In-Service inspection based on wireless sensors

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ABSTRACT: This paper promotes the concept of application of wireless sensors developed at the Bridge Research Center for rapid installation and low power requirements for in-service real-time bridge inspection. The concept focuses on obtain useful data avoid closing the traffic and causing inconvenience to public and indirectly affecting economy; rapid installation and low power consumption for in-service real-time bridge inspection on the concept of application of wireless sensors compared to wire networks; real-time measurements and statistical analysis can be performed which is more practical in estimating a bridge capacity. Load distribution of the deck-beams can be estimated; as well as the estimation of the load carrying capacity of the bridge can be proposed based on preliminary inspection. Plans and procedures of the field inspection are detailed as well as the data processing and the preliminary analysis results are presented. The effectiveness and feasibility of the proposed real-time inspection based on wireless sensors approach are illustrated via the practical inspection of a deck beam bridge.

1 GENERAL INSTRUCTIONS

Bridge Inspection plays a major role in providing safe infrastructure for our nation. In conventional bridge inspection[1], visual inspection is performed on the basis of experience to overview and analyze the bridge's overall condition and elements of the bridge including the concrete cover, steel bar corrosion, crack on the beam (the cracks' width, depth, length and its development direction to estimate the possibility of distress), etc. It is not sufficient in case of many serious defects. If needed, physical tests and advanced destructive and non-destructive evaluation techniques (NDE) are performed. Most of the NDEs are expensive to use in the field and sometimes not feasible for the field applications.

Many NDE technologies based on acoustic emission, thermal, ultrasonic, magnetic, electric, chemical and radiographic methods have been developed. Some of them are developed and some are still in research stage. All of these technologies used for bridge inspection focus on the testing of materials' characteristics and sometimes can only be used in the laboratory. Especially for the local inspection, these NDE techniques are mostly limited by the experimental costs and the complexity of real bridge structures.

NDE techniques can be effectively used in estimating the local characteristics of the bridge element, but are not efficient in estimating the overall behavior of the bridge, especially in-service evaluation of the bridge.

In this paper, it is proposed that following a cursory visual examination, identify critical locations at the bridge and inspect these locations by installing sensors. Most commonly used sensors include displacement-meter, tiltmeter, strain gage, etc. for static test; while accelerometer is mostly used for dynamic test. Data acquisition from the sensors needs pre-planning for the traffic control, load steps to be followed, time duration for the test, location of the truck on the bridge, data stabilization etc.

Currently, much interest has been generated by wireless sensors for various applications. These are devices that incorporate communication, processing, sensors, sensor fusion, and power source into a package currently about two cubic inches in size-networked autonomous sensor nodes. The wireless sensors are designed to be low cost, non-obtrusive, unattended or unmanaged, and dynamically reprogrammable. Also like the electric power utility, wireless sensors should be everywhere, always available, enabling virtually all of the tools of daily life, and be invisible to its users, allow running multiple applications while providing services such as messaging protocols, periodic timer events, static, persistent data storage, swapping of system components to create necessary functionality on the fly[2] .

In this paper, wireless accelerometer and PVDF have been proposed for measuring frequency, displacement and also strain. The important characteristics of these sensors are:

1. Real-time characteristics of the bridge can be measured and statistical analysis can be performed for bridge condition estimation. This process is more practical in estimating a current bridge capacity compared to the traditional load test.
2. During the inspection, bridge closure is not required. This is an important factor in planning the bridge inspection taking into consideration indirect economic loss and inconvenience to the public due to traffic routing.

This paper promotes the concept of application of wireless sensors developed at the Bridge Research Center for rapid installation and low power consumption for in-service real-time bridge inspection. The concept focuses on obtaining useful data such as strain, displacement, frequency for estimating the actual characteristics of the bridge while in service. Plans and procedures of the field inspection are detailed as well as the data processing and the analysis results are presented in the next sections.

2 WIRELESS SENSORS AND DATA ACQUISITION SYSTEM

Wireless technology has matured over the last few decades. Wireless communications is more reliable and stable so it can be utilized for various applications for data transmission. The benefits of wireless networking include increased mobility, simple and flexible installation, and easy scalability, i.e., wireless network can conveniently be extended and re-built. Based on the improvement of IC and embedded system technologies, both cost and size of communication chips has been reduced significantly. Combined with wireless communication technology, wireless sensor network is very easy to set up and is relatively low cost compared to time-consuming and expensive wire networks. In this application, simple Radio Frequency (RF) channel with Frequency Shift Keying (FSK) modulation is employed to cut down the power consumption but still provide demanded data rate and transmit range.

