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Field observations on modal properties of two tall buildings under strong wind

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ABSTRACT

This paper presents observations on the identified modal properties of two tall buildings using ambient vibration data collected during strong wind events. A recently developed fast Bayesian frequency domain method is used for modal identification based on the measured ambient data. The approach views modal identification as an inference problem where probability is used as a measure for the relative plausibility of outcomes given a model of the structure and measured data. Focusing on the first three modes, the modal properties of the buildings are identified on non-overlapping time windows during the strong wind events, spanning periods of normal to high wind speeds. Investigation of the identified natural frequencies and damping ratios versus the modal root-mean-square value indicates a significant trend that is statistically repeatable across events.

1. Introduction

The characterization of dynamic properties of structures is essential for assessing their response subjected to dynamic loads such as due to earthquakes and strong winds. For tall buildings subjected to strong winds where the vibration is still in the linear-elastic regime by design, the dynamic characteristics consist of the modal properties, namely the natural frequencies, damping ratios, mode shapes and modal masses. At the design stage, the natural frequencies, mode shapes and modal masses can be estimated using a finite element model that incorporates the structural information regarding the geometry, structural members and mass distribution. Modern computing facilities have made very detailed finite element analysis possible (Hughes, 1987; Bathe, 1982). Nevertheless, when information about macroscopic behavior suffices, buildings are practically modeled with traditional idealization in terms of beams, columns, shear wall elements, with rigid floor assumption where applicable. Such models are not necessarily inferior to more detailed ones, because their simplicity allows sound modeling judgment and checking to be made by structural engineers during the modeling phase. On the other hand, there is currently no formal method for predicting damping values, apart from empirical regression formulas (Davenport and Hill-Carroll, 1986; Kareem and Gurley, 1996; Jeary, 1997; Satake et al., 2003).

The actual dynamic properties of buildings are often obtained by taking in-situ vibration measurements. Due to the large magnitude of force required to excite the building artificially, ambient vibration (output-only) tests (Ivanovic et al., 2000; Doebling et al., 1996; Peeters and De Roeck, 2001; Au and Zhang, in press) are often used where the vibration measurement (mostly acceleration) is recorded when the building is subjected to unknown environmental loads such as wind and ground borne vibration. Among other methods, random decrement technique has been used in the wind engineering field (Jeary, 1986; Tamura and Suganuma, 1996; Tamura et al., 1993, 1994), whose theory is essentially single-degree-of-freedom in nature. Studies on the modal properties of buildings over a wide range of amplitudes (e.g., Fukuwa et al., 1996) reveal that non-structural members play an important role when response amplitude is small. With an increasing number of tall buildings constructed around the world, their in-situ modal properties under strong winds become a timely subject of interest (Ni et al., 2011a, b; Fu et al., 2008; Li et al., 2008). In this regard, for the study of amplitude dependence from noisy field data, it is necessary to delineate real systematic trend from spurious noise effects arising from, e.g., identification error, modeling error, etc.

This paper presents observations on the identified modal properties from ambient acceleration data of two tall buildings in Hong Kong during typhoon and monsoon events. Modal identification is performed using a recently developed fast Bayesian frequency

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domain method (Au, 2011; Au, 2012a, b), whose theory will be briefly outlined. In addition to the most probable value, the method also yields the posterior uncertainty of modal parameters in the presence of data. It also allows the spectral density of modal wind load to be identified, which allows a scientific quantification of the dynamic response level in terms of the modal root-mean-square value. The amplitude dependence that may potentially be present in the natural frequency and damping ratio are investigated. The instrumented buildings are described first, followed by the strong wind events where vibration data were recorded. The method used for identifying the modal properties from ambient field data is then presented and observations on amplitude dependence are investigated.

2. Instrumented buildings

Two tall buildings, namely, Building A and B, are studied in this work. Building A is 310 m tall, 50 m by 50 m in plan. It is a tubular concrete building with a central core wall system. Building B is 320 m tall, 50 m by 50 m in plan. Lateral structural resistance is provided by two outrigger trusses at roughly one-third and two-third of the building height, with core walls near the center and mega columns at the corners. Fig. 1 and 2 show the modal directions of the first three modes of Building A and B, respectively. They were identified based on ambient data with four triaxial accelerometers placed at four corners on the roof under normal wind conditions, e.g., with wind speed below 20 km/h. The prefixes 'TX', 'TY', 'R' stand for *x*-, *y*- and torsional modes of the buildings. The numbers next to the mode label indicate the natural frequency and damping ratio. It should be noted that for Building B the principal modal directions do not align with the building sides, due to connection to a neighboring building (not shown).

