GPS IN DYNAMIC MONITORING OF LONG-PERIOD STRUCTURES

Mehmet CELEBI[1]

SUMMARY

Global Positioning System (GPS) technology with high sampling rates (~10 sps) allows scientifically justified and economically feasible dynamic measurements of relative displacements of long-period structures --- otherwise difficult to measure directly by other means, such as the most commonly used accelerometers that require post-processing including double integration. We describe an experiment whereby the displacement responses of a simulated tall building are measured clearly and accurately in real-time. Such measurements can be used to assess average drift ratios and changes in dynamic characteristics, and therefore can be used by engineers and building owners or managers to assess the building performance during extreme motions caused by earthquakes and strong winds. By establishing threshold displacements or drift ratios and identifying changing dynamic characteristics, procedures can be developed to use such information to secure public safety and/or take steps to improve the performance of the building. An actual installation on a 44-story building, the first such deployment in the world, is described.

INTRODUCTION

Seismic monitoring of structural systems constitutes an integral part of National Earthquake Hazard Reduction Program of the United States. In general, until recently, monitoring the response of structural systems for the purpose of assessing and mitigating effects of earthquakes (and also severe winds) has relied on measuring the shaking response by deploying accelerometers throughout a particular structure of interest to the scientific and engineering communities. In contrast, there are no efficient or feasible methods to measure displacements during seismic events or severe winds.

Since the Ms=6.7 Northridge (17 January 1994) and Ms=6.8 Kobe (17 January 1995) earthquakes, drift studies and assessment of susceptibility to damage of tall buildings have become important issues, particularly because so many steel-framed buildings were damaged, some severely and some lightly. In the Los Angeles area, for example, following the Northridge event, several hundred steel-framed buildings had to be examined, assessed, and repaired or retrofitted. Only three of these buildings were instrumented prior to the event, providing some limited acceleration response data to be used for interpretation of the widespread damage. Additional data, if available in real-time or near-real-time, could have been very useful for studies and for design of repair and retrofitting projects that followed. Therefore, there is a great need for better and more extensive monitoring of tall buildings.

Relative displacements, which are key to assessing drift and stress conditions of structures, are difficult to measure directly. On the other hand, measuring acceleration response requires a double integration process to arrive at displacements which is not readily automated because of the nature of signal processing that requires (a) selection of filters and baseline correction (the constants of integration), and (b) often substantial judgment when anomalies exist in the records. Consequently, this process can lead to errors in the calculation of velocities and displacements. This problem is more acute for permanent displacements. Accelerometer measurements

[1]   *U.S. Geological survey, 345 Middlefield Road, Menlo Park CA. 94025, USA, (email: celebi@usgs,gov)*

cannot be used to recover the permanent displacements at the centimeter level; and even if they could, it is questionable if it can be done in real-time. That is, the level of accuracy of displacements calculated from accelerations has not been widely verified by observations (e.g., some shake table tests performed to compare the performances of accelerometers and accelerographs have not been directed at checking displacements).

An alternative method to measure relative displacements while monitoring structural systems can be accomplished by using GPS technology, now advanced to record, in real-time and at 10 sps with an accuracy of ± 1 cm horizontally and ± 2cm vertically. This provides a great opportunity to monitor long-period structures reliably (e.g., tall buildings that are 20-40 stories or more). The majority of the tall buildings are flexible steel-framed structures, the fundamental period of which can be estimated with the empirical formula[1] , T = 0.1 N, where N is the number of stories of the building. This means that at least 20-40 data points will be recorded for one cycle of motion of a 20-40 story building vibrating at the fundamental period. This provides sufficient accuracy to assess the average drift ratio of a building. Such information can be very useful in assessing the damage to a building. Thus, there is great potential for the application of GPS technology to monitor long-period structures during earthquakes.

TECHNICAL JUSTIFICATION

In the last few years, there have been numerous studies related to the technical feasibility of using GPS to measure displacements of civil structures. Studies related to the application of GPS for static or dynamic measurements of displacements of structural systems include but not limited to those by Hyzak and others (1997), Teague and others (1995), Guo and Ge (1997), Kondo and Cannon (1995), Lovse and others (1995), Hudnut and Behr (1998), Behr, Hudnut and King (1998) and Stein and others (1997). In our study, we direct the efforts to actual permanent deployment of GPS units for dynamic measurements alongside accelerometers, and also to use the displacement measurements with GPS as a health monitoring tool.

