Tall Building during Typhoon Kammuri Using GPS

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1. Introduction

The high land prices in Hong Kong have led to an increasing number of tall and super tall buildings built in the city. On the other hand, Hong Kong is prone to tropical cyclones and typhoons. It is therefore vital to verify the full-scale dynamic performances of tall buildings under extreme wind loading conditions by comparing with the original design criteria, computational modeling and wind tunnel model testing, to determine the serviceability conditions of the buildings and to improve future building designs. In pursuit of these goals, The CLP Power Wind/Wave Tunnel Facility at The Hong Kong University of Science and Technology has implemented measurement programmes for both research and consulting projects on numerous tall buildings since 2002 [1~2].

Field measurement of wind-induced response characteristics of tall building is traditionally accomplished using accelerometers. Although accelerometers are useful in determining the dynamic properties and/or wind-induced resonant type responses of tall buildings, they are unable to resolve the global displacements of the structure, including static, quasi-static and dynamic components, which are especially of interest for structures under wind excitation. GPS, as a space observation technique in geomatics, can directly provide total displacements along two perpendicular axes, as well as in the vertical direction [3]. Over the last decade, with the improvements in both accuracy and sampling capability, GPS instrumentation has been applied increasingly for monitoring the response of tall buildings to wind [4]. This paper presents results from an ongoing research program on monitoring a tall building under typhoon conditions. The main objectives of the research are to validate the GPS results and to characterize the building's static, quasi-static and resonant responses under wind excitations.

2. Field Measurement Program Setup

The test building is located within an urban environment. It is a reinforced concrete (RC) building, with a plan area of about 80 m × 19 m, and its height is about 260 m. Two sets of orthogonally aligned Honeywell QA-650 accelerometers was instrumented on the upper floor of the building to capture both the sway and torsional responses to wind, which were used to record accelerations at a sampling frequency of 20 Hz. A Topcon CR-3 choke ring antenna has been installed together with a Topcon GB-1000 receiver at the northwest corner of the test building roof, which formed a baseline of approximately 850 m with another GPS reference station placed on top of a remote low-rise building, to measure the dynamic structural displacements, Both GPS receivers collected data at 10 Hz. An ultrasonic anemometer has also been installed at the same level to measure wind speed and direction. The test building and instrument locations are illustrated in Figure 1.

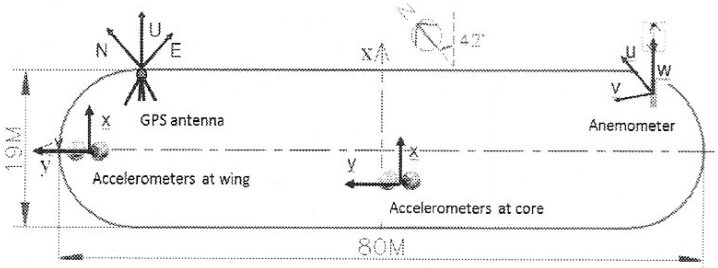

Figure 1: Test building plan and sensor orientation

3. Typhoon Kammuri

Typhoon Kammuri was the second tropical cyclone that necessitated the issuance of the No. 8 warning signal in Hong Kong in 2008. It affected the weather of Hong Kong most severely from August 5 to August 7, 2008. The path of the typhoon's eye can be observed in Figure 2 [4]. Anemometer data from the test building recorded during Typhoon Kammuri were used to calculate 10-minute mean wind speeds, which are presented in Figure 3a. The maximum 10-minute mean wind speed was 14.6 m/s measured at 9:30 on August 6. The 10-minute mean wind directions for Typhoon Kammuri were also calculated and are included in Figure 3b. The dominant wind direction of Typhoon Kammuri tended to be between 30° and 180° from August 5 to 7. This is consistent with the eye of Typhoon Kammuri passing to the south of Hong Kong.

