Monitoring of the Manhattan Bridge for Vertical and Torsional Performance with GPS and Interferometric Radar Systems

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ABSTRACT
This paper describes monitoring of the vertical and torsional displacements of the centerspan of the Manhattan Bridge using Interferometric Radar and Global Positioning Systems (GPS). The Manhattan Bridge is a particularly interesting case study due to its immense size, unique loadings, high traffic volume, age, and recent multimillion dollar rehabilitation and stiffening program. The Interferometric radar system is an non-contacting, innovative microwave radar sensor (IBIS-S) used to simultaneously measure the displacement response of multiple locations of a structure from distances up to 0.5 kilometer. GPS systems use triangulation from satellite signals to accurately locate the absolute position of a receiver and are routinely used in a variety of applications. The systems were employed to measure the centerspan deflections of the bridge under normal automobile and train traffic loadings. The GPS data characterizes the maximum deflections as well as deflection time histories of the outer roadway edges at midspan. The data acquired using the Interferometric Radar system characterized the maximum deflections as well as deflection time histories simultaneous at 80 points along the centerspan with a set-up and test time of about 3 to 4 hours. Both measurement systems compared well with one another and are promising technologies in the area of bridge deflection and vibration measurements.

INTRODUCTION AND HISTORICAL REVIEW OF THE MANHATTAN BRIDGE

In 2009 the Manhattan Bridge delivered to New Yorkers traveling across the East River one hundred years of service. They in turn rewarded it with a “tubular” stiffening system only two years ago. The engineering and management decisions and actions over the elapsing century include contributions by some of the greatest suspension bridge experts and deserve a review.

From the very onset, the many extraordinary features of Manhattan Bridge have required, highly qualified examination. First is its deceptive size (Fig. 1). At 1470 ft (449 m) its main span did not challenge the record 1600 ft (488 m) set in 1903 by the Williamsburg Bridge upstream. Its 725 ft (222 m) side spans however, add up to an anchorage-to-anchorage length of 2920 ft (891 m), surpassing the 2793 ft (852 m) overall length of its neighbor. Despite its elegance, the bridge carries traffic unsurpassed in magnitude and variety. The original structure carried four trolley tracks on its upper level, four subway tracks and three vehicular lanes on the lower level. By 1917 daily commuters using the bridge were estimated at up to 229,000. In its present modification (Fig. 2), with 7 vehicular traffic lanes and four subway tracks, the daily commuters reached 703,000 in 1939. As many as 75,000 vehicles and 970 subway trains cross the bridge daily.

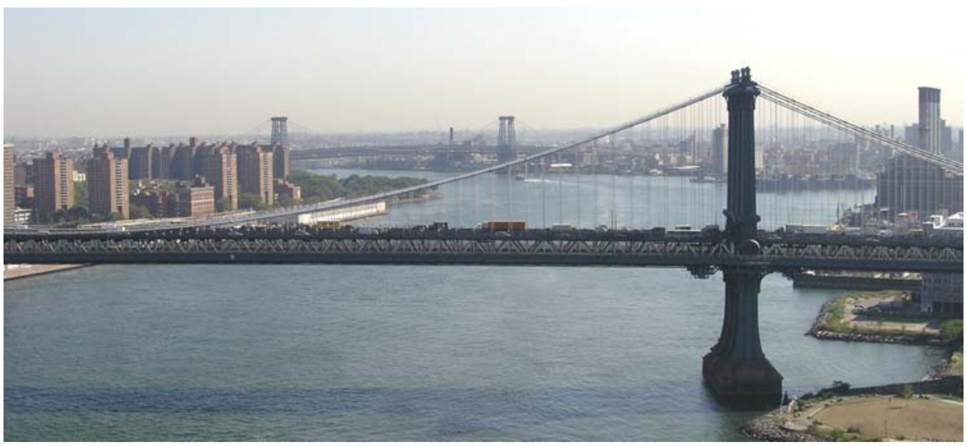

Figure 1. Manhattan (foreground) and Williamsburg (background) Bridges

The design which finally produced Manhattan Bridge was at least the third. R. S. Buck originated the proposed cable suspension version in late 19th Century. G. Lindenthal, (then) Commissioner, introduced a chain-link suspension proposal at the turn of the 20th Century. L. Moisseiff ultimately designed the bridge applying for the first time Melan’s large deflection theory, subsequently popularized by D. Steinman. R. Mojeski reviewed the design. The bridge towers were designed for up to 4 ft (1.22 m) total sway at the top, thus eliminating the need for the traditional (and liable to “freezing”) rollers under the cable saddles. Each of the four cables was composed of nearly 10,000 wires bundled into 37 strands. The Roebling Cable Company supplied the high strength galvanized wires.

