Quarterly Report

Project Title:
Development of a Self-Sustained Wireless Integrated Structural Health Monitoring System for Highway Bridges

Cooperative Agreement # RITARS11HUMD

Sixth Quarterly Progress Report

Period:
October 15, 2012 through January 14, 2013

Submitted by:
The Research Team – University of Maryland with North Carolina State University and URS

Submitted to:
Mr. Caesar Singh, Program Manager, US DOT

Date: January 24, 2013

Table of Contents

EXECUTIVE SUMMARY

I — TECHNICAL STATUS

Accomplishments by Milestone

1.1. General

- Updated Project web site (http://www.ncrst.umd.edu/) (Task 1 and Deliverable 2)
- Delivered sixth quarterly financial and technical reports (Task 6 and Deliverable 11)
- Scheduled Phase III Progress Review Meeting with Mr. Caesar Singh of RITA, USDOT on January 18th, 2013 (Task 6 and Deliverable 11)
- Presented at the TRB Conference and published several journal papers (Task 6 and Deliverable 12).
- The proposed work plan is shown below as Milestones/Deliverables. Dark Shading indicates Deliverable items and Tasks in which the Research Team has been engaged over the past quarters. Lighter shading indicates anticipated duration for Deliverables by quarters. Grid pattern shading means partially fulfilled.

Deliverables	Action	Quarter No.									
		1	2	3	4	5	6	7	8	9	10
1	Form TAC and conduct kick-off meeting. Determine baseline field test procedure (Task 1)										
2	Establish and update project web site (Tasks 1 & 6)										

3	Conduct baseline field test and finite element analysis on pre-selected bridges (Task 1)
4	Design, fabricate and characterize AE sensor and measure the performance (Task 2)
5	Develop and evaluate T-R method for passive damage interrogation (Task 3)
6	Develop and experimentally evaluate wireless smart sensor and hybrid-mode energy harvester (Task 4)
7	Implement passive damage interrogation T-R algorithm in the wireless smart sensor on bridges (Task 4)
8	Integrate and validate AE sensors with wireless smart sensor and hybrid-mode energy harvester (Task 5)
9	Develop and conduct field implementation/validation of commercial-ready ISHM system with remote sensing capability (Task 5)
10	Recommend strategy to incorporate remote sensing and prognosis into BMS (Task 5)
11	Prepare and submit quarterly status and progress reports and final project report (Task 6)
12	Submit paper to conference presentations and publication to TRB meeting or other conferences (Task 6)

Note: Deliverables items 7, 8 and 9 for the 6th quarter are partially fulfilled. They are still tested and modified by the NCSU team. The explanation of the delay is described and highlighted on page 9 under Section 1.6 - Future Plan.

1.2. Remote Health Monitoring System

- Real time strain and AE data monitoring is continuously viewed (, except two occasions due to thunderstorms and accidently pulled the plug by maintenance workers.) The following web address should display the BDI strain and AE data, both the graph and the properties.
  1) Try entering this web address into your browser (either Internet Explorer or Firefox should work fine)
  Link 1 to Remote BDI strain monitoring (link to http://166.143.163.215:8000/BDI.html)

Link 2 to Remote AE sensor monitoring (link to http://166.143.163.215:8000/AE.html)

2) It will then ask you to download the Labview plug-in, and direct you to the webpage with the download.

3) After the plug-in is downloaded and installed, you should be able to view the file.

1.3 Pilot Bridge Second Test and following activities

- MD Bridge No. 1504200 I-270 over Middlebrook Road, was first tested on March 19-21, 2012 and then second tested on June 28 &29, 2012. Here is the list of troubleshooting and configuring hardware in the field in this quarter to alleviate problems with noise and interference (Task 1 and Deliverables 1 & 3; Task 2 and Deliverables 4 & 9).
  - **October 18, 2012** – Checked the connections of Amplifiers, and the DC Power Supply. Reset connections and powered off/on all equipment.
  - **November 2, 2012** – Looked for sources of interference in the field. Brought the PXI system back to the lab. Connected PXI to the laboratory sensors and found the PXI is operating correctly.
  - **November 9, 2012** – Brought the PXI back to the field and attached test panels to compare the plots of sensor data.
  - **November 15/16, 2012** – Visited the field with North Carolina State University graduate students. Replaced one inoperable amplifier with a specialty made amplifier: coated with waterproof epoxy. Replaced all sensors and covered with plastic to guard the sensors from moisture. Found there is still interference and brought the PXI back to the lab for more testing.
  - **November 30, 2012** – Cut wires in 100ft lengths to test if interference was coming from the wires. Consulted with National Instruments (NI) for grounding solutions and for field wiring and noise considerations for analog signals.
  - **December 4, 2012** – Reconfigured the ground so all equipment was grounded to the bridge. This solved the interference problem that was disrupting the AE sensors.
- Extracted about 40 days of stress and AE data from DAQ system and moved to cloud for storage.
  - Organized data in orderly segments to facilitate plots and rainflow analyses.
  - Processed data through detrend functions to remove drift.
- Fatigue life prognosis has been developed and its flowchart is shown in Appendix A
- Flowchart of the quantitative bridge condition assessment in the Bridge Management System (BMS) has been drafted and is shown in Appendix B