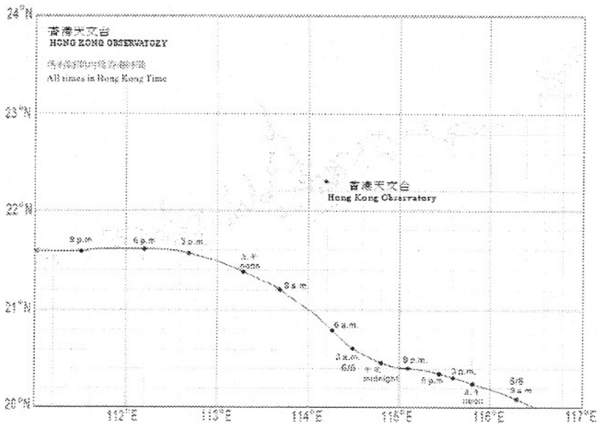

Figure 2: Track of Typhoon Kammuri near Hong Kong (After Hong Kong Observatory)

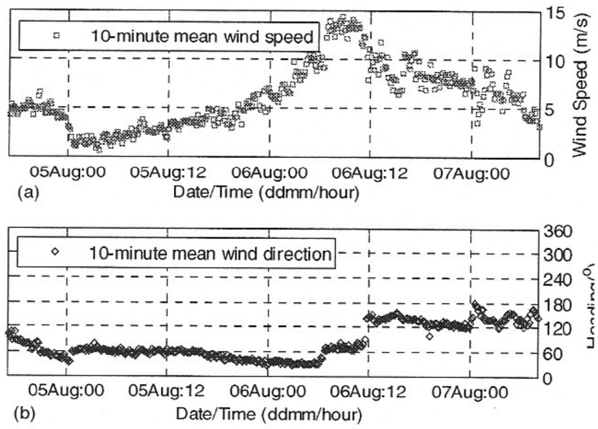

Figure 3: Measured 10-minute mean wind speed and wind direction during Typhoon Kammuri

4. Wind-induced Response Characteristics of the Test Building

The frequency content of one-hour acceleration and displacement time histories, which were measured by accelerometer and GPS separately, were determined By Fast Fourier Transform, as shown in Figure 4. According to the acceleration spectra, the following natural frequencies were identified: 0.21 Hz and 0.34 Hz, that are predominantly translation modes, and 0.44 Hz, that is predominantly a torsion mode. The alignment of the pair of accelerometers located at the building wing were responsive to the first three modes whereas the pair of accelerometers located at the building core mainly detected either the first mode or the second mode of vibration that are essentially orthogonal modes with predominant components along the X axis and Y axis respectively. The difference between the orthogonal natural frequencies is attributed to the different stiffness in the X and Y directions associated with the building shape. Comparing the acceleration and displacement spectra, it can be seen that the first three mode natural frequencies of the building can be identified from the GPS record. The spectral energy determined from the GPS displacement exhibited elevated levels of variance over the acceleration spectra and it was almost constant at the high frequency side-band of the natural frequency, which is attributed to static and quasi-static displacement of the building and the background noise of GPS. This finding is consistent with the complex nature of GPS technology.