Model Tests Simulating A Tall Building

Figure 1 depicts a photo and the overall set-up for a simple experiment to simulate a 30-40 story flexible building to investigate the feasibility of using GPS technology to monitor tall buildings. The length, thickness, and width of the two bar specimens were selected to yield fundamental periods of approximately four seconds in the weak direction. The width was varied to show the sensitivity of measurements during vibration and at 10 Hz sampling rate. Each bar was fixed at the base and the GPS unit was attached at its tip. By providing an initial displacement, each bar was set to free vibration and its motion was recorded. Results are summarized in Table 1. Figure 2 shows the particle motion and time-history of one of the tests performed. The axes of the bar were at an angle to the NS (and EW) direction. Therefore, the NS and EW components of displacements are identical in phase and proportional in amplitude. Also, since the GPS unit is not symmetrically and concentrically mounted in the weak direction (photo in Figure 1), the amplitudes of positive and negative displacements measured are not the same. The detection of the effect of the eccentric mass adds to the assurance that the measurements are accurate and sensitive. These simple tests and results were and can be duplicated easily and readily.

Table 1. Results of Tests with GPS Units

BAR	Height	Width	Thickness	Measured		Damping
	H (m)	B (cm)	t(cm)	Freq. [f(Hz)]	Period [T(s)]	[ξ](%)
A	1.82	3.8	0.32	0.245	4.08	~ 2.0
B	1.82	5.0	0.32	0.296	3.38	~ 2.0

[1] For most flexible buildings, the fundamental period (T) is approximated by 0.1N, where N is the number of floors of a building (even though the fundamental period can vary between [0.05-0.15]N depending on the flexibility of the building). Therefore, to simulate a 40-story building, we set the period (frequency) equal to 4 s (0.25 Hz) and proportioned the length, width and thickness of the cantilever.
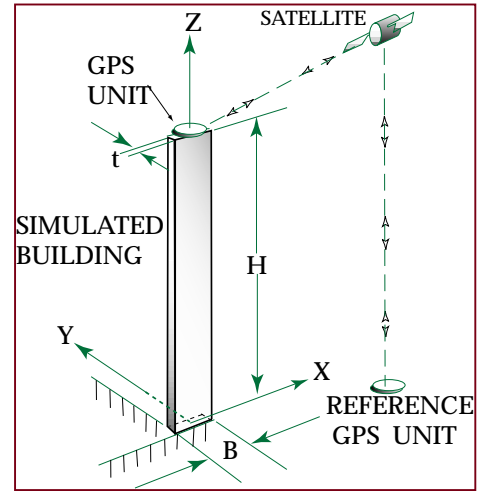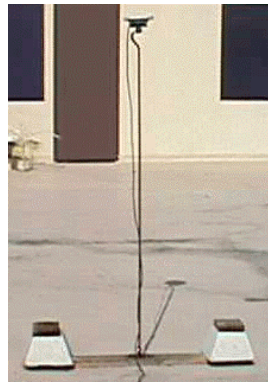
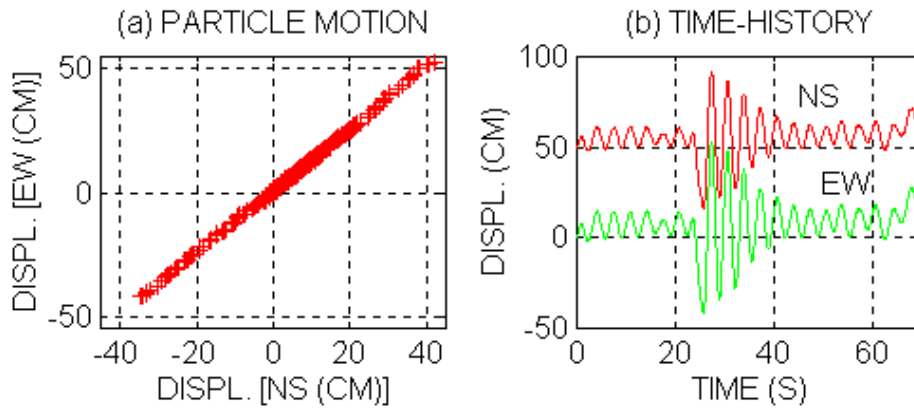**Figure 1. Photo and schematic of test set-up for using GPS for dynamic monitoring of tall buildings.**

