Remote Radar Monitoring for Bridge Load Testing and Stay Cable Forces

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ABSTRACT: A case study is first presented for monitoring bridge displacement using a remote, non-contacting interferometric phase radar system (IBIS-S) and results compared to a conventional bridge load test using string potentiometers. Secondly, bridge stay cable forces were determined remotely using the IBIS-S to measure multiple cable displacements/resonances excited by wind/traffic loads. The IBIS-S resonant frequency/tension force results compared very well with a mounted accelerometer on a cable.

INTRODUCTION TO IMAGING BY INTERFEROMETRIC SURVEY OF STRUCTURES (IBIS-S) RADAR SYSTEM

The IBIS-S (now IBIS-FS model) system is manufactured by IDS GeoRadar of Pisa, Italy based on interferometric and wide band waveform principles (Taylor, 2001). It is composed of a sensor module, a control PC and a power supply unit. The sensor module (Fig. 1) is a coherent radar system which generates, transmits and receives the electromagnetic signals to be processed in order to compute the displacement time-histories of measurement points belonging to the investigated structure without contacting the structure. The sensor module, including two horn antennas (Fig. 1) for transmission and reception of the electromagnetic waves and it exhibits 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 center frequency of 17.2 GHz with a bandwidth of 17.1-17.3 GHz in the US per FCC regulations; hence, the radar is classified as Ku-band. 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 0.0004 inch (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. The module has a USB interface for connection with the control PC. The main operational characteristics of IBIS-S system are summarized in Table 1.

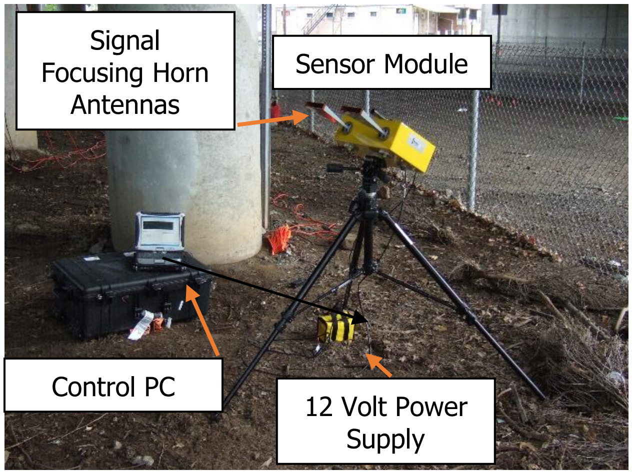

Figure 1. IBIS-S System Components

Table 1. IBIS-S Operational Characteristics

Parameter	
Maximum operational distance for 0 to 40 Hz dynamic response frequency (static monitoring to 1000 m)	500 m
Maximum sampling frequency (Nyquist frequency of 100 Hz)	200 Hz
Displacement sensitivity (accuracy of 0.0004 inch)	0.01mm
Operative weather conditions	All

INTERFEROMETRIC RADAR PRINCIPLES

Professor Carmelo Gentile of Politecnico di Milano, Dept. of Structural Engineering in Italy conducted research on the use of the IBIS-S on bridges for static and dynamic monitoring well as stay cable force measurement (Gentile, 2009). 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.

The IBIS-S system is capable of providing range resolution, i.e., to distinguish different targets in the scenario illuminated by the radar beam. Specifically, 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:

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

where c is the speed of light in free space. Since $\tau = 1/B$ per Eq. 3), the range resolution may be expressed as:

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

Eq. (2) highlights that range resolution increases (corresponding to a smaller numerical value of Δr) as the frequency bandwidth (B) 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:

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

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 $f_k = f_o + k\Delta f$ (k=0,1,2, …, N–1) long enough to allow 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:

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

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 0.75 m; in other words, two targets can still be detected individually by the sensor if their relative distance is greater than 0.75 m. The range resolution area is termed range bin. The radar continuously scans the bandwidth at a rate ranging up to 200 Hz (100 Hz Nyquist), so that the corresponding sweep time Δt of 5 ms is in principle well suited 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 illustrated in Fig. 2, showing an ideal range profile obtained when the radar transmitting beam illuminates a series of reflection targets at different distances and different angles from the system. The power amplitude intensity peaks in the lower plot of Fig. 2 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 steel members of a bridge or by some simple passive metallic reflectors.