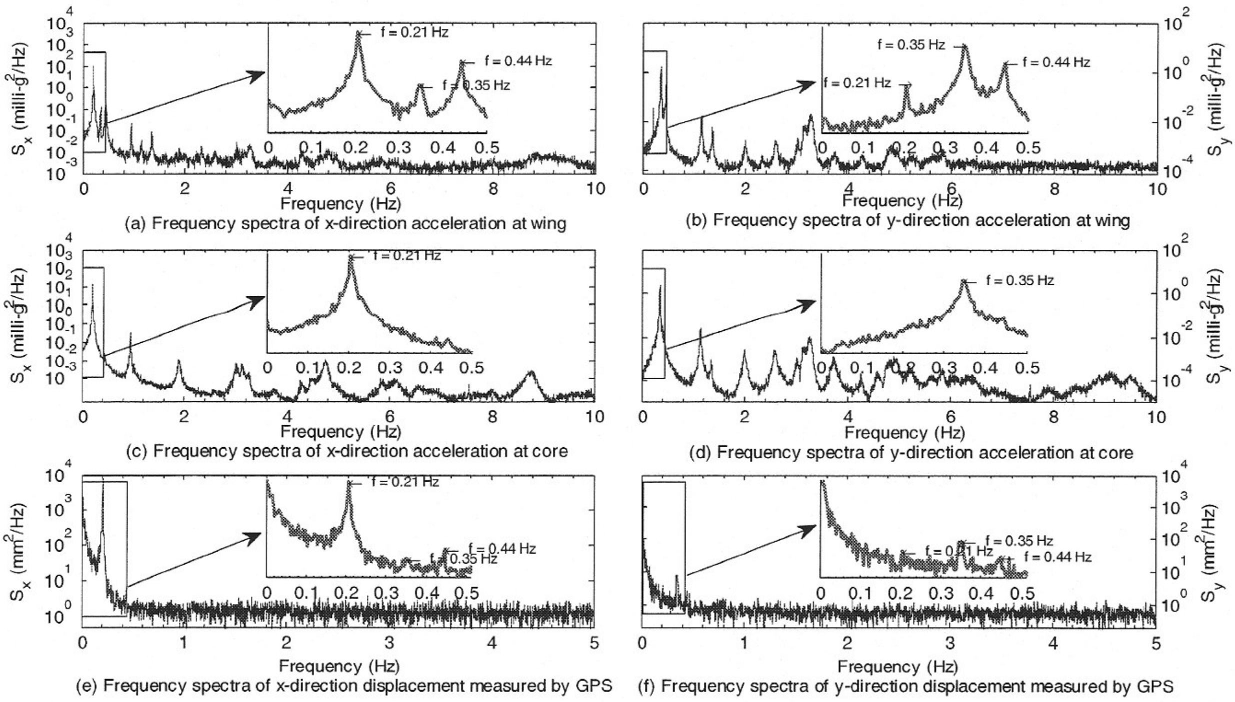

Figure 4: Frequency spectra measured by accelerometers and GPS

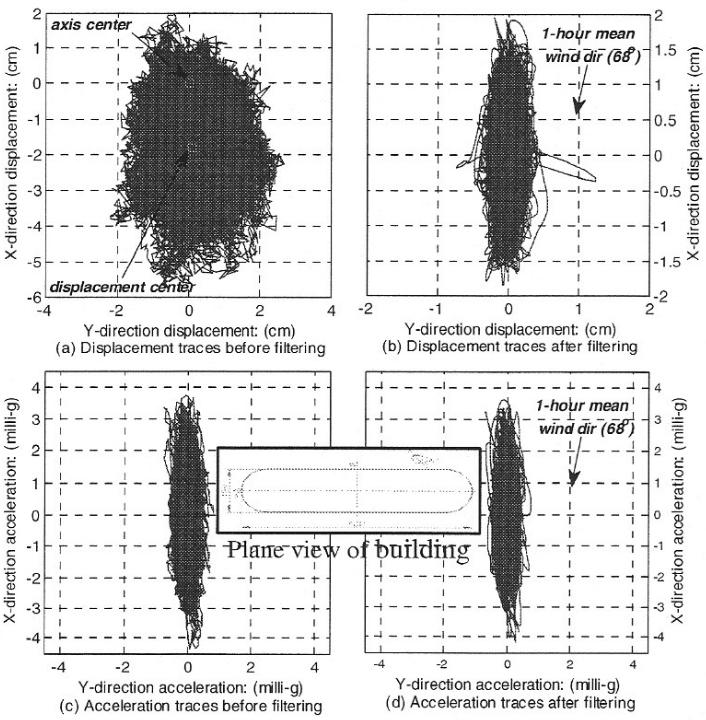

Figure 5: Representative 1-hour measured displacement and acceleration traces before and after filtering