In this study, both PVDF and accelerometer have been developed as wireless sensors and are integrated with a wireless data acquisition system.

2.1 *Wireless PVDF sensor*

Piezoelectric materials generate charge (or voltage) under mechanical deformations. The amplitude and frequency of the signal is directly proportional to the mechanical deformation of the piezoelectric material. The resulting deformation causes a change in the surface charge density of the material so that a voltage appears between the electrode surfaces. Practically speaking, the lowest frequency measurable with piezo film is in the order of 0.001Hz. PVDF is principally used as sensors to measure the structural dynamic response. One of the realistic applications of PVDF sensor is for strain measurement or strain rates in mechanical and structural components based on their electromechanical coupling effects, which also constitutes a major subject of current research regarding so-called smart materials and structures as the strain signal is dynamic.

In this case, a PVDF transducer is called a dynamic strain gage. A change in length of PVDF sensor element creates a charge or voltage signal across the electrodes. It is a common practice to attach a piezoelectric polymer film on the structure surface and detect the strain-induced electric charge or the current via metal electrodes. The load or other factors and temperature changes may result in overall length changes of a structure or parts of the structure.

In order to compare these effects with calculated length changes, it is necessary to measure these quantities and calibrate the sensor accordingly. For better interpretation of the obtained data, a calibration factor between PVDF sensor and strain gage has been derived based on lab-environment experiments. The experiment was conducted on a cantilever beam. Both PVDF sensor and strain gage were attached to the same surface and same position of the beam. Excited by a shaker at the free end at a certain frequency, the response of both PVDF sensor and strain gage were recorded by an oscilloscope. The calibration of the strain gage gives the relationship between the strain gage output in terms of voltage and the corresponding strain value. Depending on the calibration factor, the voltage output from PVDF sensor can be converted into strain gage output and hence presented as strain value. Figure 1 shows the wireless circuit board attached to a PVDF patch. Fig 2 shows the components of integrated wireless sensor for PVDF.

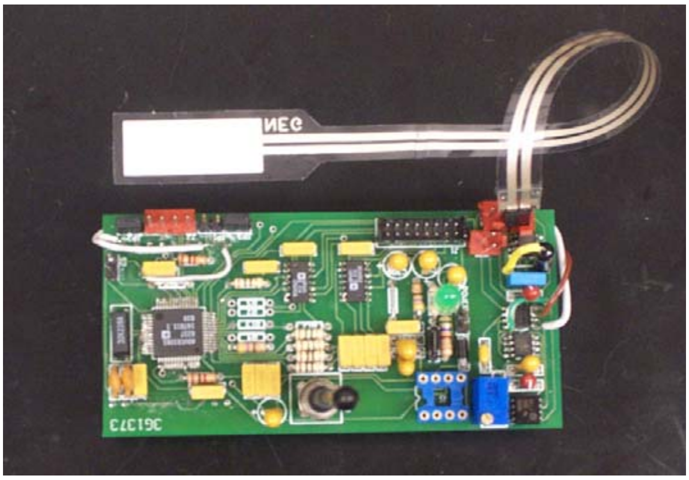


Figure 1. Caption of a typical figure.

Features of Wireless PVDF sensor includes:

- Up to 8 PVDF sensors can be connected to single unit
- Operating Temperature Range (ºC)
  -20 to +85
- PVDF Sensor Bandwidth (Hz)
  50
- Wireless Operating Range (feet)
  <500 outside
  <200 inside

