wind-induced responses of a target building whose figure is different with the test models are to be predicted by the neural network method simulated on four similar buildings. In the present paper, the system is briefly introduced and the dynamic responses of several high-rise buildings are calculated. Wind-induced responses of some of the high-rise buildings are simulated with neural network method based on the data of other buildings with similar figures. The simulated results agree well with the directly calculated results based on its test data, which shows that the system meets the accuracy requirement of engineering application and can be used for preliminary design of high-rise buildings.

1. Introduction

The wind-resistant design of high-rise buildings is generally based on wind loading codes, wind tunnel test or computational fluid dynamics (CFD) method. In the preliminary design stage of high-rise buildings, the design codes have limitations on providing wind load parameters and the wind tunnel test has a bad economy due to the uncertainty of the project. The method based on database of aerodynamic loads, which consists of a large number of wind tunnel test data, will be more convenient and economical for the wind-resistant design of high-rise buildings. The purpose of this method, which is not intended to replace wind tunnel test, is to estimate the wind loads and wind-induced response for the preliminary design stage of high-rise buildings when it is not suitable for test.

NatHaz Aerodynamic Load Database (NALD) is developed by Kareem et al [1], which can provide wind-induced response caused by wind along the direction of model axes for the preliminary design of high-rise buildings. In order to estimate the wind-induced response of the target building, an off-line software based on the Western University Aerodynamic Database (WAD) is developed by Kim [2].Zheng et al [3] develop two design wind load expert systems based on wind tunnel test data and wind codes, respectively.

For other systems, the basic premise is that the wind loads and wind-induced response of a building can be determined using the aerodynamic forces of another building with a similar figure, whose model previously tested in wind tunnel. This thesis is just the further study on the basis of the previous work. Two to four tested models, whose figures are similar with that of target building, can be picked up according to user demand and then the wind loads and wind induced responses of the target building can be analysed based on neural network to provide more accurate predictions. In addition to the general results, the system also has more functionality, such as providing results at several wind angles, considering wind direction factors of the target building location, providing combination coefficients of equivalent static wind load and providing sensitivity analysis on the dynamic properties of the structure.

2. Introduction to Online Analysis System for Wind-induced Response

2.1 Development of Analysis System

At present, the system consists of aerodynamic loads obtained from high-frequency base balance (HFBB) tests on 36 rectangular section rigid models of high-rise buildings. As shown in Fig. 1, these models have a variety of side ratios and aspect ratios. In four kinds of wind fields, each of the models was tested at 16 wind angles, so that the total amount of data is up to 2304 sets in the system. High-frequency base balance test data or wind pressure measurement test data of rigid models with other figures, such as rounded rectangular section, chamfered rectangular section, recession rectangular section, triangle section, pentagon section, hexagon section, opened figure, et al, will be added into the database in the future.

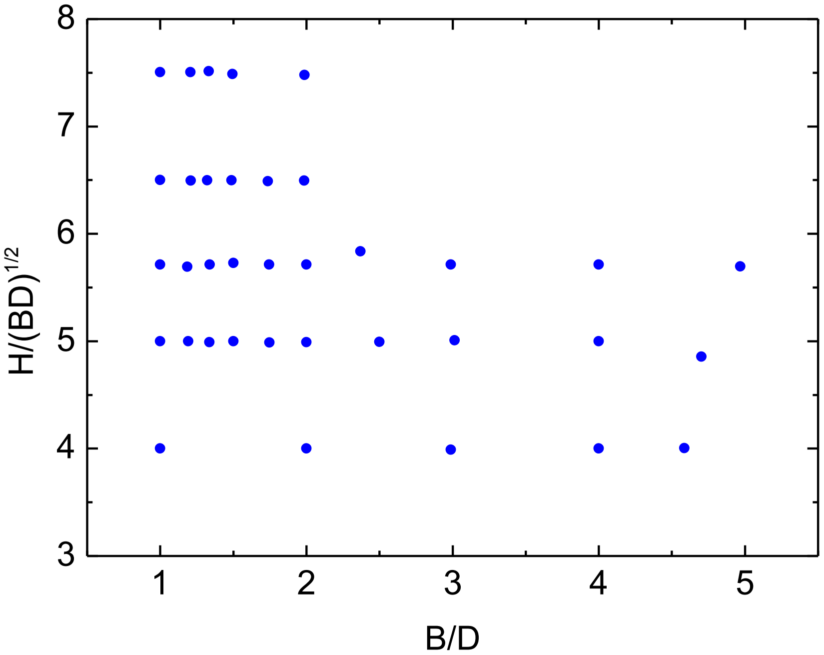

Figure 1. Model summary.