Figure 2. Particle motion and time-history of relative displacements (NS and EW components) of simulated test specimen.
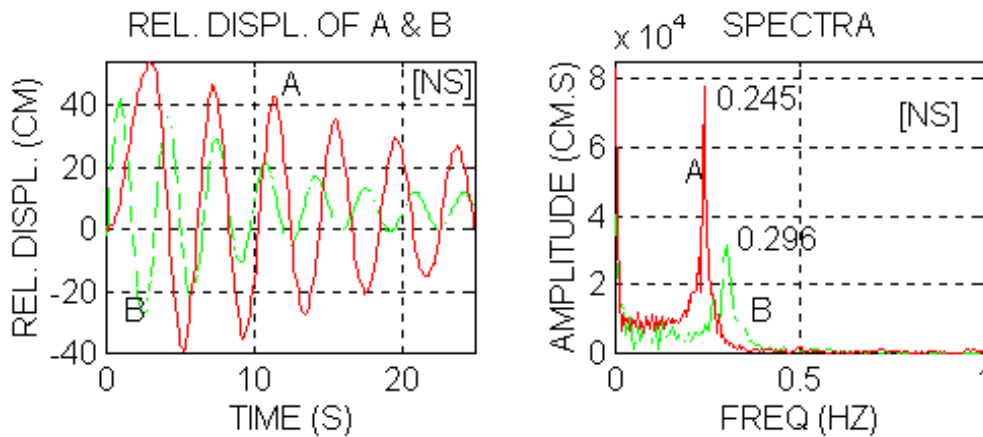

Figure 3. Relative displacements of two test specimens (NS components only) in free-vibration and corresponding amplitude spectra identifying the fundamental frequencies of the test specimens.

Figure 3 is a plot of NS components of measured relative displacements and corresponding amplitude spectra of Bars A and B. The figure shows the accuracy and sensitivity of the GPS monitoring technology at ten samples/second. The measurements differentiate between the frequency of the free-vibration response of the two

bars with different dynamic characteristics. From the data, the fundamental frequency (period) of the two bars are identified to be 0.245 Hz (4.08 s) and 0.296 Hz (3.38 s) respectively. Also, a damping percentage of approximately 2% is extracted. This simple test shows that sampling at 10 Hz with GPS units provides a clear and accurate displacement response history from which drift ratios and dynamic characteristics of the specimen can be derived (Çelebi et al., 1997, 1999 and Çelebi, 1998). The implications of this go beyond just the measurements. It can be shown that identification of variation of dynamic characteristics can be used to identify not only different structural systems, but also possible nonlinearities that occur during vibration (e.g., due to damage and plastic behavior of the structural members, components and/or joints, or to soil-structure interaction under varying amplitudes of input motions).

REAL-TIME MONITORING

Perceived Real-Time Monitoring

Initially, we are planning to deploy the GPS units only on tall buildings that are already instrumented with accelerometers. This will facilitate comparison of absolute and relative displacements measured by GPS and calculated by double integration of accelerations. The GPS units will be configured to provide data to indicate the real-time average drift ratios and changes in the dynamic characteristics of the buildings. This information can be made available to building managers (or interested parties) in real-time or whenever a predetermined displacement threshold is reached. The building managers can assess the response of the buildings according to (a) different threshold displacements (e.g., A, B and C as shown in Figure 4), (b) drift ratios, or (c) changing dynamic characteristics. If a situation is serious, the management can make decisions to evacuate the building for additional inspection. Therefore, one by-product of the effort would be to secure the safety of the occupants and significant contents of the building. Thus, a real-time structural health monitoring environment will be created. At least three GPS units per building are required to monitor a tall building: two of the units should be deployed on the roof to detect translational and torsional response of the building, and the third unit will serve as a reference ground station to evaluate relative displacement. The ground site also needs excellent sky visibility.
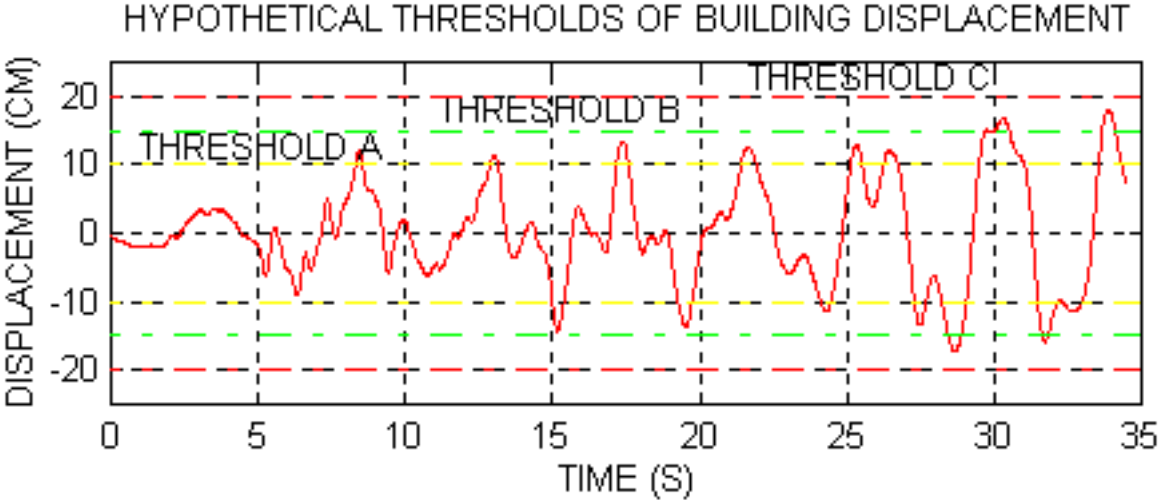