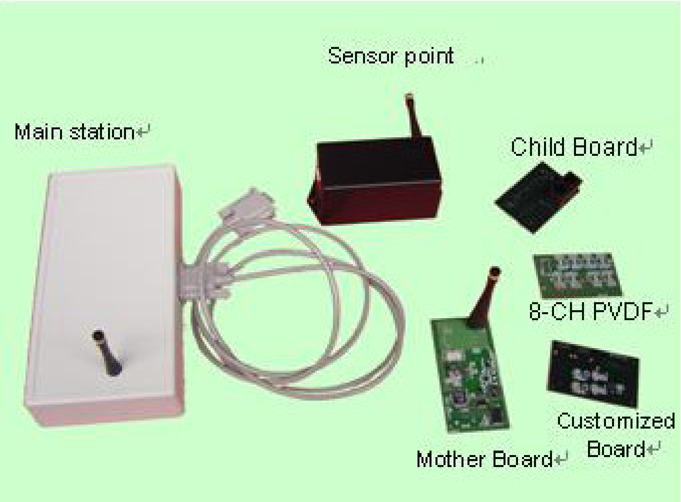


Figure 2. Photograph of various components of Wireless PVDF Sensor

2.2 *MEMS Accelerometer*

A high accuracy, high stability, low cost, low power, complete dual axis accelerometer with signal conditioned voltage outputs, all on a single monolithic IC by Analog devices has been integrated with wireless setup for civil infrastructure application. The accelerometer used meets the demanding performance specifications required by Vehicle Dynamic Control system manufacturers, including an extended operating temperature range and higher sensitivity. It can measure both dynamic acceleration (e.g. vibration) and static acceleration (e.g. gravity). It also can be used as a tilt sensor. The outputs are analog voltages proportional to acceleration. The accelerometer is 5mm x 5mm x 2mm in size with 8 lead hermetic LCC package. Figure 3 shows a photograph of accelerometer attached to a wireless unit.

The wireless accelerometer has the following specifications:

- Acceleration Input Range (g)
  ± 200mg
- Operating Temperature Range (ºC)
  -30 to +85
- Sensitivity 100mg /V
- Accelerometer Bandwidth (Hz)
  0.1 - 100Hz
- Wireless Operating Range (feet)
  <500 outside
  <200 inside

Figure 3. Wireless Accelerometer

2.3 *Framework of Wireless Smart Sensor*

The framework of the wireless smart sensor includes a microprocessor, wireless communication devices and optional memory devices for data storage (Figure 4). Both hardware and software for wireless sensor are selected based on the requirements of the sensor network. Embedded microcontrollers that consume little power for operation are used for this application.

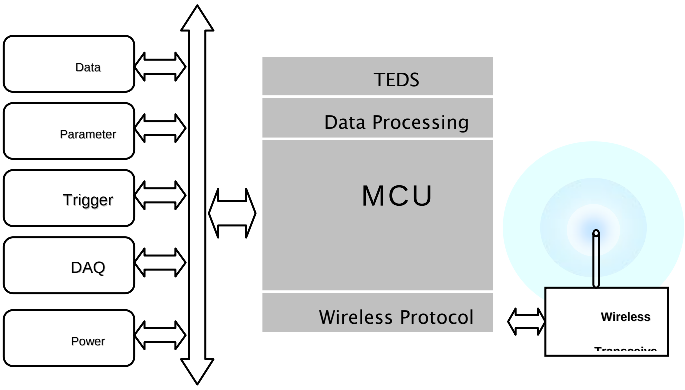


Figure 4. Wireless Sensor Network Framework

A microprocessor is included for analog/digital signal conversion (ADC), data storage & communication control on the Wireless Smart Board. Analog signal is generated by sensors and sent to the Sensor Conditioning Board. Analog signal conditioned by the conditioning circuit is transmitted to the microprocessor on the Wireless Smart Board via the board-to-board connector for analog-digital signal conversion. Digital signal is either transmitted back to the base-station for the real-time demo or saved on chip waiting for further process. Compatible software has been developed both for the microprocessor and for the PC which works as the base station. Received data can be analyzed using the developed software or by other analysis software for advanced analysis.

