

Design of a Bridge Vibration Monitoring System (BVMS)

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Abstract – The average age of the 607,380 bridges in the U.S. is 42 years old. All bridges are required to be inspected every two years, and the frequency of these inspections increases as they age. The current bi-annual cost to inspect all bridges is \$2.7 billion and each bridge requires 1-3 days for on-site inspection, depending on the complexity of the bridge. The longer it takes to identify a deficiency; the more stress that is exerted on other components of the bridge, resulting in a domino effect creating more defects. According to the Federal Highway Administration’s 2009 statistics, \$70.9 billion is needed to address the current backlog of deficient bridges. Advances in technology provide an opportunity to reduce the cost by 23.7%-26.9%, and improve the quality of bridge inspections by migrating from a periodic manual bridge inspection paradigm (e.g. once every 2 years or less) to an event-based inspection (e.g. inspect only when needed).

Index Terms – Data Acquisition Unit (DAU), Bridge Vibration Monitoring System (BVMS)

INTRODUCTION

Bridges are a prominent of the modern transportation system, used to connect highways, cross-rivers, and join countries. Bridges in the U.S. are owned by the Federal Highway Administration (FHWA) states or local municipalities. By Federal mandate, bridges in sound condition must be inspected every two years. Bridges in inferior conditions must be inspected more frequently.

The bridge inspection process is a manual inspection process. The on-site inspection takes 1-3 days for the inspection. Preparation of bridge inspection takes several weeks of planning [1]. Currently, the manual inspection, on average, costs \$4,500 per inspection, which makes a total bi-annual inspection cost for all U.S. bridges of \$2.7 billion [9].

With 607,380 bridges in the country, with average age 42 years, fatigue damage is increasing faster than the growth in inspection and repair [9]. The bridge structural deficiencies from ageing, result in a demand for an increased frequency of the inspection cycle from 2 years to 6 months. This quadruples the bi-annual inspection cost. This also increases delays to users of the bridges closed during inspections.

I. Bridges and Bridge Failures

The four main types of bridges are: arch, beam, cantilever, and suspension. The scope for this project will be limited to the Theodore Roosevelt Bridge, which is a beam bridge in Washington DC. There are three main sections to a beam bridge: the deck, the substructure, and the superstructure. Each section contains subsections, and the inspection thoroughly details every step for inspecting each part of every subsection. The FHWA defines a set of general inspection procedures as part of its strict inspection protocol, and each major task has several minor steps under it. The inspection is subjective and suffers from differences in inter-rater reliability [15].

Bridge failures can be categorized into general failure types, each of which correlates to a component on the bridge. Some of the highest failure percentages originate from the piers of the substructure with a 20.65% failure percentage, the floor beams of the superstructure with a 16.3% percentage, and the roadway of the deck with a 13.05% percentage [7].

Each bridge exhibits a pattern of structural vibration when subject to external forces such as: wind and/or traffic. As a bridge gets older its structural vibration patterns change. Loss of mass through rusting or deterioration of concrete results in increased acceleration in the vibration for the same set of external forces. Also, changes in properties of the material (e.g. elasticity) cause changes in the vibration patterns. Accelerometers placed strategically on the bridge can be used to detect these changes and form the basis for an efficient monitoring system.

II. Periodic Manual Historical Data

Analysis of historical data provided by the Virginia Department of Transportation (VDOT) for 17 bridges consisting of 20 inspections since 1973 defined number of defects per inspection per bridge, the frequency of defects found per bridge, the total number of repairs required per inspection per bridge, and the lag between detection of defect and the actual repair per bridge [9].

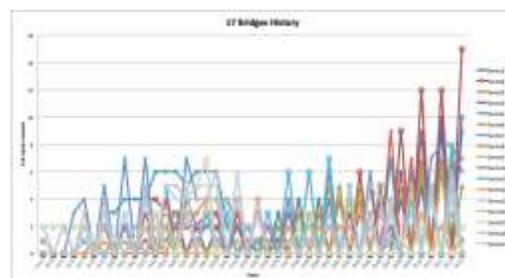


Figure 1: Periodic Repairs Events for 17 different Bridges

The repair events identified indicate an exponential increase over the years with a slightly downward curve shown due to the bridges actually being repaired. However, the lag time between detection of defect and the actual repair can take more than 8 years (figure 2). This all depends on the bridge engineers' prediction of how long the bridge can remain as is without being repaired. This delay in response has an impact on the bridge's behavior. The main effect can be seen in the second half of the bridge's lifetime where the number of repairs needed increases exponentially. The scientific explanation of this phenomenon is the repairs identified in the beginning cause complications as the repair time increases. When a defect is identified in a specific part of a bridge, it infers that this part of the bridge is not handling the stress that it is designed to handle which causes another part of the bridge to handle that stress. The other part is now handling more stress than it is designed so it fails, which causes a chain reaction in increasing stresses. By the time the repair is made for the first part, other parts have already been defected due to the extra stress that was put on them.