Figure 4. Hypothetical thresholds of displacements. The time-history of displacements shown is actually integrated from accelerations recorded at the 38th floor (accepted in lieu of roof) of a 44-story building. The actual record is amplified by 20 times for illustration purposes.
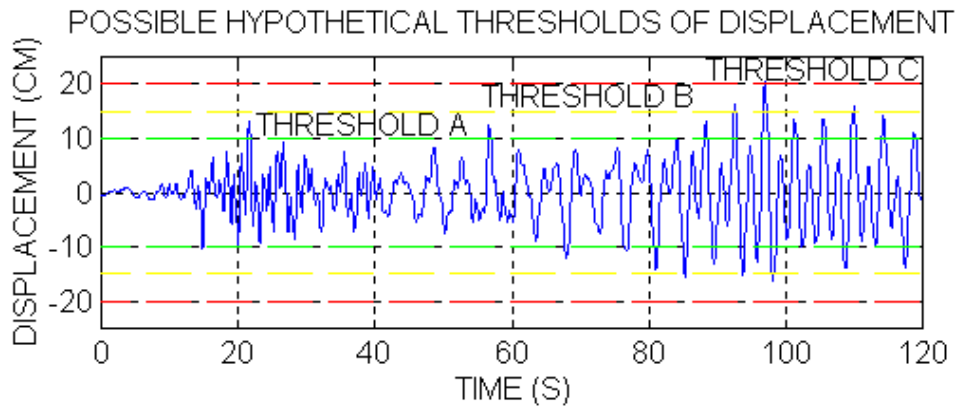
Figure 5. Hypothetical thresholds for displacement (from double-integration of recorded acceleration) of channel 21 (vertical at mid side-span) of Vincent Thomas Bridge (1994 [M=6.7] Northridge earthquake).

Similar deployments are being planned for other types of long-period structures. One project in development at this time is for deploying GPS units on one of the long-period suspension bridges such as the Golden Gate Bridge and Bay Bridge (San Francisco) or Vincent-Thomas Bridge (Los Angeles). As in the case of tall buildings, changes in dynamic characteristics after the displacements at critical locations of a bridge have exceeded predetermined thresholds, can be calculated in near-real-time (Figure 5). When warranted, the management can make decisions to inspect the bridge (e.g., decisions can be made to stop the traffic, thus securing the bridge safety, which is one of the objectives of lifeline earthquake engineering). With the GPS technology, we can furnish time-dependent displacements for the relative movements of critical locations of structures. For example, for the bridges, GPS units placed at pre-selected locations of bridge elements can indicate, in real-time, the amplitude of the displacements of the decks and towers, as well as movements of key bridge elements relative to local bedrock reference points. Thus, movements of the piers relative to the abutments, the top of a tower with respect to its base, or the span with respect to the ground, can be made at a centimeter-level of precision, in real-time. We will recover both the dynamic motions that accompany the earthquake, as well as the static or permanent displacements experienced by the bridge once the shaking has stopped. Such permanent displacements affect the state of stress of a bridge, and provide evidence for distortion or failure of bridge elements or subsidence of piers due to ground compaction induced by earthquake shaking.