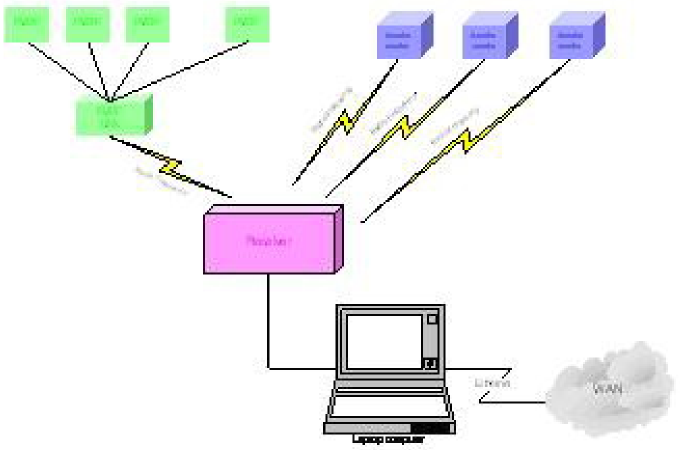
Different conditioning circuits have to be designed for different types of sensors according to their specific purpose, depending on generated signal feature and required output signal for ADC. Based on such a layout, another type of sensor can be easily developed by changing the conditioning board of this layout. The purpose of the conditioning circuit is to provide smooth analog signal which represents the desired feature's condition of the monitored structure in a particular range. This range is between 0 volts to 2.5 volts restricted by the analog-digital conversion port of the ADuC 832. In the system developed a single Sensor Conditioning Board can be connected to 8 independent PVDF film sensors at the same time which provide conditional analog signal for the 8 ADC channels of the microprocessor.

The sensor conditioning circuits is a high input resistance low pass filter. For a dual axis accelerometer, acceleration and tilt signal for each axis and one temperature sensor signal are collected for ADC. The analog signal for acceleration is modified to provide a clear response as low as 20μg. DC component and high frequency noise have been restricted and the cut off frequency of the low pass filter is 100Hz. For the analog signal representing the tilt response a low pass filter is needed to get the DC component of the output.

2.4 *Data acquisition and transmission system via Internet*

Since the accelerometers and PVDF sensors are all wireless sensors, the wiring and installation becomes very easy. In this inspection, a laptop computer is used to store data and also specific software is running on it to display and analysis data in real time. A wireless transceiver is connected to the laptop to transmit the received data to the laptop. Accelerometers are attached on the beam surface. They send data directly to the receiver through RF. PVDF sensors are connected to the 8-channel PVDF unit using wire. Then the data is sent to the receiver. The layout can be illustrated in the following diagram.

If internet is available at the field, the laptop can be connected to it. And then all the real-time data and the analysis results can be accessed remotely.



3 REAL-TIME INSPECTION PROCEDURE

A 6 span prestressed concrete beam bridge with the longest span of 75.9 ft and 33 ft wide, located in the Illinois was inspected. The bridge consists of 11 adjacent prestressed concrete beams joined along the length by shear key and transverse tie rods at the diaphragm locations.

Visual inspection of the bridge showed 4 spans with areas of concrete cover spalling at the bottom with exposed corroded reinforcements. The exposed reinforcement is the transverse steel of the wire mesh (8 x 3 – W 2.5 x W 5.5). In case of prestressed beam, most of the time the wire mesh is in contact with the prestressing steel, hence it of concern to the bridge authorities as the corrosion of prestressing steel can lead to sudden failure. The other concern is the differential vertical displacement of the adjacent beams which leads to discrepancies in the estimated load distribution between the beams. Hence it is of prime importance to measure the load distribution along the transverse direction and estimate the remaining capacity of the bridge.

3.1 *Objectives of the inspection:*

1. To find the differential deflection of the deck-beams under service load;
2. To find the load distribution of the deck-beams (It can be calculated by the value of the ratio of the strain/deflection[3]);
3. Based on the preliminary inspection analysis results, a load test may be proposed to estimate the load carrying capacity of the bridge.

Photograph of the underside of the bridge is shown in Figure 5. Corroded rebar mesh is visible through concrete spalls.

Figure 5. Photograph of the underside of the bridge span

3.2 *Inspection Procedure:*

3.2.1 *Sensor locations on Prestressed Deck Beam Bridge*

Sensor types and locations are shown in the schematic in figure 6. It must be noted that beams 1 – 6 were first instrumented and the data recorded and then the next set of beams, Beams 6 -11 were instrumented and data recorded. This was due to the number of sensors available for testing and since the purpose of the preliminary test was to check the applicability of the wireless sensors hence this arrangement was chosen as the best alternative.

Wireless sensors were installed at locations shown in the Figure 4. No traffic closure was required as all the sensor installation was done underside of the bridge beams and the span chosen was not over water hence no special equipment was needed for installation. A photograph of the PVDF patch installed with the wireless unit is shown in Figure 7.