The traffic configuration of the bridge (Fig. 2) caused torsion of the cross-section and fatigue cracks were observed early on. In the 1950’s D. Steinman reported to the City that the bridge will never be free of this problem so long as subways travel on their present tracks. It was estimated that the difference in elevation between the opposite fascia at mid-span under asymmetric train distribution is routinely about 3 ft (0.91 m) and can reach 8 ft (2.44 m) under extreme conditions. In the 1980s the City embarked on a 30 year rehabilitation of the bridge at a cost of $902.72 million (2008). The bridge was stiffened under several contracts. The effect was achieved by creating "torque tubes" with new braces under the roadways and strengthening the truss diagonals (Fig. 3). A number of other options were considered and found less suitable.

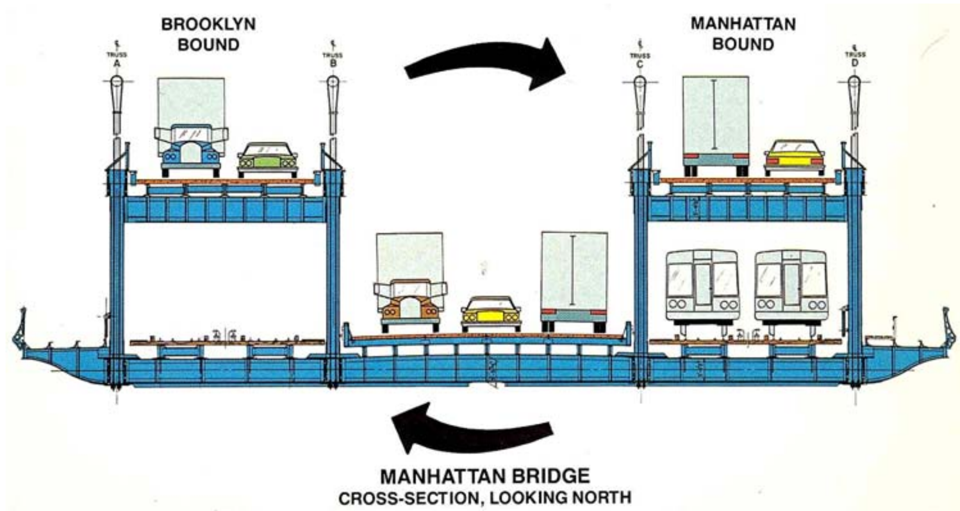

Figure 2. Current Manhattan Bridge traffic layout

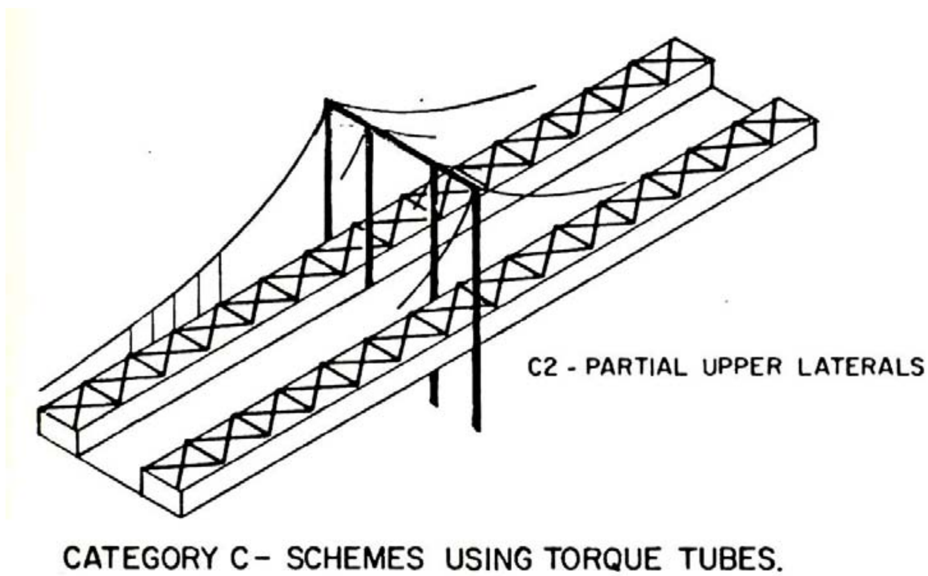

Figure 3. Manhattan Bridge stiffening system layout

The effect of the bridge stiffening in reducing the torsion of the main span is of considerable interest. Measuring the global movements of a structure of this magnitude with sufficient accuracy appeared possible by Global Positioning Systems (GPS). A more recent alternative appeared to be the Interferometric Radar Method. The opportunity to compare the findings is particularly exciting since both of these systems are relatively new bridge management tools.