According to the location of the target building provided by the user, the system can call the exact values, which does not require user to enter, of the basic wind pressures in various regions of China for calculation. The basic wind pressures can be customized for these buildings that are not in China. Currently, the directionality of the basic wind pressures are not considered in load code of China[4], which has an effect on the accuracy of wind load. Thus, wind direction factors of 34 cities in China are collected in the system, which are calculated by Zhang method [5].

Detailed information with regards to dynamic properties of buildings such as mode shapes, natural frequencies is typically unavailable during the preliminary design stage. Some empirical equations of dynamic properties of buildings are collected, which are just related to the shape of buildings. The calculated values of equations will be recommended to the user as a reference. For example, the scopes of natural vibration periods, regard to translational and torsional directions, will be determined with Eqs. (1)–(4) proposed by Zhang [6], where T_{tra_max}、T_{tra_min}、T_{tor_max}、T_{tor_min} are the limits of recommend scopes in seconds, and H is the height of structure in meters (excluding top subsidiary structure).

$$T_{tra\_max}=0.015H+0.89 \tag{1}$$

$$T_{tra\_min}=0.0138H+0.52 \tag{2}$$

$$T_{tor\_max}=0.0061H+1.43 \tag{3}$$

$$T_{tor\_min}=0.0053H+0.81 \tag{4}$$

The mode shapes, regard to translational and torsional directions, will be determined by Eqs. (5)–(6) that are fitted by Liang et al [7], where ϕ_z、ϕ_θ are the mode coordinates of translational and torsional directions at height z, respectively.

$$\phi_z = \sin[\frac{\pi}{2}(\frac{z}{H})^{1.8}] \tag{5}$$

$$\phi_\theta = (z/H)^{0.8} \tag{6}$$

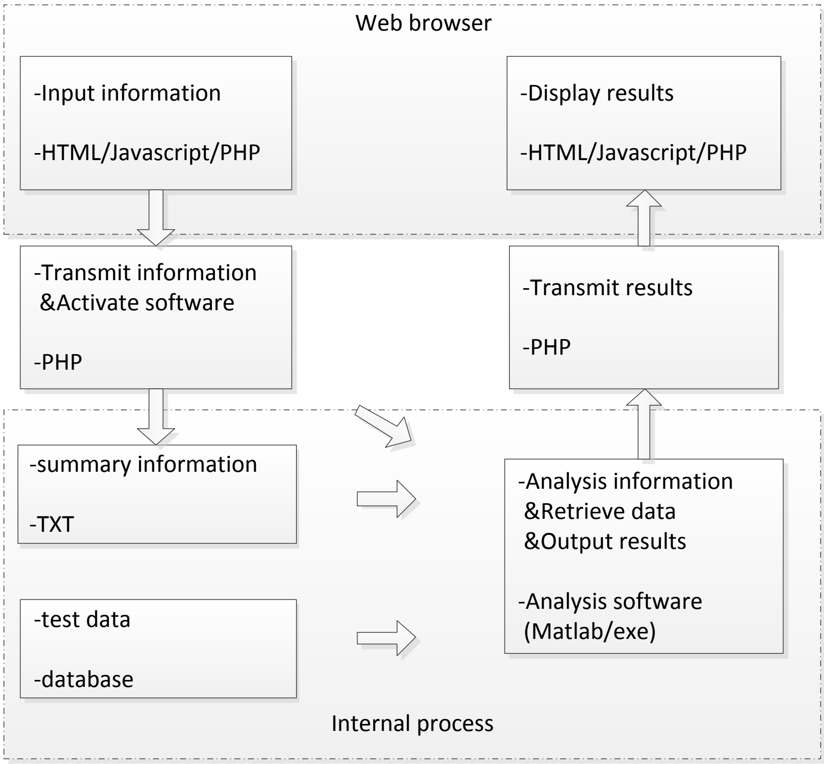

Figure 2. The framework of system.

Above all, time-histories data of base force (moment, shear and torque) coefficients in all test cases are stored in the system. Using these data, the mean and background wind loads on each floor of buildings will be obtained based on the assumption that the aerodynamic force coefficients of each floor are exponentially related with the height. Further, the resonance wind loads and acceleration will be obtained based on dynamic properties of structure and random vibration analysis.

A Matlab-based analysis software is developed to act as the background program, which uses above-mentioned scientific research results, the wind tunnel test data and the random vibration theory. A variety of computer languages such as HTML, JavaScript, and PHP are used to compile files, in order that information can be input from the browser and transmitted. The framework of the system and the role of various tools are summarized in Fig. 2.