3.2.2 *Installation, data processing procedure in the field*

Steps followed for the test:

1. Install strain gages & PVDF at the specified locations and check the connections for each channel
2. Install accelerometer, LVDT and check the connections.
3. Test and collect data for about 2-3 hours, process the data from strain gages/PVDF to find the directly loaded beam, also get distribution value of the beams, this is a statistical value.
4. Collect data from every sensor and analyze the data for load distribution and the directly loaded beam deflection model in real time, (test for 30 minutes)
5. If needed move the sensors to other locations depending on the preliminary analysis results to obtain data for other beams.

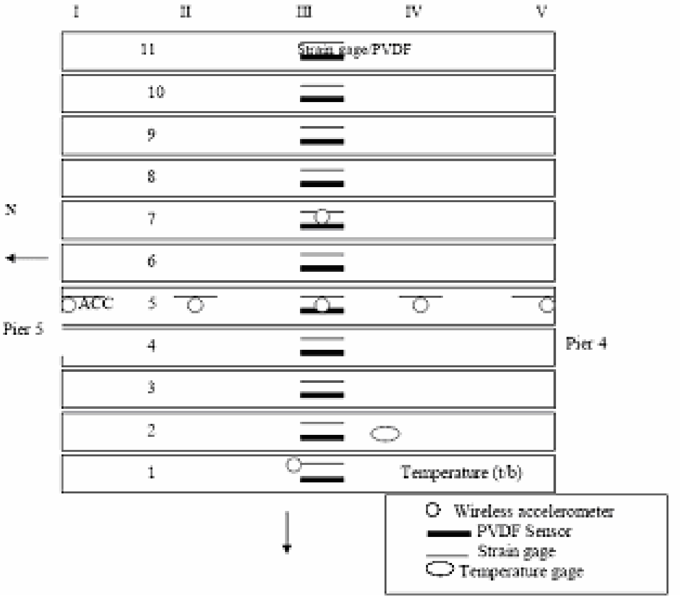


Figure 6. Location of the sensors

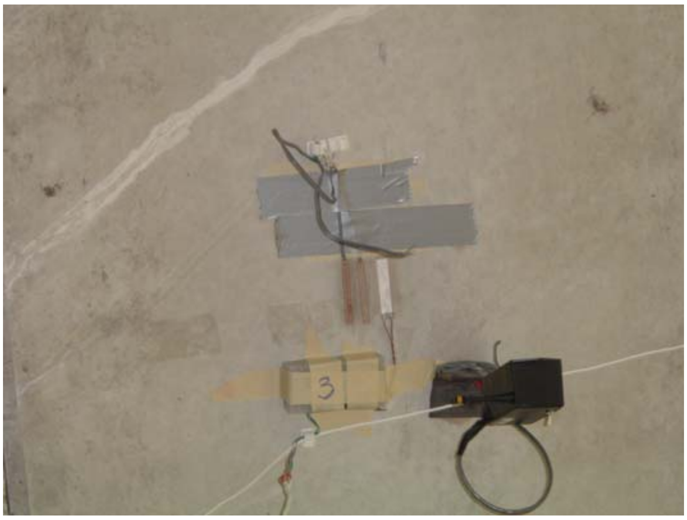


Figure 7. Wireless PVDF installed on the beam 3

4 ANALYSIS RESULTS AND DISCUSSION

The preliminary data obtained from the first test is presented in this section. Subsequent tests have been planned based on these results. Since only 6 strain gage conditioners were available at the time of testing hence half of the bridge beams for the span chosen were monitored at a time. Hence some data maybe not reflect the actual condition of the total 11 beams of the bridge. This has been taken into consideration while drawing conclusions from the obtained data. Data for each type of sensor is presented in the following sections.