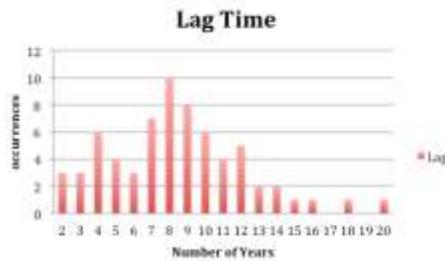


Figure 2. Lag Time between Detection of Defect and Actual Repair

PROBLEM/NEED STATEMENT

The process of evaluating all the bridges is time-consuming for most bridges, with the inspection taking as much as 3 months. There are many associated costs, with the bi-annual inspection costs at \$2.7 billion for all bridges in the U.S. The degradation of old bridges with an average age of 42 years places increasing demand to inspect bridges more frequently resulting in increasing costs and time. Also, the inspection often requires heavy equipment, forcing lane closure to ensure safety for all inspection personnel. Despite these precautions, many dangers are inherently present for the inspectors. Additionally, the current manual inspection is very subjective as inspectors rate the bridge condition based on their personal preference [9]. This makes the manual inspection prone to errors and flaws making the system unreliable.

Therefore, there is a need for FHWA to improve the quality of the bridge inspection method while saving time and reducing costs and safety risks.

STAKEHOLDER ANALYSIS

There are five primary stakeholders of the bridge inspection system as shown in figure 1: (1) Federal Highway Association (FHWA), (2) Department of transportation (DOT), (3) Design Engineers, (4) Inspection Team and (5) the Construction team. Bridge Users are the secondary stakeholders. There is a tension between the bridge inspectors and their management. Bridge inspectors are obligated to other stakeholders to perform the highest quality inspections. The DOT and state DOTs need to complete the inspections with high quality but low cost and time. If the inspection quality could be improved and the time of cost and inspection reduced, the inherent tension would be eliminated.

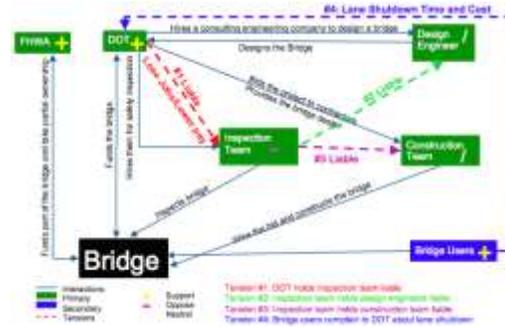


Figure 1: Stakeholder Analysis

CONCEPT OF OPERATIONS

The make the bridge inspection system more efficient, an alternate concept is proposed. The proposed concept of operation is to transition from a previously **Periodic Inspection** process that would inspect bridges every 2 years to an **Event-Based Inspection** process that will only inspect bridges when there is a deficiency detected. Upon detecting a deficiency, a group of inspectors will be sent to the bridge to manually inspect the whole bridge. The new system would be a lot more efficient than the existing system since there would be no wasted inspections. The same amount of money could be spent inspecting bridges that need the inspection due to deficiency compared to inspecting even when the bridge is in a great condition.

The proposed alternative system therefore, is the Event-Based Bridge Vibration Monitoring System (BVMS). All bridges undergo some form of dynamic loading, which causes them to vibrate. Therefore, each bridge has a unique vibration fingerprint which comes from the mass, stiffness, and material of the specific bridge. Changes in the vibration fingerprint caused by the deficiencies can be detected using accelerometers. The inputted initial fingerprint frequency of the bridge is the event inspection's natural frequencies. This identified customary Gaussian distribution has natural frequencies with a mean of 5 Hz, and standard deviation of 1 [13].