For prolonged vibration recording during a strong wind event (typhoon or monsoon wind), the equipment deployed (Fig. 3) consists of a triaxial force balanced accelerometer (noise floor about 0.5 $\mu g/\sqrt{\text{Hz}}$) paired with a 24 bit digital signal recorder. Data was logged at a sampling rate of 50 Hz on a compact flash card. For each building, the sensor was placed at the same location in all strong wind events, in a secure room on the roof of the building. For typhoon events the equipment was deployed to the building site on the day when typhoon signal T1 was issued, usually in the summer. The latter is a stand-by signal indicating a tropical cyclone centering within 800 km of Hong Kong and may affect the territory. The procedure was similar when a monsoon wind signal was issued, usually in the autumn or winter.

3. Strong wind events and data

The vibration data investigated in this study were measured during two monsoon events and two typhoon events, namely, Typhoon Goni and Koppu. Table 1 summarizes the duration of data obtained in different events. Fig. 4–7 give an overview of the wind condition and magnitude of the recorded vibration data in different events. The wind speed and direction are 10-min average recorded at the Hong Kong Observation (HKO) Waglan Island station (22°10′56″N,114°18′12″E, equivalent wind speed at 90 m altitude). Building A and B are located in the northwest of the Waglan Island station at a distance of 15 km and 30 km, respectively. The bottom one or two plots show the acceleration time history of the building(s) measured during the event. Only the data in the sensor *x* direction is plotted as the plot for the sensor y direction is similar. The vertical vibration is of little relevance.

Typhoon Goni visited Hong Kong during 4–6 Aug 2009, traveling from South–East of Hong Kong at a speed of 9 km/h. As seen in Fig. 4, the wind speed ranged between 22 km/h and 60 km/h; and there was not much change in the wind direction. One month after Typhoon Goni, Typhoon Koppu visited Hong Kong. Koppu traveled faster than Goni, at a speed of 20 km/hr. It landed Hong Kong at about 11 am on 14 Sep 2009. As seen in Fig. 5, the wind speed ranged between 25 km/h to 120 km/h and its direction between North–East to South. Note that as the wind load (both mean wind and stochastic part) generally scales at least with the square of wind velocity, an order of magnitude increase in the structural response can be expected from normal

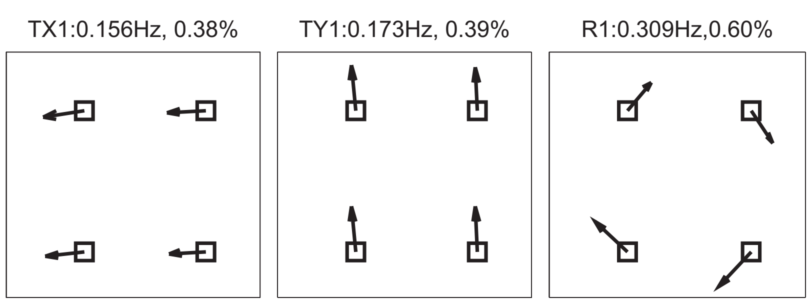

Fig. 1. Identified modes of Building A identified under normal wind; figure top shows the mode nature, natural frequency (Hz) and damping ratio (%).

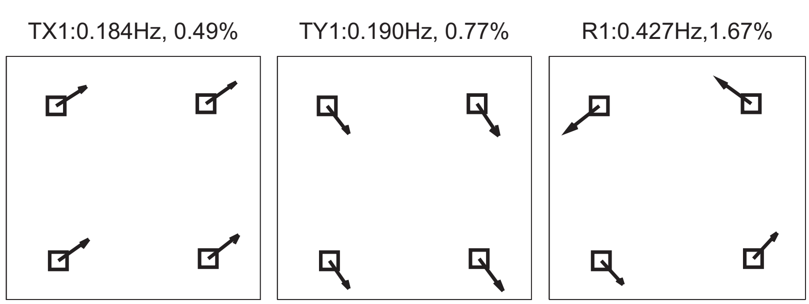

Fig. 2. Identified modes of Building B identified under normal wind; Fig. top shows the mode nature, natural frequency (Hz) and damping ratio (%).