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 eq. 5); this technique is based on the comparison of the phase information of the back-scattered electromagnetic waves collected in different times

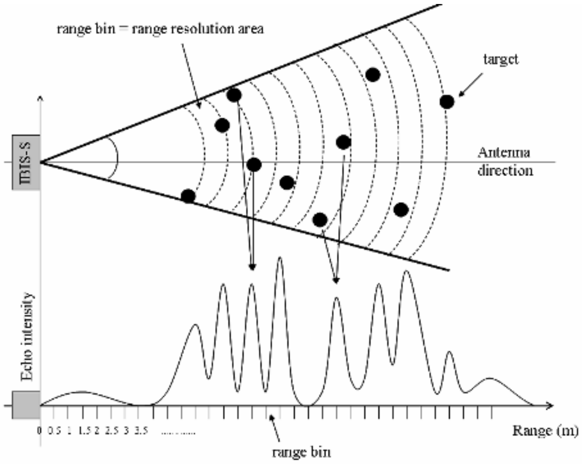

Figure 2. Radar range reflector resolution concept

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:

$$dp = -\frac{\lambda}{4\pi}(\phi 2 - \phi 1) \quad (5)$$

where λ is the wavelength of the electromagnetic signal. This is illustrated in Figure 3 below.

The sensor module emits a series of electromagnetic radio 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 of a bridge *d* can be easily found by making some geometric projection, as shown in Fig. 4.

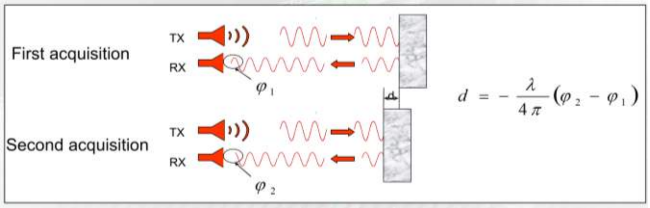

Figure 3. Interferometric displacement data (dp) analyzed by comparing phase information of different times of reflected radio waves from the reflector with an accuracy of less than 0.0004 inch (0.01 mm) for wavelengths of 0.75 inch (19 mm)

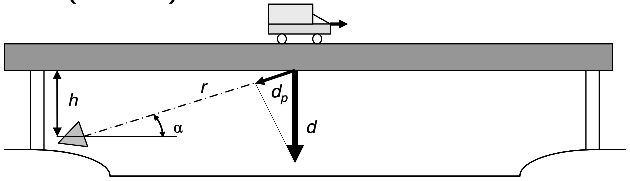

Figure 4. Radial displacement (dp) vs projected vertical displacement (d) for a bridge reflector

IBIS-S MONITORING OF LOAD TEST OF STEEL GIRDER BRIDGE

The IBIS-S system was used to monitor vertical displacements during a conventional bridge load test performed by Drexel University with the aid of the New Jersey DOT on the New Jersey Route 23 Bridge which crosses over Route 202 and the Norfolk Southern Railroad in Wayne Township, New Jersey and is shown in Figure 5 below. The 2010 project was part of the Federal Highway Administration (FHWA) Long-Term Bridge Performance Project (LTBPP) that was conducted by Rutgers University along with Parsons Brinckerhoff and other members of the research team.

The IBIS-S investigation conducted by the authors focused on measuring the displacements induced by ambient traffic vibration and static load tests as well as the measurement of the natural vibration frequency of the monitored bridge span as excited by ambient vibrations from normal traffic loading conditions. The IBIS-S radar system was deployed to measure the vertical displacements at the naturally reflective structural steel cross-bracing diaphragm locations between girders 2W2 and 2W3 as well as at three aluminum corner reflectors which were connected to the bottom flange of girder 2W3 (see Figures 1 and Figure 6 – corner reflectors are required for concrete bridges but optional for steel bridges). The measurements were performed under both normal ambient traffic and controlled load test conditions. The IBIS-S unit set-up time was approximately 1 hour, which is ideal for rapid load tests.