2.2 The use of analysis system

With a concise and friendly interface, the user can complete wind-induced response analysis conveniently. As shown in Fig. 3, the process for estimating the preliminary design wind loads on a target building are divided into the four parts: information input, analysis results selection, confirmation of information, and acquisition of results. The user is required to input the wind environment, the shape, and dynamic properties of the target building in order to complete the part of information input. The part of analysis results selection consists of the selection of the desired analysis results and the desired model. After calculation, the analysis results will be displayed in the form of pictures and downloaded in the form of tables.

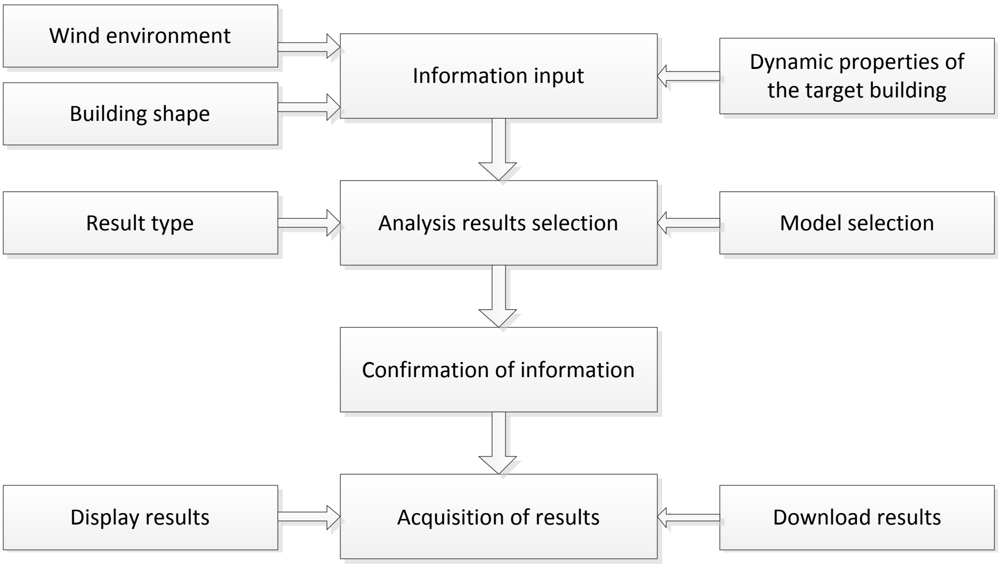

Figure 3. The process of system.

3. The wind-induced response prediction based on Neural Network

3.1 Introduction to Neural Network

Neural network is a kind of mathematical model, which processes information by imitating the brain structure of synaptic connections. Neural network can solve complex, multi-variable problems in the case of incomplete information, so it has been gradually applied to the wind engineering field.

Many scholars [8-10] have done researches on wind-induced interference effects of high-rise buildings using neural network. Gu and Zhou [11] proposed a method base on neural network, by which the wind pressure coefficient and the power spectrum of the unknown point on the large span roof can be predicted using limited wind tunnel test results.

3.2 Calculation of wind-induced response based on analysis system

In present paper, wind-induced responses of 36 high-rise buildings are calculated by the analysis system. All models are scaled up to the height of 200m in practice. The wind directions and body axes of model are illustrated briefly in Fig. 4, and each of the models is calculated at 16 wind angles. The dynamic properties of structures are as follows: layer mass density ρ=1500kg/m^2; damping ratio for wind load calculation ζ_{wl}=0.03; damping ratio for acceleration calculation ζ_a=0.02; number of stories n=50; inter story height ΔH=4m; natural frequencies are determined by median of Eqs. (1)–(4), f_x=0.281Hz; f_y=0.281Hz; f_θ=0.4561Hz; mode shapes for all three directions are determined by Eqs. (5)–(6). All models are assumed to be located in terrain category D of the Shanghai region, and their x-axes and y-axes face the south and east, respectively. Wind direction factors of design wind velocity are taken into account in each of the models, which are illustrated by Fig. 5 in detail.

The results of wind-induced responses include the base forces, the acceleration at the top of models and equivalent static wind loads with combination coefficients [12]. The base forces consist of the base shears, the base bending moments in two orthogonal directions and base torque at 16 wind angles. Accelerations of both translational directions, torsional acceleration at corners and their combined values are provided at 16 wind angles. Equivalent static wind loads corresponding to wind speed of 50-year return interval and 100-year return period are applied for strength and stiffness checking. In consideration of a small probability of wind loads on three directions reaching extreme values simultaneously, it is unreasonable to apply equivalent static wind load of all three directions on structure at the same time. Thus, 48 groups of combination coefficients for wind loads in three directions are provided to achieve security and improve economy.