Figure 5 presents GPS-measured displacement and accelerometer-measured acceleration traces for one representative hour of the Typhoon Kammuri before and after digital filtering. It is observed from Figure 5a that the locus of the displacement traces before filtering has a bias of approximately -20 mm in the X direction. This bias reflects the static displacement caused by the mean wind, as is observed from the arrow representing the hourly mean wind direction. Through the application of a 0.1~1 Hz band-pass digital filter to capture the contributions from the first three modes and to remove noise, the GPS displacement trace exhibits a response shape that is similar to the acceleration trace measured from accelerometers. Furthermore, and as expected, it is also clear that the largest components of response were aligned with the alongwind direction corresponding to the prevailing wind direction.

Displacement and acceleration response measured in the X direction for 24 hours during Typhoon Kammuri and the

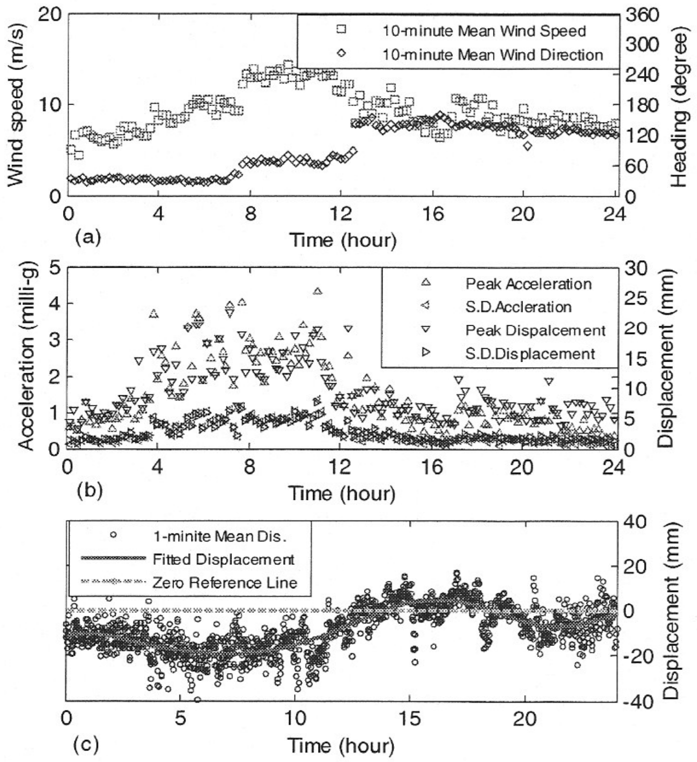

Figure 6: 24-hour measured displacement and acceleration during Typhoon Kammuri

corresponding 10-minute mean wind speed and wind direction are presented in Figure 6. Resonant displacement (Figure 6b) extracted from the GPS signal were well correlated with acceleration and generally increased with increasing wind speeds. By subtracting wind-induced resonant responses and multipath effects from the total displacement, the quasi-static displacement of the building can be captured, as shown in Figure 6c. A general trend of increasing displacement with increasing wind speed is also observed. Discrepancies between the quasi-static displacement and the wind speed are believed to be caused primarily by changes in wind direction illustrated in Figure 6a.

One-hour acceleration and displacement time-histories that contain the measured peak value were band-pass filtered over the range of 0.1 to 0.25 Hz to capture the first mode response, as shown in Figure 7. The GPS resonant displacement was also compared with accelerometer data by double-differentiating the displacements with respect to time. It can be observed from Figure 7 that acceleration determined from the GPS displacement are very similar to accelerations measured by accelerometer. This is more evident in the magnified 150 s windows in Figures 7b, 7e and 7h. The damping for the first mode of the building was also estimated by the random decrement technique (RDT). Figures 7c, 7f and 7i show the random decrement signatures, from which damping ratios are estimated using the logarithmic decrement method: 0.78% from the measured acceleration, 0.73% from the GPS displacement, and 0.76% from the GPS-derived acceleration.