Figure 5. New Jersey Route 23 Bridge looking west – IBIS tested Girder 2W3 is in the background

Figure 6. View over IBIS air horn antennas of the corner reflectors (see inset photo) at potentiometer locations on Girder 2W3

The 3 corner reflectors (R1, R2 and R3) were mounted as close as practical adjacent to the Drexel string potentiometers (see Figure 7) that were attached to the bottom of Girder 2W3 with weights on the ground below at the locations shown in Figure 8. The Girder 2W3 load test was conducted statically with 6 loaded dump trucks (see Figure 9 - 460 kip total load) at the ¾ (North), ½ (Middle) and ¼ (South) span locations.

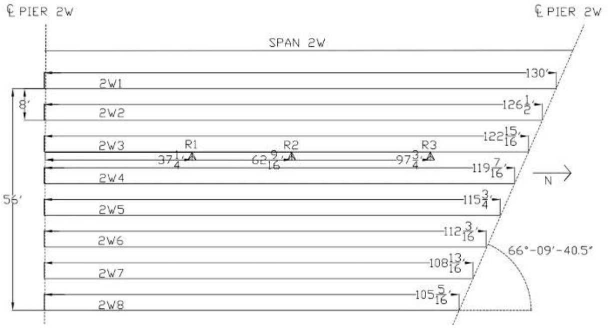

Figure 7. Framing Plan of Span 2 indicating Aluminum Corner Reflector Locations R1-3 and Drexel Potentiometers SB2-3-1, SBS-3-2 and SB2-3-3, respectively

The results of the IBIS-S displacement monitoring of Girder 2W3 for static load tests at ¾, ½ and ¼ span positions are presented below in Figure 10. As expected, the largest displacements were measured for the mid-span loading with a maximum of -0.857 inch at R2.

Figure 8. Drexel string potentiometer on Girder 2W3

Figure 9. 6 loaded dump trucks – static test

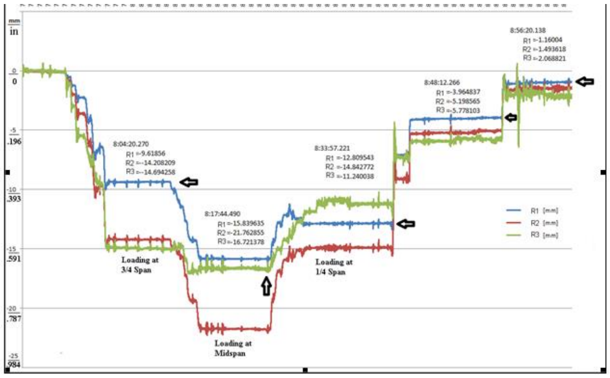

Figure 10. IBIS-S measured displacements of Girder 2W3 at Receivers R1, R2 and R3 for static load tests at ¾, ½ and ¼ span (left to right, north to south above)

A comparison of the IBIS-S results vs. the potentiometer results is presented in Table 2. Review of the table indicates very close agreement with differences ranging from 0.032 to -0.049 inch. Due to the bridge skew the maximum displacement was recorded at R2 and not R1 when the load was positioned at the ¼ span.

Table 2. Static Load Test Displacement Results for IBIS-S vs. Potentiometer Results

6 Trucks Span 2 Location	Potentiometer/ IBIS-S Reflector	IBIS-S Maximum Displacement (inch)	Potentiometer Maximum Displacement (inch)	IBIS-S vs Potentiometer Displacement Difference (inch)
3/4 Span (north)	SB2-3-3 R3	-0.579	-0.530	-0.049
1/2 Span (mid)	SB2-3-2 R2	-0.857	-0.846	-0.011
1/4 Span (south)	SB2-3-2 R2	-0.584	-0.616	0.032

The IBIS-S was again shown to be very comparable to conventional string potentiometer displacement results. The setup time for an IBIS-S test with the 3 corner reflectors was only about an hour which is much shorter than the time required to set up the string potentiometers. The IBIS-S system was also used to record the dynamic responses of the bridge to ambient traffic. Time-history plots of displacement, velocity and acceleration are presented for the mid-span corner reflector R2 location in Figures 11-13, respectively.