GLOBAL POSITION SYSTEM (GPS) TESTING

GPS instruments were used to measure displacements, especially the very low frequency displacements such as the deflection produced by passing subway trains or the very low frequency motions caused by wind loading. Such pseudo dynamic motions have very little accompanying acceleration and are often undetected by accelerometers. The basic idea behind relative position GPS motion monitoring is that with one GPS antenna located at a non-moving position near the structure, and with another on the moving structure, one is able to measure accurately the relative displacement (e.g. Kogan et al. [1]). Because one is fixed, this relative motion is actually the absolute motion. Close proximity (within a few kilometers) is required so that the unknown time error of the satellite signal traveling through the atmosphere to the antennae is assumed to be the same.

The GPS receiver was set to sample at 10 samples per second throughout all of the tests. This permits a theoretical range of observation of up to 5Hz, the Nyquist frequency.

The four GPS antennae were placed on the upper deck and on the tops of the towers to permit line of sight to the satellites. The stationary reference GPS unit was placed at the Brooklyn side anchorage on the Manhattan-bound side of the bridge. A typical installation of the antennae on the bridge deck is shown in Fig. 4. Note that the relatively stiff beam setting the antenna out from the bridge is there to move the antenna out from under the bridge cable which would otherwise obstruct a significant portion of the sky (and in turn the satellites). The study was part of the dynamic analysis of the bridge performed by Columbia University Dept. of Civil Engineering and Weidlinger Assoc. for New York City Department of Transportation.

Figure 4. GPS receiver mounted on Manhattan Bridge

A sample of the recorded signals (Fig. 5) shows the vertical deflection on either side of the outer roadways at the mid-span of the bridge over a one hour period. Note, of course, that the GPS provides a 3-dimensional measurement and therefore transverse as well as longitudinal measurements are also recorded. Accuracy is lowest in the vertical direction. The downward deflection is on the order of 25 cm and the upward motion peaks on the order of 10-15 cm (due primarily to deck torsion). Furthermore the baseline (zero) deflection is somewhat arbitrarily chosen, although it is consistent for all recorded channels. The torsional motion is of particular interest. Since the maximum of 15 cm is obtained for a fascia relative to the centerline, it can be concluded that the total torsional amplitude between the two fascia at mid-span is about 1 ft (30 cm). The peak to peak displacement is of the order of 35 cm.

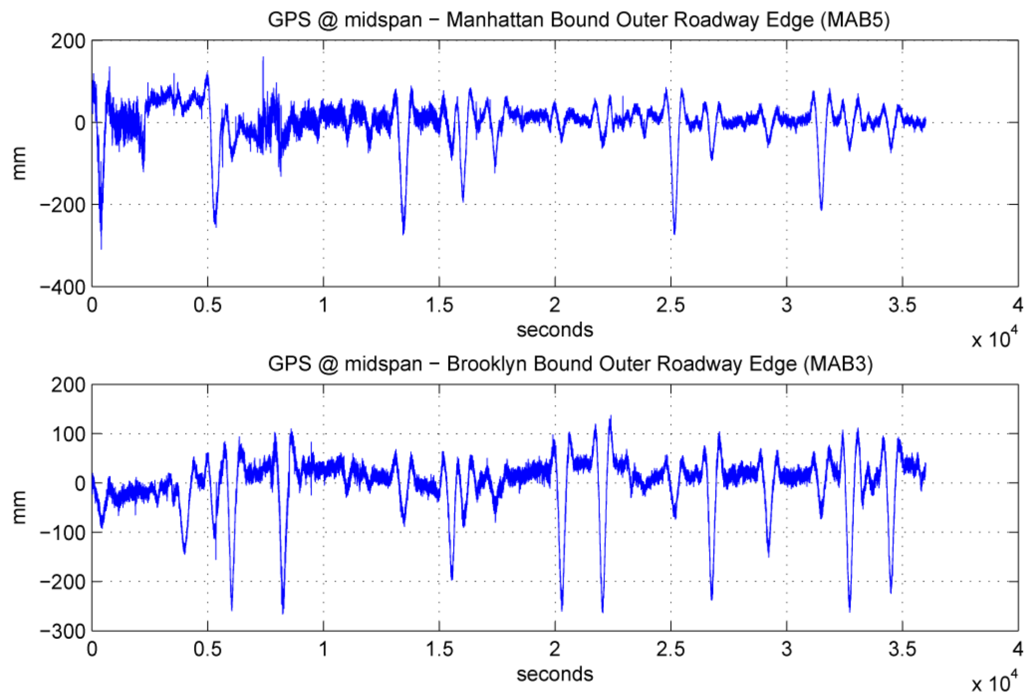

Figure 5. GPS receiver data showing the outer roadway edge deflections of the Manhattan Bridge

INTERFEROMETRIC RADAR SYSTEM OVERVIEW

IBIS-S is an innovative microwave radar sensor, developed by the IDS company of Pisa, Italy in collaboration with the Department of Electronics and Telecommunication of the Florence University. It is able to simultaneously measure the displacement response of several points belonging to a structure with accuracy on the order of a hundredth of a millimeter. IBIS-S can be used to remotely measure structural static deflections as well as vibrations to identify resonant frequencies and mode shapes. In addition to its non-contact feature, the new vibration measuring system provides other advantages including quick set-up time, a wide frequency range of response and portability.