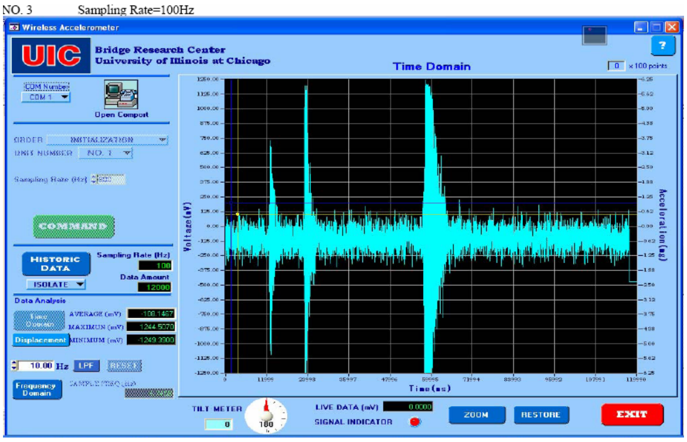
4.1 *Wireless Accelerometer*

4.1.1 *Testing data*

Sampling rate: 100 HZ

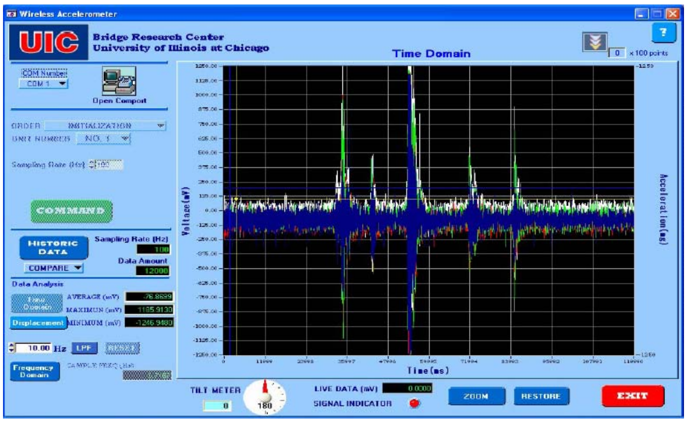
Data process methodology: Maximum/peak value of 100 as the acceleration value. Two minutes data collection period for each group of beams. Load distribution is defined as the ratio of peak amplitudes for each beam to the sum of peak amplitudes of all the beams in the group. Wireless Sensor response installed at Beam#3 are shown in Fig. 8. Table 1 shows the peak amplitudes for each beam the percentage distribution considering the 5 beams under inspection. Figure 9 shows a comparison of the accelerometer response for beam # 1, 2, 3, 4 and 5.

NO. 3 Sampling Rate=100Hz



Sampling Rate (Hz) 100
Data Amount 12000
AVERAGE (mV) -108.1467
MAXIMUN (mV) 1244.5070
MINIMUM (mV) -1249.3900

Figure 8. Response from wireless sensor on Beam#3



Sampling Rate (Hz) 100
Data Amount 12000
AVERAGE (mV) -76.8699
MAXIMUN (mV) 1185.9130
MINIMUM (mV) -1246.9480

Figure 9. Comparison of Response from wireless sensors on Beam#1, Beam #2 and Beam #3

Table 1. Peak Amplitudes for each beam and percentage distribution

Beam	1	2	3	4	5
Total peak amplitudes	2040.75	1649.94	1722.87	1490.77	1625.87
Percentage (%)	23.93	19.34	20.2	17.48	19.06

The data shows that all the beams equally share the load. Accelerometers give global characteristics of the beams. Hence it indicates that shear key and tie rod are in good condition. It can be noted from Table 1 that beam#1 has relatively high distribution. This has been discussed in a later section justified by theoretical calculation.

Beam#1 (exterior or facia beams) shows higher distribution percentage. The observations can be justified by following reasons.

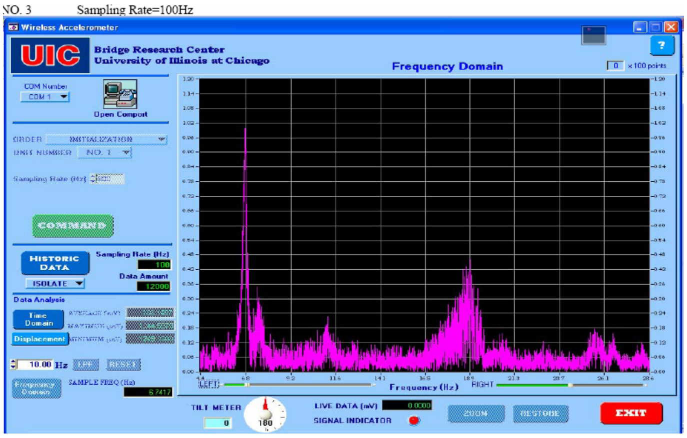
(i) The sides of facia beams are exposed to de-icing salt and drainage runoffs. This leads to deterioration in terms of cracking, spalling and reinforcement corrosion and thus results in lower stiffness.