1.4 AE Sensor

- Long-term remote acoustic emission monitoring of the existing fatigue cracks has been carried out on the I-270 Middlebrook Bridge near Germantown, Maryland since July 10, 2012. In the last quarter, unexpected issues like noises (see Figure 1) came up and several field trips to debug the problem were arranged. Finally, the problem was determined to be related to grounding of sensor electrical circuit, and after proper grounding measure was taken the noise went away. Continuous collection of AE signal data was resumed after fixing this noise problem on December 6, 2012. On November 14 and 15, 2012, another comprehensive field test of this steel I-girder bridge was conducted (see Figure 2). Three piezoelectric AE sensors were replaced with new sensor installations, as shown in Figure 3. These AE sensors were checked to ensure they are working during field test. On site integration test with NCSU participation was conducted for November 14, 2012. In addition, laser distance sensor was employed to monitor bridge deflections at a typical sampling rate of 10 Hz remotely with an accuracy of 1 mm and measurement range up to 500 m. A major cause for the fatigue crack is believed to be live load induced stresses in the diaphragm connection welds resulting from differential deflections between adjacent girders. The laser distance sensor operates on the basis of non-contact comparative phase measurements with amplitude modulation, which is much less costly than laser Doppler vibrometry scanner. Sample signals of the laser distance sensors are shown in Figure 4.

- Characterization test of piezo film AE sensor on six full-scale welded tubular joint specimens in the lab was completed in December 2012. Typical AE signals collected with piezo paint AE sensor used to monitor fatigue crack growth are shown in Figure 6. Piezo paint AE sensors are installed on the steel tube specimens as shown in Figure 5-(a). Seven piezo film AE sensors are installed on each specimen to monitor any AE signal caused by fatigue crack initiation and propagation. The correlation between one AE feature – AE hits or counts vs. load cycles and crack length is plotted in Figure 5-(b). This correlation has a potential to be used for quantifying crack length, which provides critical data for fatigue life prognosis.
- Integrating wireless sensor board with piezo paint AE sensor was examined in the lab test of welded tubular joint specimen WTJ-6, as shown in Figure 7-(a). Sample AE signals collected with wireless piezo film AE sensors of different sampling rate of 200 kHz is shown in Figure 7-(b).

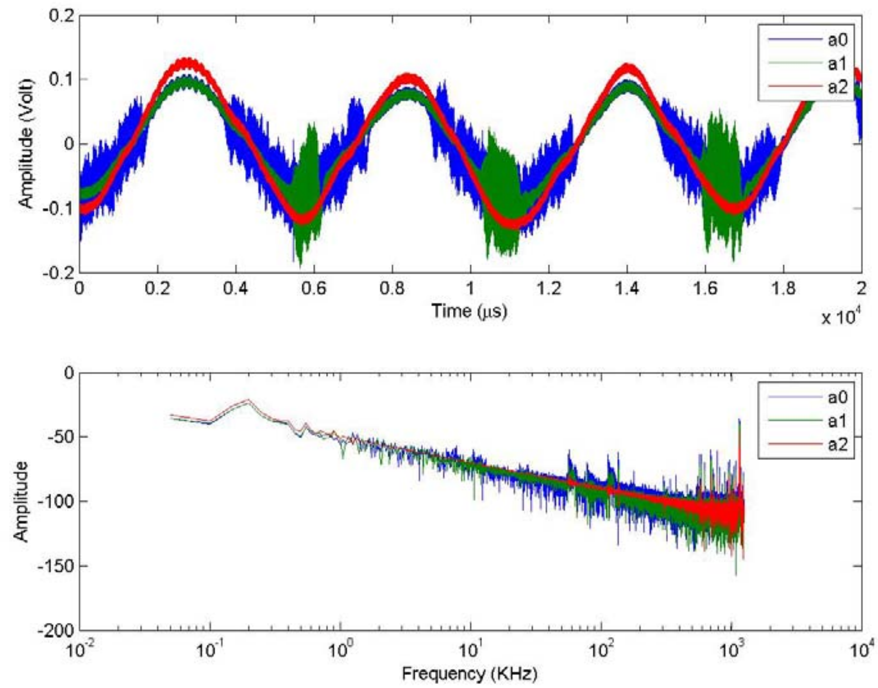
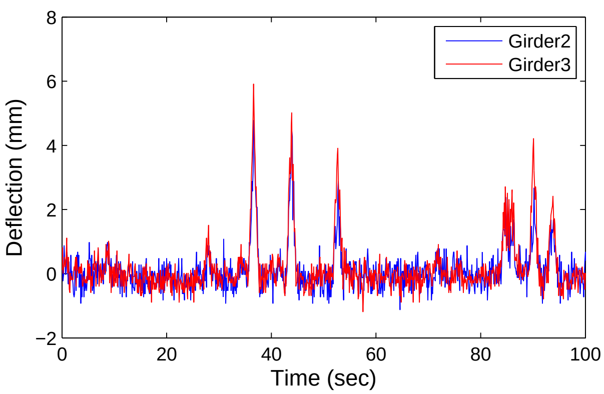


Figure 1. AE signals with overwhelming EMI noise due to grounding issues measured by the piezoelectric paint AE sensors during long term monitoring