By using the Theodore Roosevelt Bridge as a sample bridge, 31 fracture critical locations with the highest shear and moment can be identified. 31 BDI Accelerometers are used to place at the middle of the spans for high moment

and at each of the piers for high shear. These accelerometers are specifically designed for dynamic structural testing and measure frequencies in x, y, and z directions.

BRIDGE VIBRATION MONITORING SYSTEM

I. Requirements

The BVMS shall identify bridge vibration patterns that are different than the reference pattern for more than 7 days.

The BVMS shall monitor all bridge components.

The system shall alert the Data Acquisition Unit (DAU) with frequencies of each accelerometer each day.

The BVMS shall be accurate 95% of the time

II. Design

The BVMS shall consist of the following functional components: Acceleration detection sensors, Digital Acquisition Unit (DAU), communication between sensors and DAU, Base monitoring unit, and communication between DAU and base monitoring unit.

The vibration data is collected and stored in the time domain. For analysis it is converted from the time domain into the frequency domain using Fourier Analysis.

VIBRATION MODEL

Both the Periodic Manual Inspection and Event-based BVMS use the Vibration Model. This model generates natural frequencies with a random Gaussian distribution number generator to replicate how the structure responds to vibration, such as, the external forces that the bridge component would exhibit in the real world. This number generator generates numbers between 4-7 Hz most frequently, although the given range is from 0-10 Hz. This is due to the fact that the natural frequencies that are most frequently observed in bridge vibrations range most commonly from 0-10 Hz. With the mean at 5 Hz, the highest probability ranges from 4-7 Hz. If the natural frequency is one standard deviation away, it's considered in a good condition, if its two standard deviations away it's considered in fair condition, and so forth.

The system continuously monitors the readings from each of the placed accelerometers depending on the total simulation time wanted. Since, these natural frequencies are obtained per day, there is an Omega Array that resets the previous randomized values to verify that it is not stored allowing the new generated number to take the spot per day.

Another Array called Broken Array exists in order to store the identified condition of each accelerometer's natural frequency per day. The output of the Broken Array however, varies for the periodic manual inspection and the Event-based BVMS. The Broken Array adds a 0 to the for-loop per accelerometer if the identified condition is good, otherwise it adds 1. If the placed accelerometer already identified a repair needed for that given location it will not add it once again, as it already states that the particular location has a deficiency.

The Vibration Model outputs the following per bridge: the total number of defects depending on the total simulation time, the location of the defect due to the

condition of the natural frequency experienced by a particular accelerometer, the frequency of defects found, total number of repairs required, and total inspections needed.

The Vibration Model is verified by having vibration natural frequencies inputted from the terminal as well as from separate text files. Outputting the periodic manual historical data presented by VDOT also validates it.

LIFE-CYCLE COST MODEL

I. Method of Analysis

There are three main components in the method of analysis, which are: *Calculate Repair Events*, *Adjust Repair Events*, and *Calculate Life Cost Cycle*.

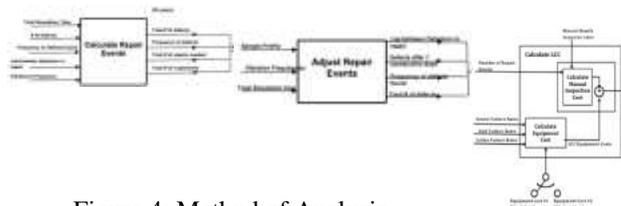


Figure 4: Method of Analysis

The *Calculate Repair Events* uses the Vibration Model to input the event inspection's natural frequencies in conjunction with the periodic historical data acquired from VDOT. The randomly generated Gaussian numbers simulated within the Vibration Model then uses the inputted data of number of defects per inspection, the frequency of defects found, and lag between detection of defect and the actual repair. This is done to calculate the repair events of the 17 VDOT bridges per year for the 40 years periodic historical data.

The Broken Array in the Vibration Model used to store the identified condition of each accelerometer's natural frequency per day is used differently for the *Calculate Repair Events*. The identified condition is sent to the base after the yearlong simulation, to replicate the periodic manual inspection. Thus, replicating what each of these VDOT bridges would encounter, validating the Vibration Model outputting the algorithm of the periodic historical data. The stochastic identified repaired events algorithm serves as a sample profile to implement the *Adjust Repair Events*.