(ii) The interior beams have more friction bonding between beams compared to exterior beams.

Table 2. Frequency Analysis Results for the Beams 1-5

Beam	f1	f1(twin)	f2	f3	f4
1	6.70 -6.79	7.2 0	11.18 -11.35	19.35 -19.45	-
2	6.70 -6.79	7.2 1	11.18 -11.35	19.35 -19.45	-
3	6.70 -6.79	7.2 0	11.18 -11.35	19.35 -19.45	29.24
4	6.70 -6.79	7.2 0	11.18 -11.35	19.35 -19.45	-
5	6.70 -6.79	7.2 0	11.18 -11.35	19.35 -19.45	-

NO. 3 Sampling Rate=100Hz



Sampling Rate (Hz) 100
Data Amount 12000
SAMPLE FREQ (Hz) 6.7417

Figure 10. Frequency Analysis plot for Wireless Sensor installed at Beam #3

Frequency analysis plot for the beam#3 is shown in Figure 10. The software developed at the Bridge Research center has been used for measurement and analysis of the accelerometer and PVDF data. Frequency analysis of the data obtained from 5 beams is shown in table 2.

Most of the beam data had twin peaks as indicated in table 2. No explanation has been found for this behavior, further tests may reveal the cause for this kind of behavior.

4.1.2 *Comparison with FEM Analysis*

On the basis of FEM analysis (details not described in this paper), we can assume that the 11 beams span can be regarded as a double-direction plate with a small camber. The constrained condition of the plate is that: two sides on the pier are simple-support while the other two sides have no constraint. The four sides of the plate deflect under centrally positioned load, while deflections on the supported-sides are relatively small as they are constrained, two free sides can deflect more. This assumption needs to be verified in the load test on the bridge, as well as compared to FEM dynamic analysis results to gain a complete and logical explanation for the deck beam bridge deterioration assessment.

The FEM dynamic analysis results can provide the first 10 mode frequencies of Bridge under consideration. But the acceleration measurement provides the first 5 mode frequencies from wireless accelerometers. Hence, damage assessment based on the FEM simulation and dynamic measurements for the first 5 modes is shown in Table 3.

Table 3. Comparison between FEM Analysis and Accelerometer Measurements Analysis

Mode #	**1**	**2**	**3**	**4**	**5**
FEM Analysis	6.6	12	20.1	30.7	31.5
Measured Result	6.6	11.5	18.9	26.1	28.6

4.2 *PVDF Sensor*

This was the first application of PVDF sensor on a concrete bridge. Most of the previous application involved steel beams. PVDF sensors give local characteristics response due to imposed loads. Figure 11 shows the response of PVDF sensor installed on Beam 3. Figure 12 shows the frequency distribution plot for the dynamic response from Beam 3.

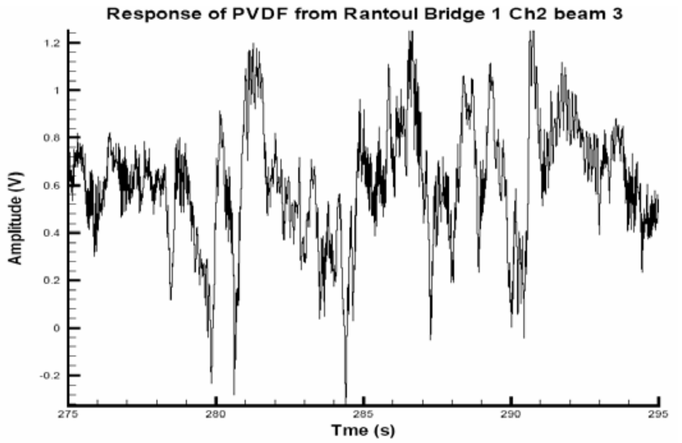


Figure 11. Response of the PVDF Sensor located at beam 3 of the bridge.