A demonstration test of the IBIS-S system was performed on the Manhattan Bridge in New York, NY. The primary objective of the demonstration was to measure the deflection time-histories and maximum deflections of the midspan of the Manhattan Bridge under normal automobile and train traffic loading. The IBIS-S system was deployed on the Brooklyn side bank below the bridge superstructure. The test demonstration required one-half of a field day, which included field set-up time and all data acquisition. Due to the non-contacting nature of the system and operational range, all testing was performed with no traffic disruption and minimal field support requirements.

IBIS-S Radar System Description

The IBIS-S system is based on interferometric [2] and wide band waveform principles. It is composed of a sensor module, a control PC and a power supply unit. The sensor module (Fig.6) is a coherent radar, generating, transmitting and receiving the electromagnetic signals to be processed in order to compute the displacement time-histories of measurement points belonging to the investigated structure. The sensor module, including two horn antennas (Fig. 6) for transmission and reception of the electromagnetic waves, exhibit a typical super heterodyne architecture. The base-band section consists of a Direct Digital Synthesis (DDS) device to obtain fast frequency hopping. A tuneable sine wave is generated through a high-speed D/A converter, reading a sine lookup table in response to a digital tuning word and a precision clock source. The radio-frequency section radiates at a central frequency of 17.2 GHz with a maximum bandwidth of 300 MHz; hence, the radar is classified as Ku-band, according to the standard radar-frequency letter-band nomenclature from IEEE Standard 521-1984 [4]. A final calibration section provides the necessary phase stability; design specifications on phase uncertainty are suitable for measuring short-term displacements with a range uncertainty lower than 0.01 mm. The sensor module is installed on a tripod equipped with a rotating head, allowing the sensor to be orientated in the desired direction (Fig. 6). The module has an USB interface for connection with the control PC and an interface for the power supply module.

The control PC is provided with the software for the system management and is used to configure the acquisition parameters, store the acquired signals, process the data and view the initial results in real time. Finally, the power source is a 12 V battery. The main operational characteristics of IBIS-S system are summarized in Table 1.

Table 1. IBIS-S Operational Characteristics

Parameter	
Maximum operational distance (for minimum 40Hz sampling frequency)	500.00 m
Maximum sampling frequency	200.00 Hz
Displacement sensitivity (accuracy)	0.01 mm
Operative weather condition	All

Figure 6. View of the new *IBIS-S* sensor

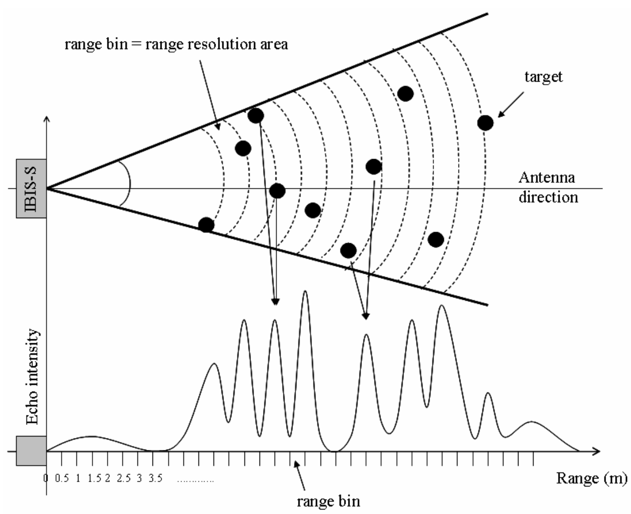

Figure 7. Radar range resolution concept

IBIS-S Radar Basic Principles

The ability to determine range (i.e. distance) by measuring the time for the radar signal to propagate to the target and back is surely the distinguishing and most important characteristic of radar systems. Two or more targets, illuminated by the radar, are individually detectable if they produce different echoes. The resolution is a measure of the minimum distance between two targets at which they can still be detected individually. The range resolution refers to the minimum separation that can be detected along the radar's line of sight.

IBIS-S system is capable of providing range resolution, i.e. to distinguish different targets in the scenario illuminated by the radar beam. Peculiarly, this performance is reached by using the Stepped-Frequency Continuous Wave (SF-CW) technique.