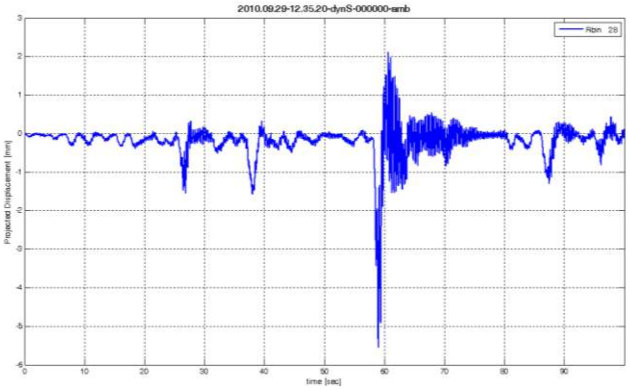

Figure 11. Vertical displacement response of reflector R2 during ambient traffic vibrations

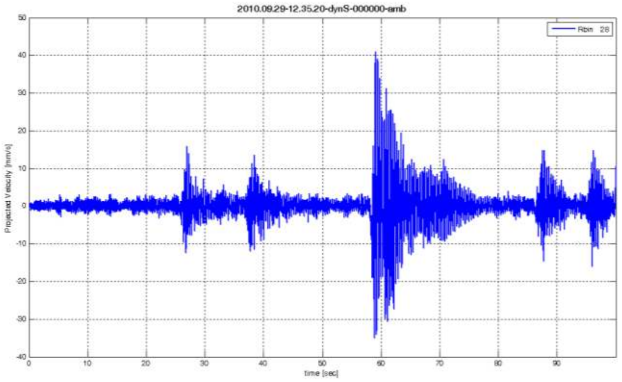

Figure 12. Vertical velocity response of reflector R2 during ambient traffic vibrations

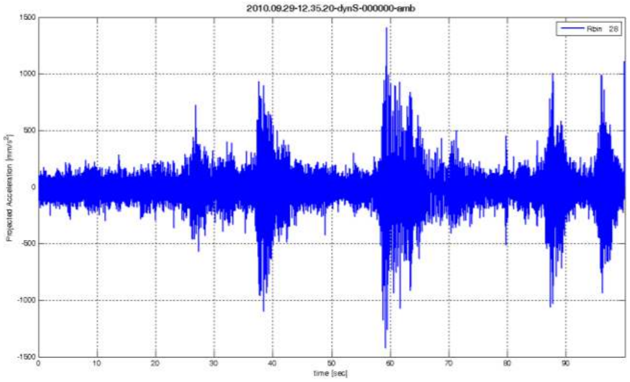

Figure 13. Vertical acceleration responses of reflector R2 during ambient traffic vibrations

A Fast Fourier Transform (FFT) can be applied to the time history vibration data of any of the measurement locations to determine the natural resonant frequency of the bridge span. Figure 14 below displays the frequency power spectrum of the velocity vibration data from reflector R2. The fundamental frequency of span 2 of the bridge was found to be 2.76 Hz.

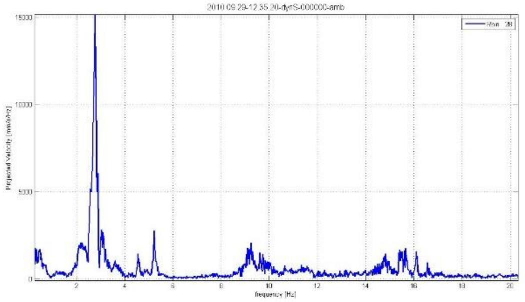

Figure 14. The fundamental frequency of Span 2 of the southbound bridge is the large resonant peak at 2.76 Hz

IBIS-S TESTS FOR BRIDGE STAY CABLE FORCES

The application of the IBIS-S system to measure the natural frequencies of bridge stay cables in order to predict their tension forces based on taut-line theory is also discussed in a paper by Professor Gentile (Gentile, 2010). The IBIS-S was found to very accurate at measuring natural frequencies/force and stay cable displacements in his research. The application of the IBIS-S to measure stay cable vibrations is illustrated below in the following case history.