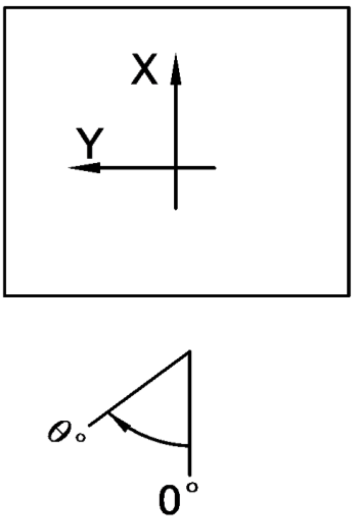

Figure 4. Cross section of model.

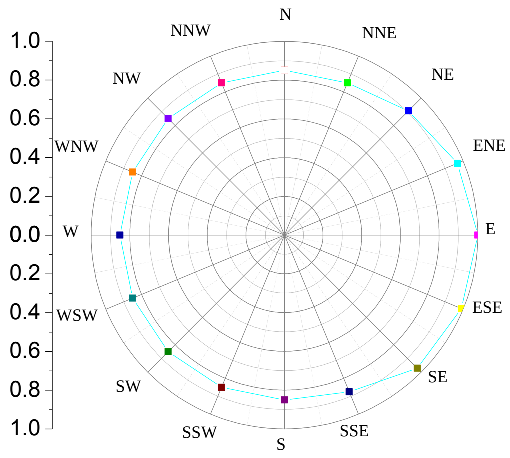

Figure 5. Wind direction factors in Shanghai.

3.3 Analysis of neural network predict results

Wind-induced responses of 17 high-rise buildings are selected as true values that are compared with predict results based on neural network. In the system, four similar models are picked up to predict wind-induced responses of the target building, so the common ground of 17 selected models is they are surrounded by four other models in Fig. 1. For example, as shown in Table 1, the “true” wind-induced responses of target building with a figure like model M1, which are calculated based on the wind tunnel test data of model M1, are compared with the results predicted by neural network method based on the test data of similar models M2-M5.

Table 1. Target model and similar models.

Model name	M1	M2	M3	M4	M5
Aspect ratio	5.7	5.7	5.7	6.5	5
Side ratio	1.2	1	1.35	1.2	1.2

Since the extreme values of various responses are concerned by designers in the preliminary stage of a high-rising building, the maximum and minimum values of all base forces and the maximum values of acceleration are compared. The comparison of the “true” values of wind-induced responses with the predict values is shown in Figs. 6–11. The values of all responses are the extreme values of all wind directions. As shown, most of the predict results are in the region for an error of fifteen percent. Not only the base shears and moments in two orthogonal directions are in the allowable error region, but also they agree well with the true values. Since high-rise buildings with rectangular cross section have good symmetry, which leads to a smaller torque, predict results of partial models are near boundaries of allowable error region. Acceleration of both translational direction and total acceleration are included in the Fig. 11. As shown, predict results of partial models are larger than true values, which are still not far from the boundaries of allowable error region. The conservative predict results can still be used in the preliminary design stage of high-rise buildings.

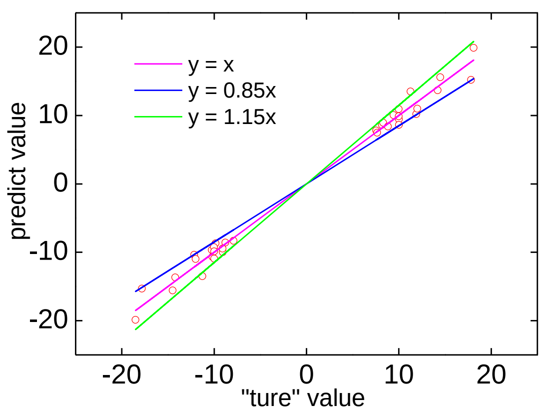

Figure 6. Shears along x-axis (10^3kN).

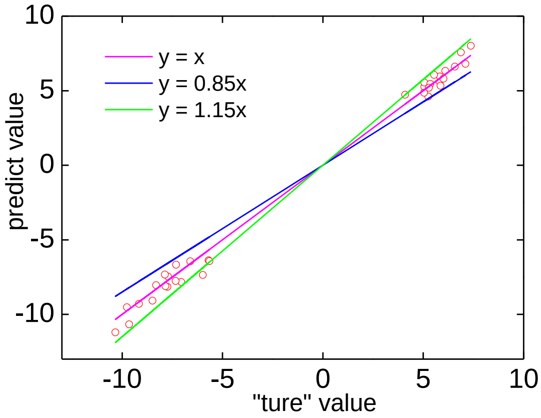

Figure 7. Shears along y-axis (10^3kN).