Pulse radars use short time duration pulses to obtain high range resolution. For a pulse radar, the range resolution Δr is related to the pulse duration τ by the following [2]:

$$\Delta r = \frac{c\tau}{2} \quad (1)$$

where c is the speed of light in free space. Since (see e.g. [5]) τ = 1/B, the range resolution (1) may be expressed as:

$$\Delta r = \frac{c}{2B} \quad (2)$$

Eq. (2) highlights that range resolution increases (corresponding to a smaller numerical value of Δr) as the frequency bandwidth of the transmitted electromagnetic wave increases; hence, closely spaced targets can be detected along the radar's line of sight. The SF-CW technique exploits the above concept to provide the IBIS-S sensor with range resolution capability.

The SF-CW technique is based on the transmission of a burst of N monochromatic pulses, equally and incrementally spaced in frequency (with fixed frequency step of Δf), within a bandwidth B:

$$B = (N-1)\Delta f \quad (3)$$

The N monochromatic pulses sample the scenario in the frequency domain similarly to a short pulse with a large bandwidth B. In a SF-CW radar, the signal source dwells at each frequency fk = fo + kΔf (k=0,1,2, …, N−1) long enough to allows the received echoes to reach the receiver. Hence, the duration of each single pulse (Tpulse) depends on the maximum distance (Rmax) to be observed in the scenario:

$$T_{pulse} \geq \frac{2R_{max}}{c} \quad (4)$$

In the IBIS-S sensor, the SF-CW radar sweeps a large bandwidth B with a burst of N single tones at uniform frequency step, in order to obtain a range resolution of 0.50 m; in other words, two targets can still be detected individually by the sensor if their relative distance is greater than 0.50 m. The range resolution area is termed range bin. The radar continuously scans the bandwidth at a rate ranging up to 200 Hz, so that the corresponding sweep time Δt of 5 ms is in principle well suitable to provide a good waveform definition of the displacement response for a civil engineering structure.

At each sampled time instant, both in-phase and quadrature components of the received signals are acquired so that the resulting data consists of a vector of N complex samples, representing the frequency response measured at N discrete frequencies. By taking the Inverse Discrete Fourier Transform (IDFT) the response is reconstructed in the time domain of the radar: each complex sample in this domain represents the signal (echo) from a range (distance) interval of length cTpulse/2.

The amplitude range profile of the radar echoes is then obtained by calculating the magnitude of each bin of the IDFT of acquired vector samples. This range profile gives a one dimensional map of scattering objects in the viewable space in function of their relative distance from the equipment.

The concept of range profile is better illustrated in Fig. 7, showing an ideal range profile obtained when the radar transmitting beam illuminates a series of targets at different distances and different angles from the system. The peaks in the lower plot of Fig. 7 correspond to "good" measurement points and the sensor can be used to simultaneously detect the displacement and the transient response of these points. These good reflective points could be either given by the natural reflectivity of some points belonging to the structure or by some simple passive metallic reflectors applied on it.

Once the image of the scenario illuminated by the radar beam has been determined at uniform sampling intervals Δt, the displacement response of each target detected in the scenario is evaluated by using the Differential Interferometry technique (see e.g. 0); this technique is based on the comparison of the phase information of the back-scattered electromagnetic waves collected in different times.

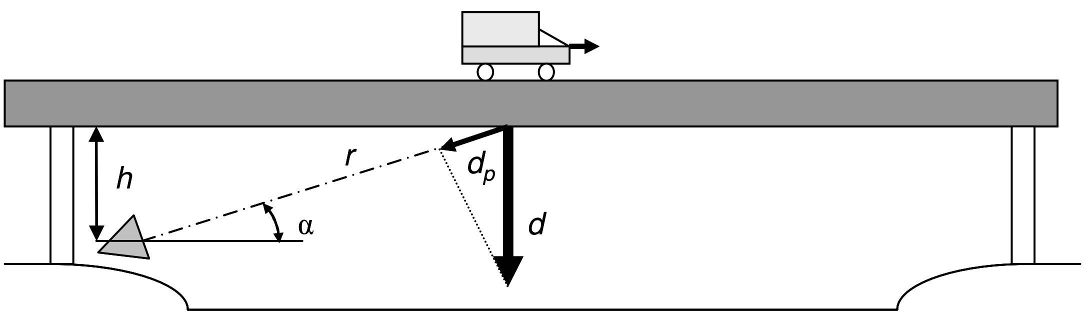

Figure 8 Radial displacement vs. projected displacement

Generally speaking, when a target surface moves with respect to the sensor module (emitting and back-receiving the electromagnetic wave), at least a phase shift arises between the signals reflected by the target surface at different times. Hence, the displacement of the investigated object is determined from the phase shift measured by the radar sensor at the discrete acquisition times. The radial displacement dp (i.e. the displacement along the direction of wave propagation) and the phase shift $\Delta\varphi$ are linked by the following:

$$d_p \propto \frac{\lambda}{4\pi}\Delta\varphi \quad (5)$$

where λ is the wavelength of the electromagnetic signal.