Figure 2. Field test on the I-270/Middlebrook Road Bridge, Maryland

Figure 3. New installation of piezoelectric film AE sensor near existing fatigue crack on connection plate on Girder #3

(a)


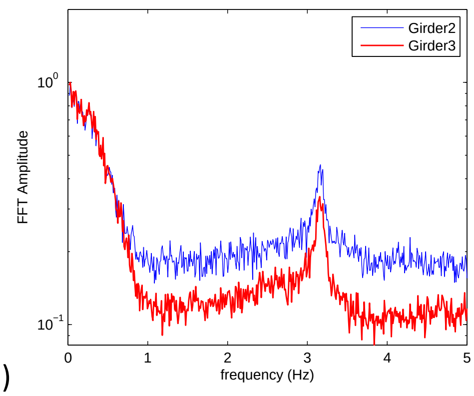
(b)


Figure 4. Measured girder deflections: (a) sample time series; (b) FFT spectrum (average of 36 records) (fundamental frequency identified as 3.16 Hz)

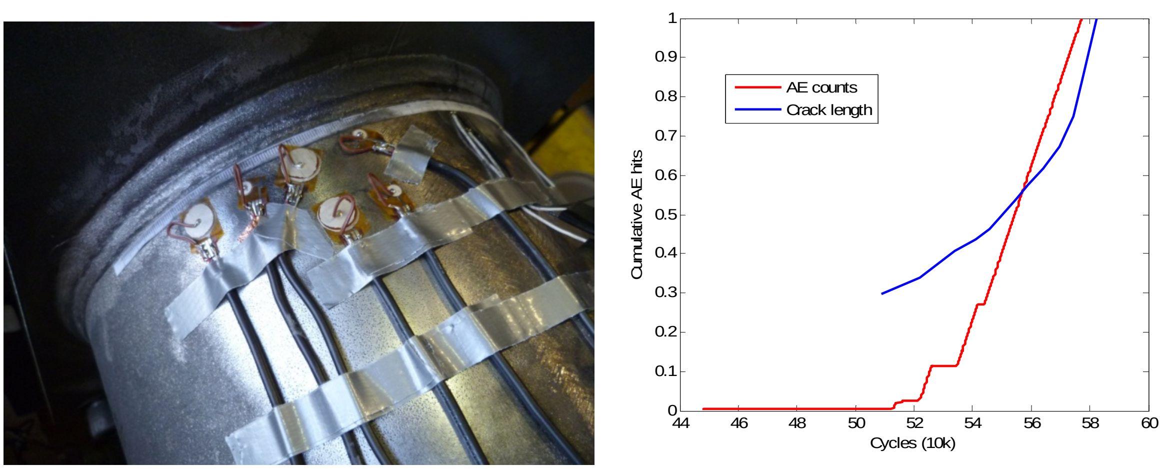


Figure 5. Piezo film AE sensor array (left) and Relation between cumulative AE signal counts (hits) and loading cycles of the fatigue test

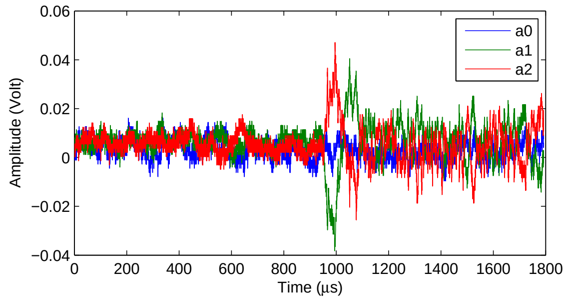


Figure 6. Typical AE waveform measured by piezoelectric paint AE sensor at early stage of crack initiation in fatigue test of the welded tubular joint specimen

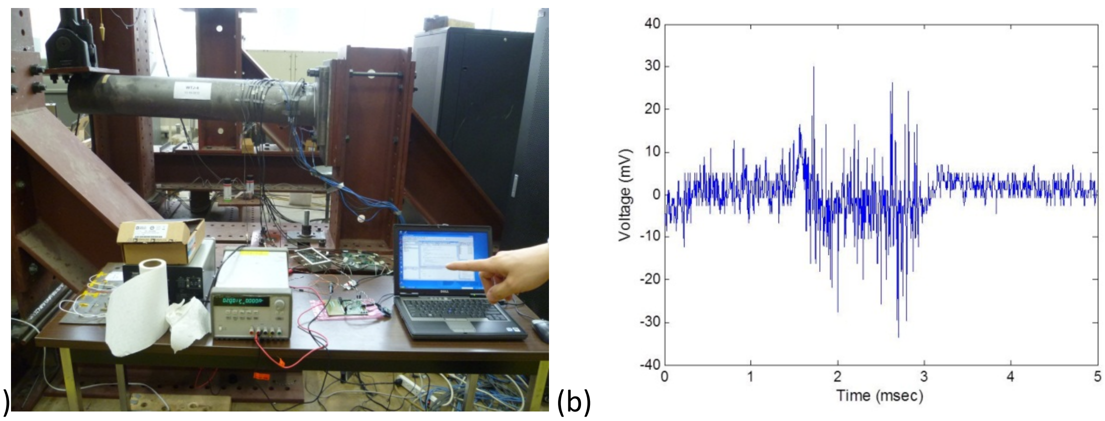
(a) 