Current Deployments on Tall Buildings

Deployment of GPS units on the roof of two buildings in Los Angeles has been completed, and we are in the process of deploying GPS units on the roof of a building in San Francisco. Figure 6 shows the actual deployment on the roof of one of the buildings in Los Angeles. As it happens with field deployments, physical obstacles and constraints necessitate alternate approaches. In this case, the window cleaner machinery on the roof of the 44-story building travels on rails near the parapet and uses the parapet continuously. Therefore, any deployment had to be planned away from the parapet wall. To solve this problem, a stiff auxiliary support frame (Figure 6) was erected. The figure also shows the GPS antenna and the radio antenna to communicate with the reference station so that differential displacements are obtained.

Requisite Software

Requisite software is being developed to assess and mitigate the two natural hazards (earthquake and severe wind) affecting the structures by using the displacements measured by the GPS units. Figure 7 shows a screen image of software being developed to assess displacements observed with GPS and provide alarm (warning). Such collected information on the response of the structure during strong motion events (or strong winds) can be used to make decisions for further evaluation of the susceptibility to damage of the structure, and future repair/retrofit schemes may be developed.

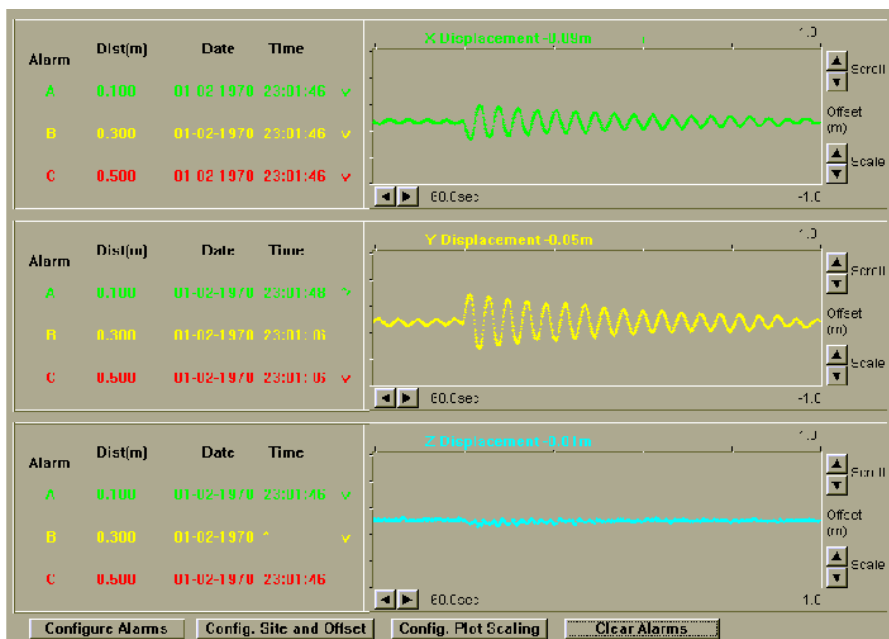**Figure 6. Deployed GPS Unit and Necessary Frame System**

Figure 7. Software developed to provide alarms at three thresholds of displacement of an instrumented structures with GPS.

Benefits and Other Applications

- The collected information on the response of the structure during strong-motion events (or strong winds) can be used to make decisions for further evaluation of the susceptibility to damage of the structure, and future repair/retrofit schemes may be developed.

- The recorded data can be used to analyze the performance of the structure and such results can be used to improve future analyses/design procedures.

  The data collected can also be used to assess long-term displacements of critical locations of structural systems (e.g., permanent displacements, settlement of foundations, long-term deformations due to change of temperature and the plate tectonic deformation spanning the San Francisco Bay and parts of the Los Angeles Basin) and to develop methodologies on how the findings can be incorporated into useful practical design procedures.

CONCLUSIONS

It is shown that recent advances in sampling rates of GPS technology allow real-time dynamic monitoring of long-period structures such as tall buildings and long-span bridges. The advantage over conventional monitoring using accelerometers is that relative displacements can be measured reliably in real-time and with sufficient accuracy to assess potential damage to the structures. The technical feasibility is illustrated through two tests conducted on two vertically cantilevered bars that simulate tall buildings, and an ambient test of a 44-story building. Both approaches show that GPS monitoring of long-period structures provide sufficiently accurate measurements of relative displacements such that dynamic characteristics of the vibrating systems can be accurately identified. This capability can be used for structural health monitoring purposes. Procedures and software are being developed to permanently deploy GPS units on tall buildings and suspension bridges.

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