The sensor module emits a series of electromagnetic waves for the entire measurement period, and processes phase information at regular time intervals (up to 5 ms) to find any displacement occurring between one emission and the next. It is worth underlining that the interferometric technique provides a measurement of the radial displacement of all the range bins of the structure illuminated by the antenna beam; once the radial displacement *dp* has been evaluated, the vertical displacement *d* can be easily found by making some geometric projection, as shown in Fig. 8.

INTERFEROMETRIC RADAR DEMONSTRATION ON MANHATTAN BRIDGE

Thanks to the collaboration between IDS, NYC Department of Transportation and Olson Engineering Inc. a demonstration test on the Manhattan Bridge was performed using the high precision IBIS-S radar sensor. The aim of the test was to measure both the vibrations and static deflections of the main span of the bridge under normal traffic conditions.

Two subsequent tests were performed pointing the sensor first towards the centre and then to the edge of the main span trying to estimate the torsion given by the asymmetric configuration of the traffic. In both situations IBIS-S was placed under the bridge on the Brooklyn side illuminating the whole main span with the radar beam therefore allowing the accurate displacement measurement of around 80 points along the bridge span at the same time (one each at about 5.5 m spacings). Figure 9 presents an overview of the installation.

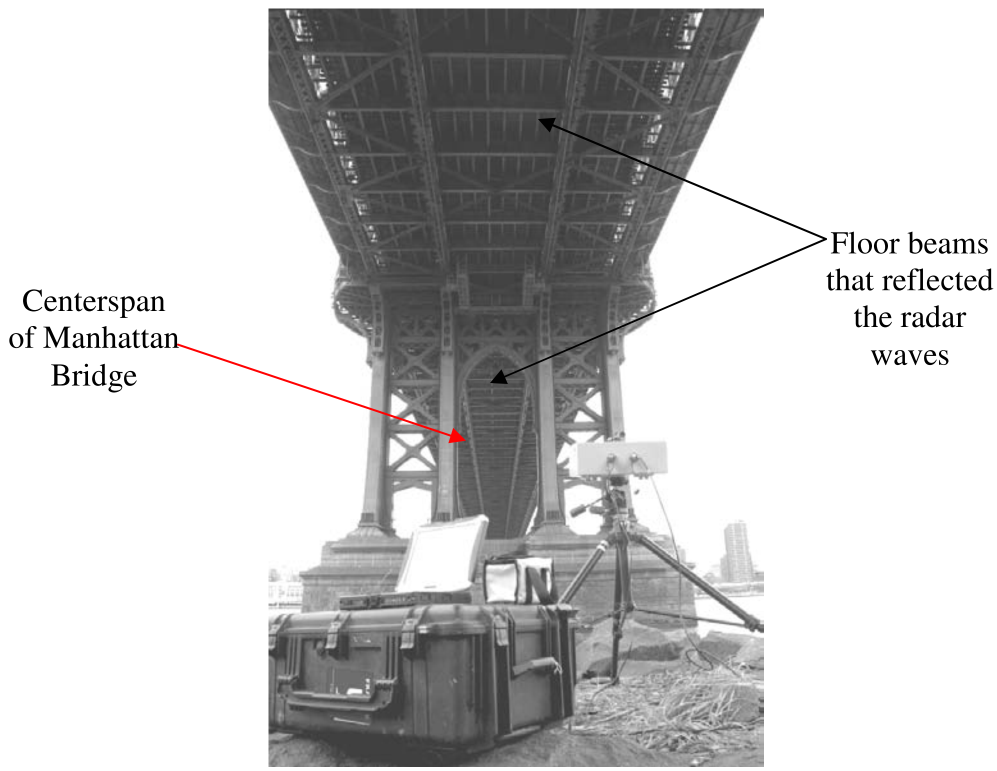

Figure 9. IBIS-S installation during the Manhattan bridge demonstration test from the Brooklyn side

The excellent natural reflectivity of the micro-wave from the metallic floor beams was provided equally distributed measurement points along the tested span without any artificial reflectors on the structure (sometimes necessary for concrete or other non-metallic structures). To each of the floor beams corresponds a sharp peak on the IBIS-S range profile and therefore a good quality point whose displacement can be measured by analyzing the phase variations trough the differential interferometric technique. Figure 10 presents a portion of the IBIS-S Power Profile: a high level of backscattered signal in the range bin in which a crossing beam is located gives a high Signal to Noise Ratio and therefore high accuracy in the measurement of the displacement.