Figure 7. (a) Test setup for validation test of wireless piezo film AE sensor on welded tubular joint fatigue test and (b) Sample AE signal collected by wireless piezo film AE sensor at 200 kHz sampling rate

1.5 T-R Method, Energy Harvesting and Smart Sensor

Accomplishments of these tasks by NCSU team are detailed in Appendix C and summarized here:

- New wireless sensor board integrated into piezoelectric sensor and accelerometer was designed, and the hardware of which has been soldered. The performance test of piezoelectric sensors is preparing, and will be carried out in a few days.
- The Miniature wind turbines, a total of 16, have been designed and manufactured, which will be installed in a short time.
    - The performances of wireless accelerometer sensors and the whole WSN were tested again in the lab, which also carried out in field test of I-270 Middlebrook Bridge in Maryland and Bearfort #25 Bridge in North Carolina. These works have been done to make sure that all sensors can correctly work in the whole system.

1.6 Future Plans

Pilot Bridge Testing (UMD team led by Dr. Fu) –

- Continue monitoring, evaluating and validating results from the 2nd pilot testing bridge (MD Bridge No. 1504200 I-270 over Middlebrook Road)
- Long-term monitoring using AE sensors on the pilot test bridge in Maryland
- Preparing field testing the proto-type ISHM system on the pilot test bridge in NC
- Collecting more W-I-M data to simulate more traffic through FEM models for all pilot test bridge in Maryland
- Validating test data with FEM results for the cause of fatigue.

AE Sensor (UMD team led by Dr. Zhang) -

- Continuing the long-term fatigue crack growth monitoring with piezo film AE sensor and remote sensing features on I-270 bridge in Maryland. Focus will be placed on analyzing the AE data collected from this field test. In the next quarter, integrating wireless piezo paint AE sensor will be examined during the field test.
- Testing and validating third-generation piezo film AE sensor couple in the lab to characterize its performance for fatigue crack localization. The sensor design has been completed and will be sent to flexible circuit manufacturer in Spring 2013. Another lab fatigue test will be conducted in this quarter to characterize the this design of piezo film AE sensor couple. The test specimen is a one-inch thick steel plate with welded connected plate. Fatigue crack is designed to initiate at the tip of the welded connection plate at load cycle number approximately 150k cycles. This near-field AE monitoring strategy refined for piezo film AE sensor couple will be employed for crack localization.

T-R Method, Energy Harvesting and Smart Sensor (NCSU team led by Dr. Yuan) -

- Test the piezoelectric sensor board with power.
  - Test the JTAG function of the microcontroller and FPGA, to ensure that the program can be downloaded correctly.
  - Test the CC2420 IC to make sure the wireless communication can work well.
- Modify the enclosure to install the new sensor board and battery.
- Finish the program of the microcontroller and FPGA.
- Debug the program and do some piezoelectric acquisition experiments in the lab.
  - Test the sensor and debug the program problem with it.
  - Using the new sensor and oscilloscope to acquire the AE signal separately and compare their data.

II — BUSINESS STATUS

- Hours/Effort Expended – As the last reporting period, PI Dr. Fu worked one month paid by his cost sharing account for 167 man-hours. Three (3) UM and two (2) NCSU graduate assistants worked three months half-time (20 hours), the quarterly accounting deadline, for a total of 1,470 man-hours (one NCSU assistant is partially cost-shared by their University.)

- Total Budget - $1,151,169 & Invoiced (12/31/12) - $465,840.66 (40.5%)
- Cost sharing committed - $1,525,063 & Cost shared (12/31/12) - $433,536 (28.4%) which is about one-to-one matched with the Federal share
- This project is back heavy toward the end and the spending will speed up in this year
- Some heavy equipment will be purchased later for the demo large span bridges
- Some expenses will be shown in the later invoices

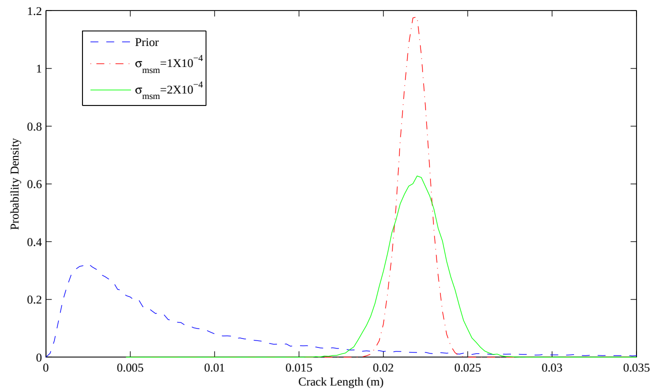
Appendix A - Fatigue Life Prognosis and its Flowchart

Appendix B – Flowchart of quantitative bridge condition assessment in the Bridge Management System (BMS)

Appendix C – Details of the NCSU accomplishments by milestone

Appendix A - Fatigue Life Prognosis and it Flowchart

Ref: Zhang, Y ., Zhou, C., Fu, C.C. and Zhou, Y.E. (2013). “Field monitoring of fatigue crack on highway steel i-girder bridge,” Proc. TRB 92nd Annual Meeting, Washington, D.C., January 13-17, 2013