5. Conclusions

Data captured during the passing of Typhoon Kammuri by an integrated field measurement system installed on a RC tall building have been used to study how GPS and accelerometer sensors perform relative to each other, and in particular the global displacements of the structure provided by GPS measurements. Analysis results showed that the resonant response obtained from both GPS and accelerometers agree well with each other in both the time and frequency domains. The damping values for the first mode extracted from the displacement and acceleration signals also agree well. By spectral analysis of the measured time series of accelerations and displacements, the natural frequencies were found to be 0.21 Hz for the X direction and 0.35 Hz for the Y direction, with a first torsional frequency of 0.44 Hz. After removing resonant displacement and multipath signals, a 24-hours quasi-static displacement time history along the X axis followed the general trend of the magnitude of the 10-minute mean value of wind speed, and a peak displacement during Typhoon Kammuri, attributable to quasi-static response, was estimated at 40 mm. Results from this paper demonstrated the applicability and performance of GPS for measuring wind-induced displacement response of tall buildings, including static, quasi-static and resonant components.

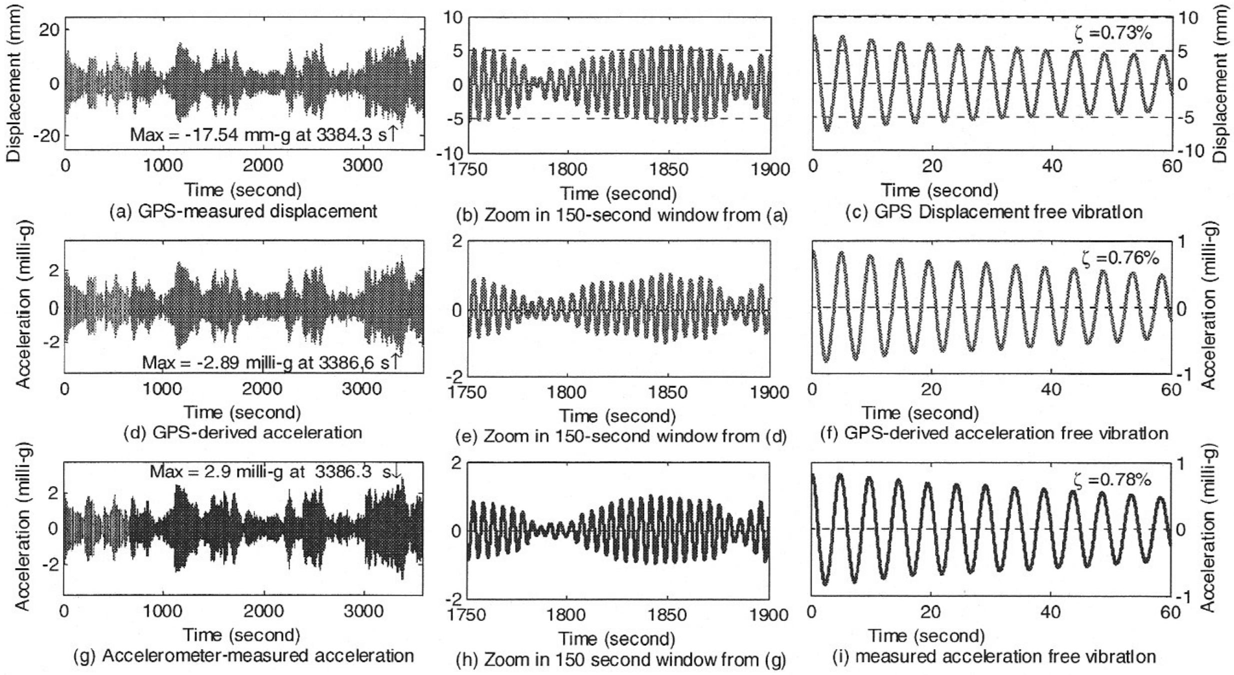

Figure 7: Comparisons between GPS-measured displacement, GPS-derived acceleration and accelerometer-measured acceleration for the first mode in time history and RD signature

6. Acknowledgements

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7. References

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