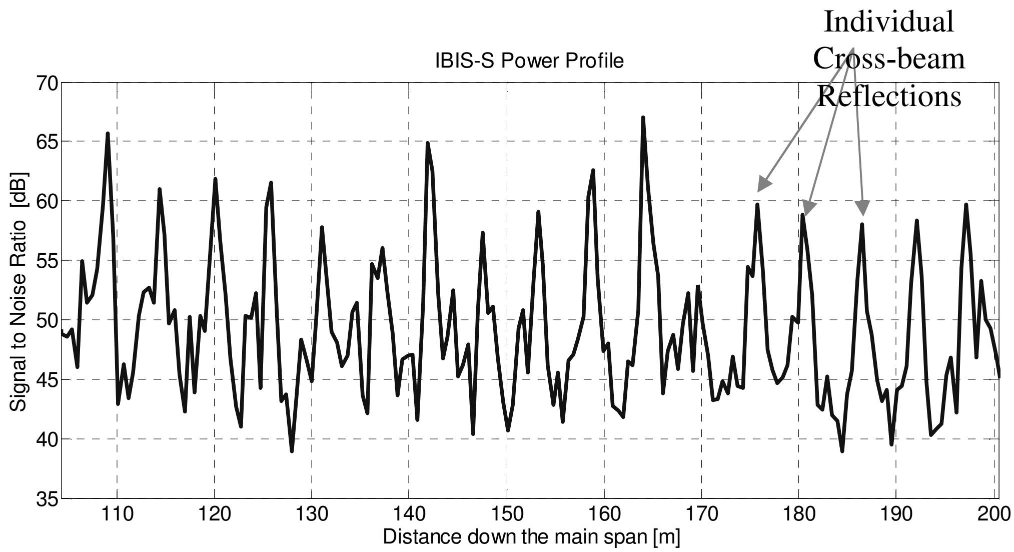

Figure 10. Portion of the IBIS-S Power Profile

Fig. 11 shows the vertical displacement of the central section of the floor beams in the main span resulting from the passage of a single train over the deck. The measured peak to peak displacement at mid-span is 33.82 cm but it decreases moving towards the bridge piers. The slow train entrance can be clearly identified by the high delay between the maximum vertical deflections of points at the different cross-sections of the span. Further, a positive vertical deformation of 5.31 cm can be observed when the train passes to the side spans. Measured peak to peak vertical deformations were about 1 cm under normal vehicular traffic (with no trains on the deck).

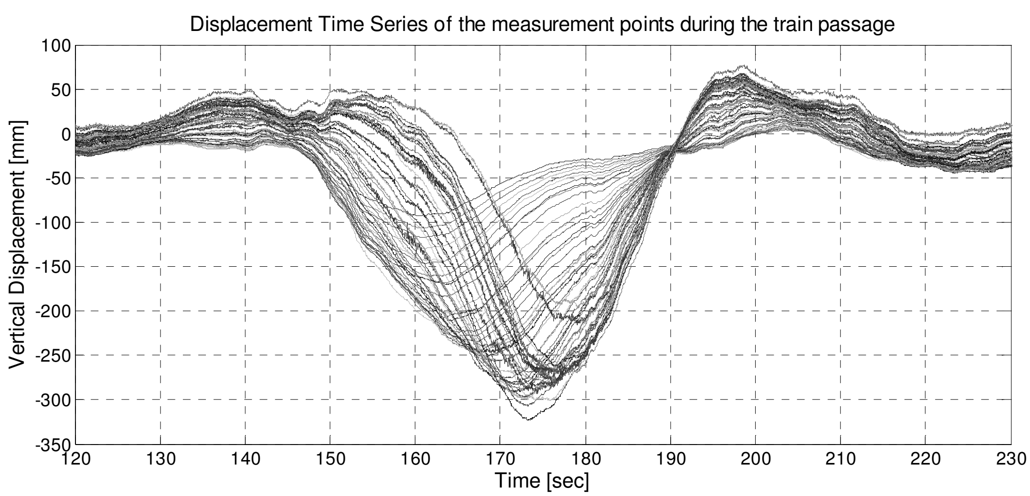

Figure 11. Vertical displacement time series of the crossing beams given by the passage of a train

Maximum peak to peak deformations measured during the passage of more than one train both for the central and for the side section of the main span are shown in Fig. 12. Both deformed static curves are close to symmetrical with respect of the centre of the span. However the one related to the edge measurement shows a maximum deflection value at mid-span which is 6.67 cm higher than the one measured for the central section. Because the scans were taken at different times, the difference between the maximum deflections mid-span must be considered as a lower bound of the torsional movement. The center of the cross section would not be at its lowest during the greatest torsional deformation. Further Fig. 12 shows significant torsional behavior at quarter-span related to the second torsional mode, as should be expected.