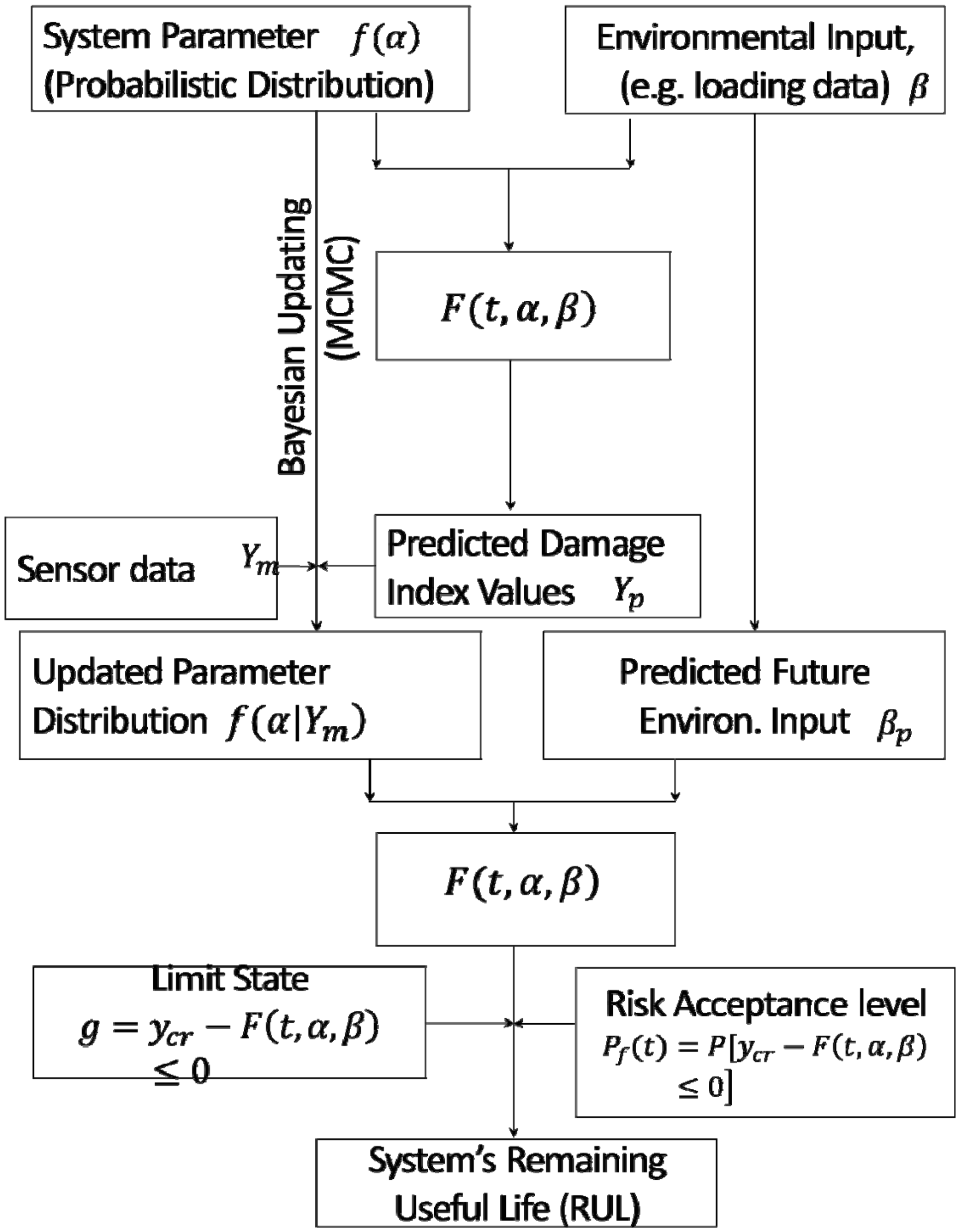
$$y(t) = F(t, \alpha, \beta) + \varepsilon\ (t)$$

- $\varepsilon\ (t)$*: error term* $y(t)$*: damage index*
- $F(t, \alpha, \beta)$*: system evolution function*

- For fatigue prognosis, the Paris law is adopted

$$\frac{da}{dN} = C(\Delta K)^m$$

- *C and m: material fatigue constants*
- ΔK: *stress intensity factor range*
- *a: crack depth; N: loading cycle*


System Parameter $f(\alpha)$
(Probabilistic Distribution)
Environmental Input,
(e.g. loading data) β
Bayesian Updating
(MCMC)
$F(t, \alpha, \beta)$
Sensor data Y_m
Predicted Damage
Index Values Y_p
Updated Parameter
Distribution $f(\alpha|Y_m)$
Predicted Future
Environ. Input β_p
$F(t, \alpha, \beta)$
Limit State
$g = y_{cr} - F(t, \alpha, \beta) \leq 0$
Risk Acceptance level
$P_f(t) = P[y_{cr} - F(t, \alpha, \beta) \leq 0]$
System's Remaining
Useful Life (RUL)

Appendix B –Flowchart of quantitative bridge condition assessment in the Bridge Management System (BMS)