From the above 5 data sets for PVDF sensors collected from Beams 1,3,4 and5;it can be observed that Beam#3 is the most frequently loaded beam which gives the highest response for the traffic in terms of dynamic response peak power. Following observations were made from the preliminary data.

1.PVDF wireless sensor seems to work on theconcrete bridge. However, it can only detect the signal from heavier traffic. For lighter loads, the response is very noisy and thus difficult to analyze. Hence, more research work needed to improve the sensitivity of the sensor.

2.In this study, beam #3 of the bridge showed largest peak amplitude. The location of the traffic was monitored visually and it showed that most of the traffic was on beam 3. Hence tracking the position of the traffic is recommended for the next inspections.

3.The frequency of the first perturbation modal of the bridge in this study was obtained as 6.45 Hz.

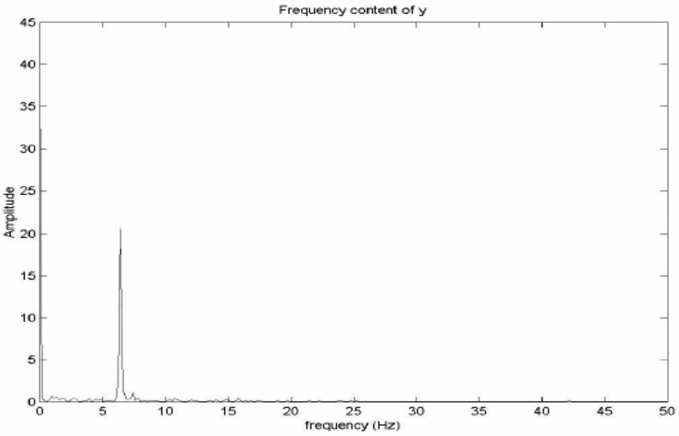


Figure 12. Frequency Analysis of the PVDF sensor data located at beam 3.

5 CONCLUSION

Application of wireless sensors developed at the Bridge Research Center for rapid installation and low power requirements for in-service real-time bridge inspection, focused on obtaining useful data such as strain, displacement and frequency for estimating the actual characteristics of the bridge while in service. From the inspection procedure and the collected data, it is concluded that:

1.The proposed real-time inspection based on wireless sensors approach is effective and feasible.

2.The data is collected for the random traffic on the bridge and hence gives true statistical information as compared to the traditional load test that gives information only for the duration of the test and for the specific vehicle load used.

3.Wireless accelerometer data gives the global condition of the beams, which gives a reasonable conclusion that the beams are sharing the load evenly and the tie-rods and hear-keys are in good condition.

4.Wireless PVDF data indicates the local characteristics of beams. Data shows that Beam 3 is frequently loaded which was verified by looking at the traffic position when the data was taken.

5. Based on real-time data acquisition for long term monitoring, periodic reports of the bridge structural condition can be obtained. It can serve as

the bridge management report file for the bridge and is cost effective for accumulation of structural data.

6.Visual observation of the underside of the beam shows no structural cracks but corroded steel-bar with very thin concrete cover. This could be attributed to construction defect of insufficient concrete cover. The bridge is a prestressed structure with shear keys between beams and tie rods at 1/3 point of the span. From the data obtained from the sensors it can be stated that the shear keys and tie rods are acting integrally to support the deck and the superstructure.

6 ACKNOWLEDGEMENT

The authors would like to thank John Morris, Bureau of Bridges and Structures and Kevin Woods, Dist.5 Bridge Maintenance Engineer for giving the opportunity to inspect the bridge and also providing us the must needed technical guidance.

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Table 4. Percentage strain distribution from PVDF sensors installed on Beams 1,3,4 and 5

	Data Set 1		Data Set 2		Data Set 3		Data Set 4		Data Set 5	
Beam	Power	Perc.	Power	Perc.	Power	Perc.	Power	Perc.	Power	Perc.
1	94.32	18.56%	345	20.48%	102.47	19.83%	195.78	18.02%	73.73	19.55%
3	225.11	44.29%	645.9	38.34%	209.73	40.59%	491.2	45.21%	153.19	40.61%
4	91.52	18.01%	347.75	20.64%	102.59	19.86%	195.99	18.04%	75.45	20%
5	97.32	19.15%	345.84	20.53%	101.88	19.72%	203.39	18.72%	74.82	19.84%