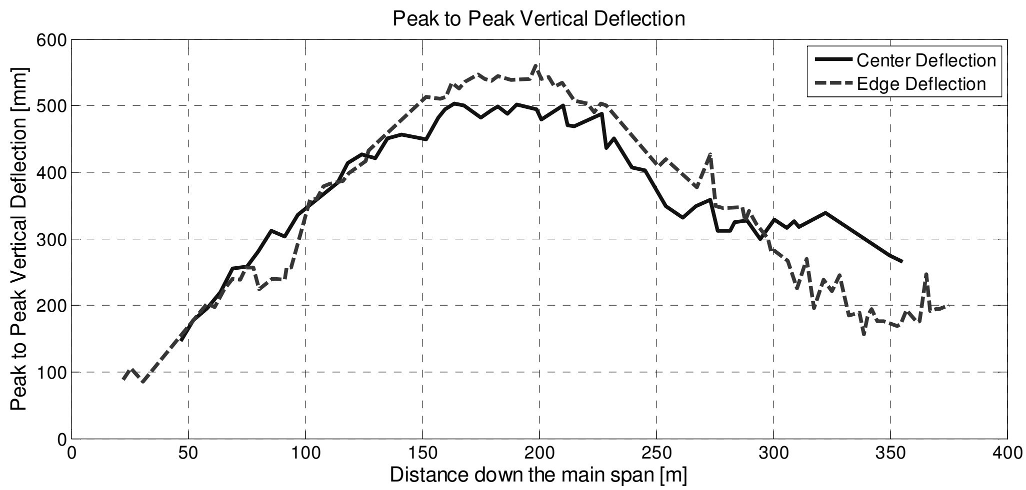

Figure 12. Peak to peak vertical deflection of the central and side sections of the main span

Jointly analyzing the results in the frequency domain through the computation of the Displacement Cross-Spectrums of the whole set of range bin combinations and averaging the results allows the identification of the frequencies which are common to all measurement points, excluding frequencies potentially given by scattered noise effects. This kind of spectral analysis on the displacement time series, measured both for the central and for the side section, leads to the clear identification of three main resonant structural frequencies. As shown in Fig. 13, the first resonant frequency is at 0.23 Hz, the second one is at 0.30 Hz while the third is at 0.49 Hz. The frequencies obtained by the GPS were 0.23 Hz, 0.31 Hz and 0.50 Hz respectively. Further, a resonant frequency peak at 0.016 Hz can be identified and was shown to be related to the slow static deformation of train.

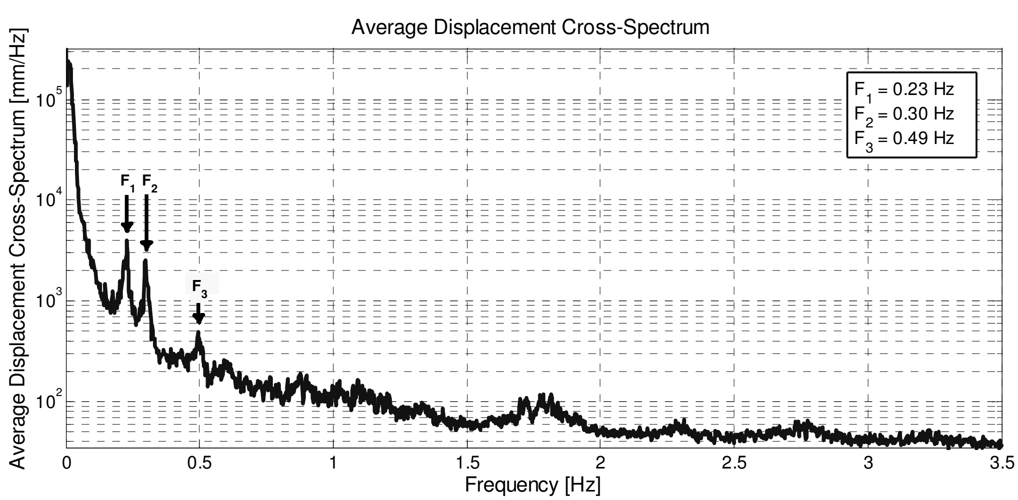

Figure 13. Average displacement cross-spectrum.

CONCLUSIONS

Health monitoring of structures by state-of-the art technology is both a new opportunity and a challenge for bridge managers. While innovations must be rapidly implemented, their contributions must be fully validated. The Manhattan Bridge monitoring by GPS and by Interferometric Radar System, conducted by the Columbia University Dept. of Civil Engineering and by IDS, respectively provided valuable information about the dynamic characteristics of the bridge, the effect achieved by the stiffening of the structure and the possibilities of both these systems.

Overall the deflection measurements and resonant frequencies measured with both the GPS and Interferometric radar systems compared well with one another. The total amplitude of displacement, peak to peak was on the order of 300 mm when loaded by a single train. Both systems have their advantages. The GPS system lends itself to long-term monitoring. The IBIS-S system can be rapidly deployed for short-term displacement and vibration monitoring. This provides for short-notice, economical static and dynamic load tests as well as for measurement of operating displacements and ambient vibration measurements needed for modal vibration analyses.

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