By Tim Saad and Chung C. Fu

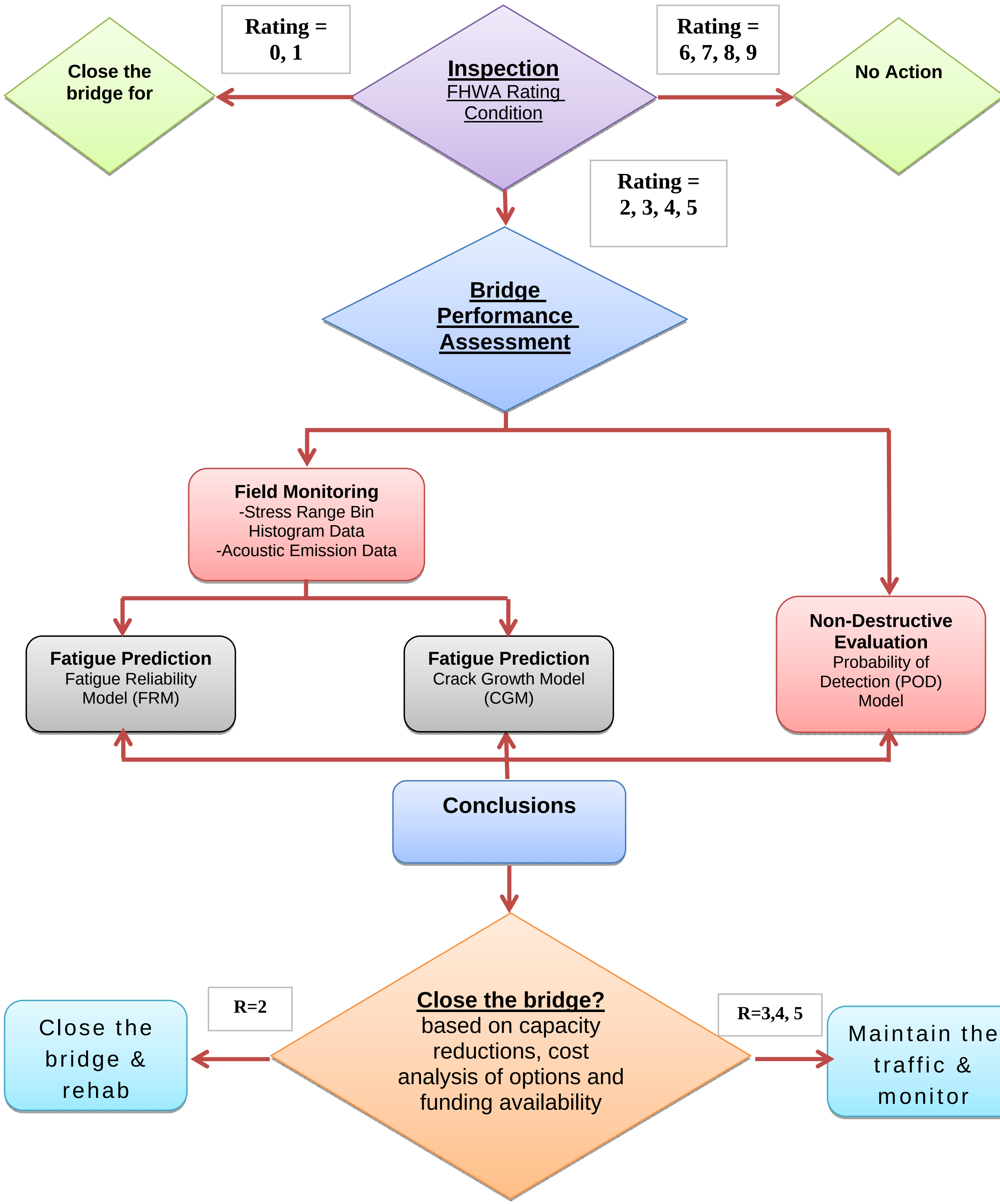


Table 1 Substructure Condition Rating by the FHWA National Bridge Inspection Standards ((FHWA) 2011)

Rating	Condition Description
9	Excellent condition
8	Very good condition – no problems noted
7	Good condition – some minor problems
6	Satisfactory condition – structural elements show some minor deterioration
5	Fair condition – all primary structural elements are sound, but may have minor section loss, cracking, spalling or scour
4	Poor condition – advanced section loss, deterioration, spalling or scour
3	Serious condition – loss of section, deterioration, spalling or scour have seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.
2	Critical condition – advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored, it may be necessary to close the bridge until corrective action is taken.
1	"Imminent" failure condition – major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put back in light service
0	Failed condition – out of service – beyond corrective action

Reference:

(FHWA), Federal Highway Adminstration. *2008 Status of the Nation's Highways, Bridges, and Transit: Conditions and Performance.* April 4, 2011. http://www.fhwa.dot.gov/policy/2008cpr/chap3.htm (accessed July 13, 2011).

Frangopol, Dan M, and Kihyon Kwon. "Bridge Fatigue Assessment and Management Using Reliability-Based Crack Growth and Probability of Detection Models." *Probabalistic Engineering Mechanics* 26 (2011): 471-480.

Appendix C - Details of the NCSU accomplishments by milestone

- The schematic design of a new wireless piezoelectric sensor board has been completed. This new board is mainly consisted of two parts. One part is using a 8-bit microcontroller to get acceleration data, store piezoelectric data in flash IC, communicate with wireless IC CC2420 and get piezoelectric data from FPGA. Another part is using a FPGA and a piezoelectric amplifier circuit to capture 3-channel piezoelectric data, store the piezoelectric data in SRAM IC and send them to microcontroller when it received command from microcontroller.