IBIS-S DATA ACQUISITION AND TEST RESULTS - The IBIS-S interferometric radar system is able to simultaneously measure the displacement response of multiple cables from 0 to 40 Hz at 1640 ft (500 m) dynamically on stay cables. The 17.1-17.3 GigaHertz (GHz) frequency radar system was used to measure the vibrations (displacements) of multiple stay cables simultaneously as shown in Figure 15.

Figure 15. IBIS-S system pointed at stay cables

Once the IBIS-S system is completely set-up, the first step in data acquisition is to verify that the power profile of the naturally reflective steel stay cables is acceptable. The reflective power profile can also be influenced by the shape of the focusing airhorn antennas used with the sensor module as well as the viewing location and angle. Figure 16 plots reflector range distance on the horizontal scale (in meters) versus Signal to Noise Ratio (SNR) on the vertical scale in (db). Each of the closest 6 stay cables correspond to a sharp peak in the IBIS-S range profile (amplitude is higher than 45 dB) while the further away stay cables were noted but more difficult to identify. Review of Figure 16 indicates that all the stay cables are good quality reflective points whose displacements can be precisely measured by analyzing the phase shifts through the differential interferometric technique described above. The power profile peaks were correlated with specific cables using a laser distance meter.

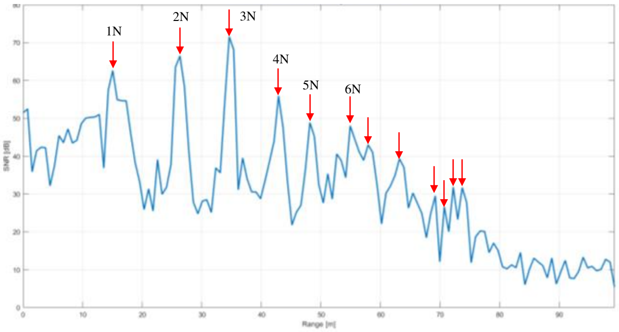

Figure 16. IBIS-S reflective signal Power Profile, presenting the reflection energy of stay cables 1N (closest to the IBIS-S unit) to 6N

As the monitored stay cables were separated by more than 0.75 m (see Fig. 16), their responses were able to be individually measured simultaneously. A vibration displacement plot of 10 seconds of ambient wind and truck traffic excitation for the 6 closest cables to the IBIS-S system is presented in Figure 17.

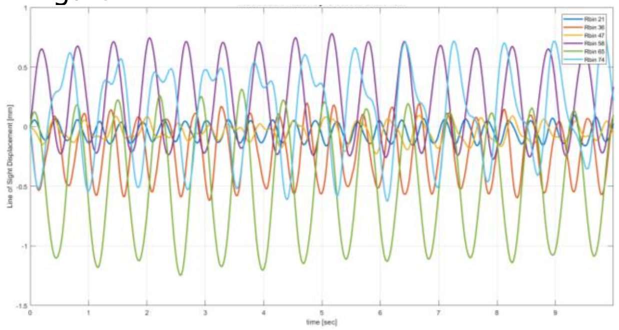

Figure 17. IBIS-S ambient vibration displacements for Cables 1N to 6N over 10 second period

As observed in Figure 17, the stay cable displacements are periodic with typically a single predominant resonant frequency. Note that the displacements shown above are in the direction of line of sight toward the IBIS-S system; however, if the angle of the cable is known (along with the angle of the radar unit) than the displacement can be corrected to present the movement perpendicular to the cable in the plane toward the measurement unit. The IBIS-S measurements of the 1N cable vibrations are presented as displacement versus time in Figure 18, and differentiated to be velocity in Figure 19 and differentiated again to be acceleration in Figure 20. Cable 1N is of particular interest as it has an accelerometer permanently mounted for structural health monitoring purposes allowing measured accelerations and resonant frequencies to be directly compared for the IBIS-S and the accelerometer (discussed later below).