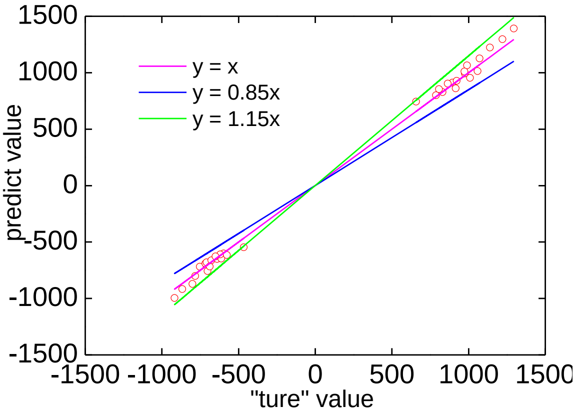

Figure 8. Moments along x-axis (10^3kN m).

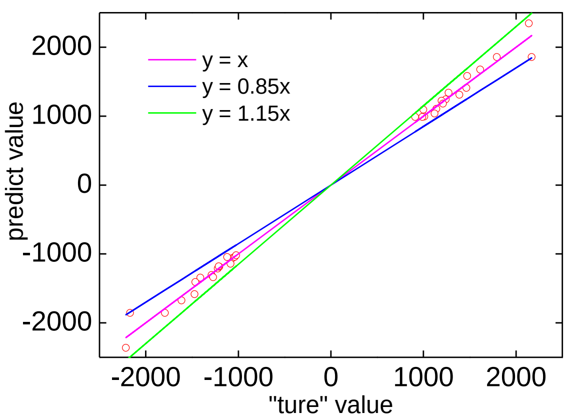

Figure 9. Moments along y-axis (10^3kN m).

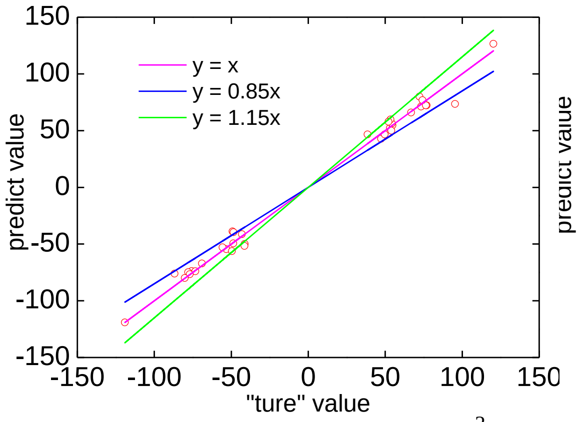

Figure 10. Torques along z-axis (10^3kN m).

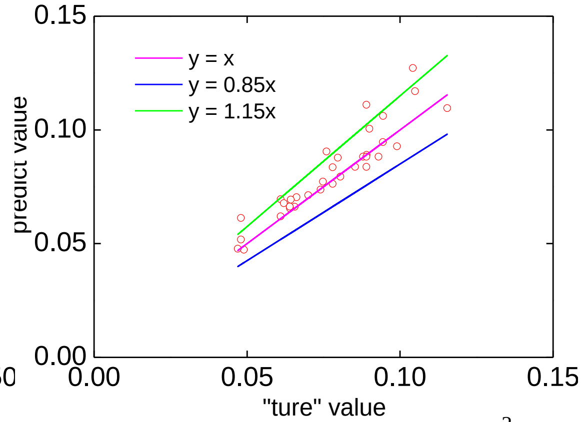

Figure 11. Accelerations (m/s^2).

4. Conclusions

An online analysis system for wind-induced response of high-rise buildings is introduced briefly. Wind-induced responses of several high-rise buildings are predicted based on neural network. The following conclusions are drawn.

(1) The system includes thousands of sets of wind tunnel test data and some research results in wind engineering, and it can help the user to obtain various wind load parameters, quickly and conveniently.

(2) The system can provide many kinds of analysis results, e.g. the base forces, accelerations at the top, equivalent static wind loads and their combination coefficients, for the preliminary design of high-rise buildings.

(3) The wind tunnel test data of models with figures like target buildings are used to predict the wind induced responses of the target building based on neural network. The predict results meet the accuracy requirements of the preliminary design stage of high-rise buildings.

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