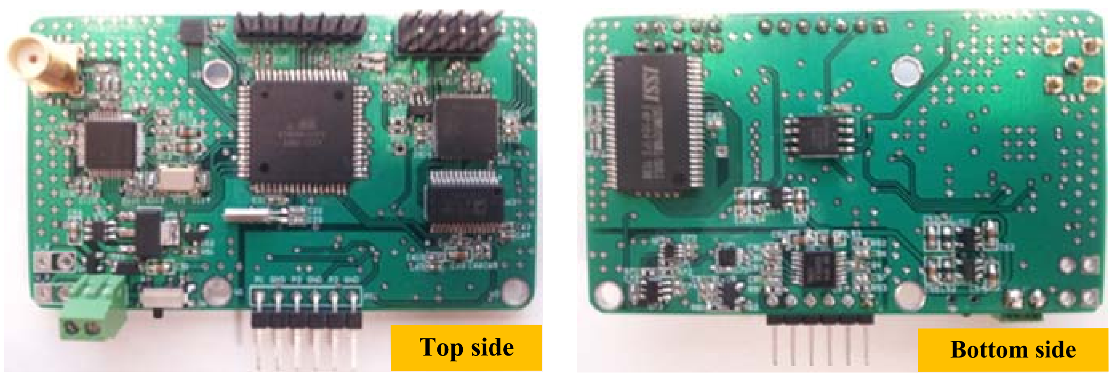


Figure 1 The new designed sensor board

- Wireless accelerometer sensor and its performance test in lab

Each single wireless sensor was tested on a shaker, which excited by a sinusoidal wave with the frequencies from 1 Hz to 60Hz. The purpose for this test is to get the resonant frequency of the whole test instrument, then observe response of the sensor under the excited frequency. Figure 2 and 3 show the FFT of the test result, we find the resonant frequency is 14Hz (the amplitude is highest) through analyzing all test cases.

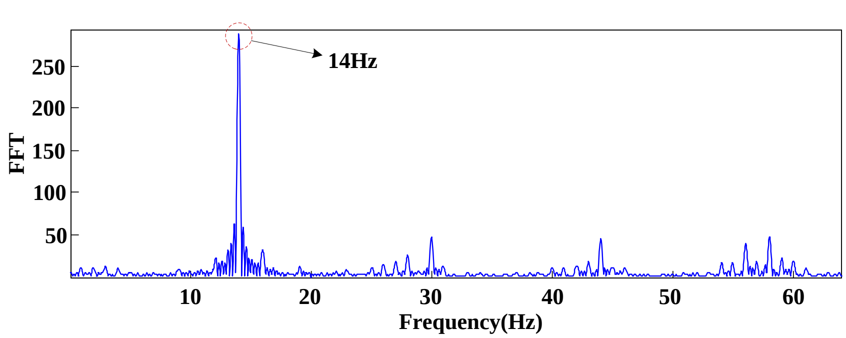


Figure 2 The FFT of sensor under 14Hz excitation

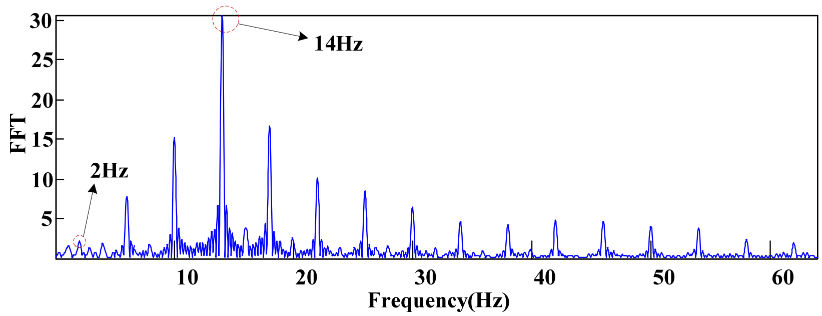


Figure 3 The FFT of sensor under 2Hz excitation

- Field test for two different bridges by using the WSN

In order to verify the reliability of the whole system, field test for two different bridges (I-270 Bridge in MD and Bearfort # 25 Bridge in NC) by using this system were carried out. Fig. 4 and Fig.5 show the test results collected by these wireless sensors.