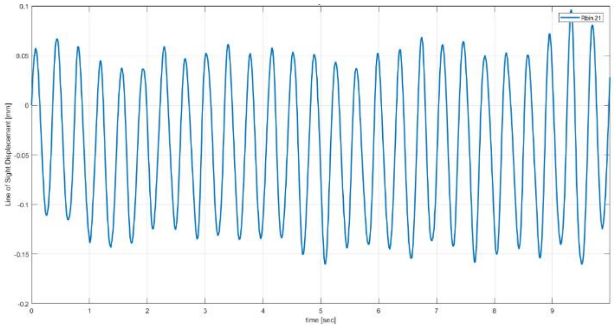

Figure 18. Stay Cable 1N displacements over a 10 second period.

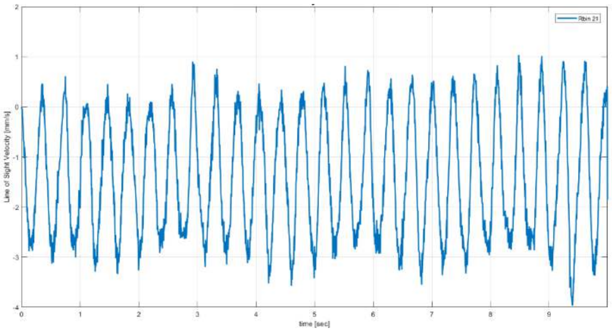

Figure 19. Stay Cable 1N velocity response from Figure 18 data over a 10 second period.

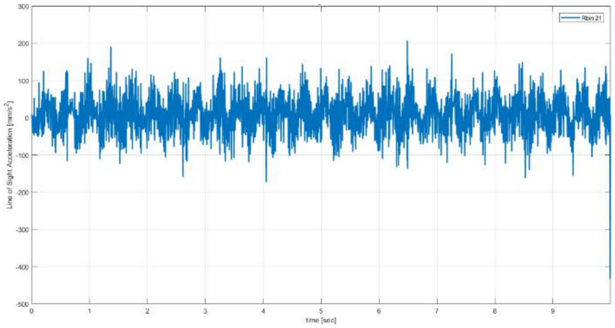

Figure 20. Stay Cable 1N acceleration response from Figure 19 data over a 10 second period.

Figure 17 shows that the peak-to-peak stay cable line-of-sight displacement of some of the longer cables was over 1.0 mm (0.04 inch). As observed in Figure 18, the peak-to-peak stay cable displacement in the line-of-sight direction toward the IBIS-S system was approximately 0.2 – 0.25 mm over this time period.

Fast Fourier Transform (FFT) analyses was applied to the displacement vs. time history vibration data of a stay cable to determine the resonant frequency of the stay cable, which is directly related to the cable tension and length as discussed below. Figure 21 presents the plot showing the resonant frequencies of cables 1N – 6N. Figure 22 presents the resonant frequency responses measured by the IBIS-S system for stay cable 1N in order to observe the multiple cable resonant modes. Note that the frequency measurements have a resolution of 0.02 Hz.

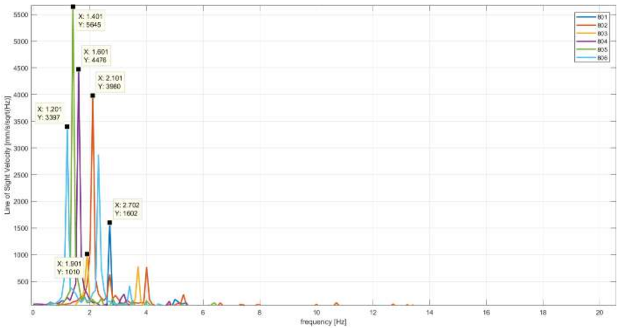

Figure 21. Stay Cables 1N – 6N, IBIS-S Resonant Frequencies. The fundamental resonant frequency of each cable is noted in the information boxes. The longer cables have progressively lower resonant frequencies, as expected.