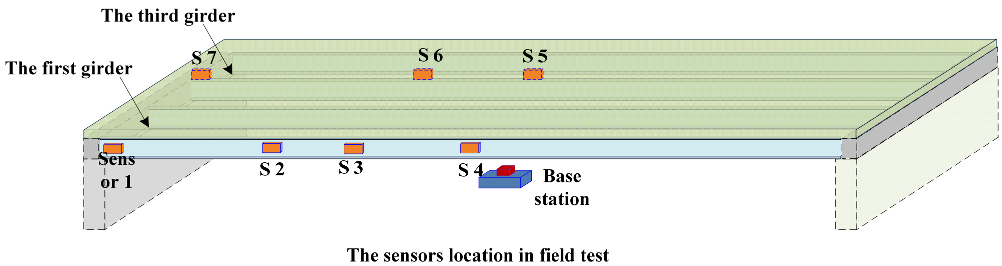
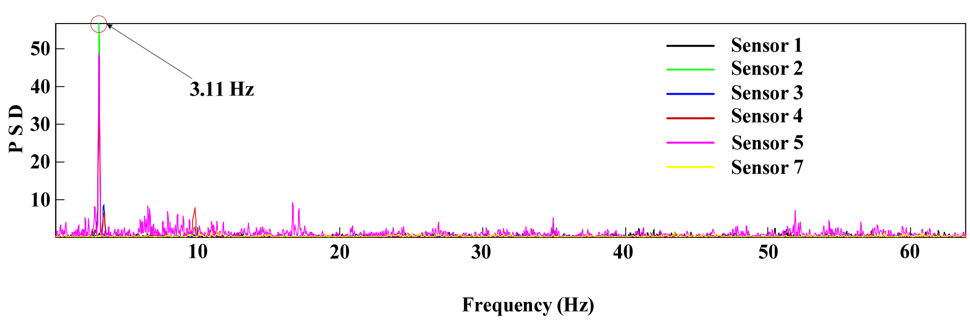


Figure 4 Sensor locations



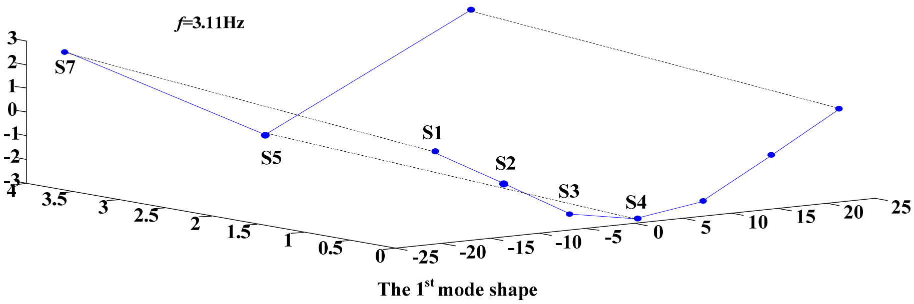
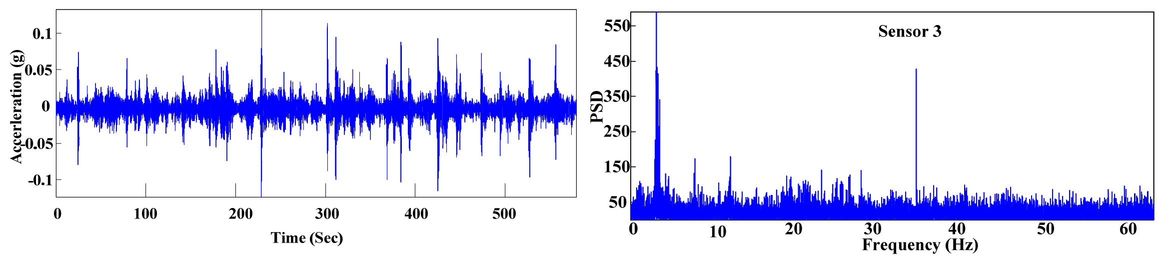


Figure 5 PSD of these sensors and the first mode shape of the bridge



(b) The time-history data of sensor 3

(c) The PSD of sensor 3

Figure 6 The results of field test of I-270 Bridge

Figure 7 is the test result of Beaufort #25 Bridge by using the WSN. From the figure we can see that the FFT result is not good enough to recognize the resonant frequency of the structure. We just can primarily estimate the natural frequency of the bridge is between 4 Hz to 5Hz.

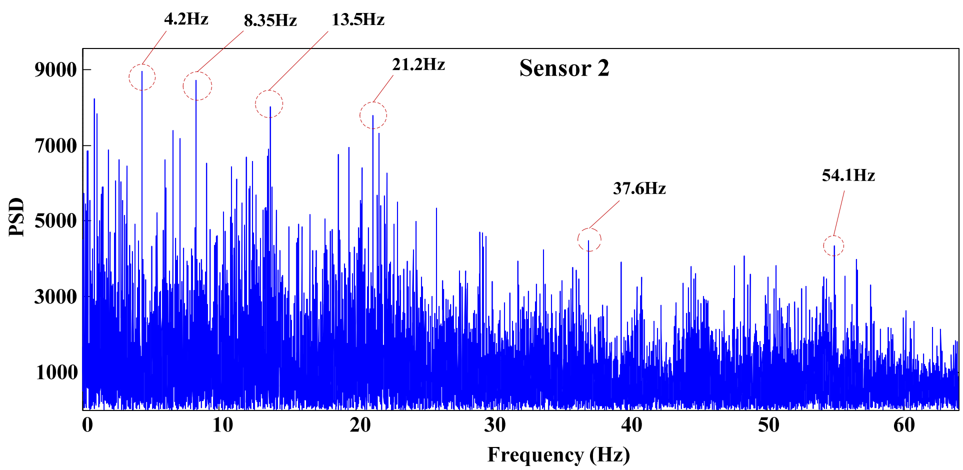


Figure 7 The results of field test of I-270 Bridge

- A total of 16 miniature wind turbines have been manufactured and arrived, which has been designed and tested in our previous work. Figure 8 shows the miniature wind turbine and its components.

Figure 8 The new designed miniature wind turbine