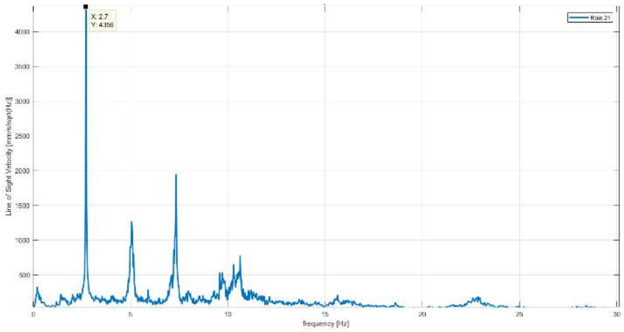

Figure 22. Stay Cable 1N IBIS-S Resonant Frequencies - note a fundamental resonance of 2.70 Hz and additional higher modes of vibration resonance at 5.0 and 7.2 Hz.

In order to have a comparison with the IBIS-S results, FFT analysis of the acceleration response versus time data from the mounted accelerometer on cable 1N resulted in a resonant frequency of 2.71 Hz as shown below in Figure 23. This is in excellent agreement with the IBIS-S measured resonant frequency of 2.70 Hz (Figure 22) and the two higher resonances at approximately 5.0 and 7.2 Hz.

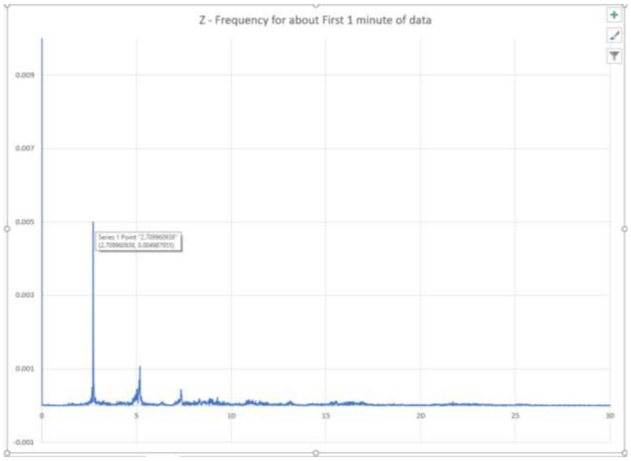

Figure 23. Stay Cable 1N Accelerometer Resonant Frequencies from time vs. acceleration response data - note a fundamental resonance of 2.71 Hz and additional higher modes of vibration resonance at 5.2 and 7.3 Hz that agree with IBIS-S resonances in Figure 22 for this cable.

Given standard cable parameters such as length and cable mass per length, the measured fundamental resonance can be used to calculated the cable tension using the following equation:

$$T = 4 * \rho * L^2 * f_n^2 \qquad (6)$$

where T is the tension force, ρ is mass per unit length, L is the length and f_n is the fundamental first mode resonance. Applying this equation to Cable 1N with its fundamental frequency of 2.70 Hz predicts a tension force of 858 kips with a cable stress of 128 ksi. This is close to the design service stress of 118 ksi for Cable 1N.

CONCLUSIONS

The IBIS-S system can be rapidly deployed for short-term displacement and vibration monitoring of steel and concrete bridges as well as stay cables and other structures. This provides for short-notice, economical, static and dynamic load tests of bridges as well as for measurement of operating displacements and ambient vibration measurements needed for modal vibration analyses. The IBIS-S system is a speed-of-light, line-of-sight technology that is also well-suited to measure natural frequencies for accurate prediction of stay cable tension forces as well as their displacements. It's ability to measure many points on bridges simultaneously makes it a powerful, accurate and economic tool for bridge monitoring and load testing (Mayer et al, 2010).

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