Figure 5: Calculate Repairs Events

The second block is the *Adjust Repair Events*, inputting the sample profile algorithm of the stochastic identified repaired events, the total simulation time as well as the event inspection's natural frequencies. This block uses the Vibration Model, nonetheless, altered by implementing the

proposed alternative of Event-Based inspections. In the *Adjust Repair Events*, the Broken Array from the Vibration Model used to store the identified condition of each accelerometer’s natural frequency per day sends each of the natural frequency of the 31 accelerometers to the DAU per day.

However, the Broken Array has a threshold of 7 consecutive days in fair or poor condition to automatically send the identified condition to the base from the DAU. The threshold of 7 consecutive days is placed in order to verify that if the condition has changed over time, that the natural frequencies change was due to a deficiency found instead of external factors affecting its change. Upon receiving an alarm from the DAU to the base, an inspector from the base will perform a manual inspection of the bridge at the location detected by the placed accelerometer. The placement of the accelerometer by default states the location and area of the defect found.

The *Adjust Repair Events* outputs the defect found for a particular location after 7 consecutive days, total number of repairs and inspections needed, the frequency of defects found, and total number of defects per year. For the *Adjust Repair Events* in particular, the output will show the day the defect was found per bridge. This is due to the fact, that it monitors the bridge’s vibrations every day, and once the defect has been found, it specifies the day the defect was identified.



Figure 6: Adjust Repairs Events

Deriving how many repair events are required leads to the *Calculate Life Cycle Cost* block, which has two subdivisions of calculate manual inspection cost, and calculate equipment cost. Identifying the number of repair events direct us to calculate manual inspection cost per alternative. Each alternative then has its own equipment cost having inputs such as the sensors, DAU, communication, and power failure rates. The conjunction of both the Manual Inspection Cost and the Equipment Cost give us the best, worst, and expected total cost of each Event-Based alternative.

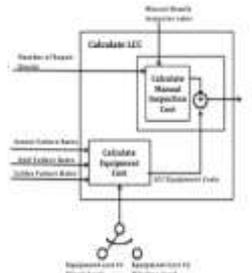


Figure 7: Calculate Life-Cycle Cost

IV. Adjust Repair Events Results

After running the Vibration Model for 1,000 iterations per bridge the average number of defects found was 1.005, having the biggest outlier being 5 defects. The output below contains the 31 natural frequencies for a yearlong run, however, the total simulation time can be managed to see results of repair events for longer lifespans. The data below demonstrates that each day the identified condition per accelerometer is sent to the DAU, and after 7 consecutive days or when the simulation is complete it sends all the data to the Base.

The Vibration Model calculates the total number of defects found, the total number of repairs and inspections needed, and the day and location of the defect.

```
Accelerometer 30:
4,340690890292232 is the number generated
Green! Good Condition!
Accelerometer 31:
5,202521551974083 is the number generated
Green! Good Condition!
Data sent to the Data Acquisition Unit (DAU)

Data sent to the Base.

Simulation complete

This year there were:
Total Number of defects found: 1
Total Number of repairs needed: 1
Total Number of inspections needed: 1
Day Defect was found: 179
Location of Defect: Accelerometer 8
```

Figure 9: Adjust Repair Events Result

By examining the periodic manual historical data we identify the threshold of 8 years as the lag between detection of defect to repair. Therefore, the Event-Based proposed alternative identifies the defect 186 days prior to the year inspection and in 8 years, it saves 4 years of lag between detection of defect to repair. Shifting the repair event profile to the left, and in a 50-year lifespan it saves 25 years of lag between detection of defect to repair. This not only reduces the amount of inspections needed but also reduces the expense of repair costs.

LIFE CYCLE COST

The life cost of the system is divided into two parts: (1) Periodic with Manual Inspection cost for the current system versus (2) the cost of the Event-based with BVMS (Wired Accelerometers Alternative) and (3) the cost of the Event-based with BVMS (Wireless Accelerometers Alternative). Since the life expectancy of a bridge is 50 years, the costs of the alternatives are being calculated for a 50 years lifespan.

I. Periodic with Manual Inspection (Current)

The current manual inspection cost is calculated by the following equation: Manual inspection cost = cost per inspection * number of inspections. The cost per inspection for the Theodore Roosevelt Bridge is \$30,000 (DOT, n.d). The number of inspections needed for this bridge is calculated to be 30 inspections during the 50-year lifespan. These 30 inspections come from a biannual inspection cycle for the first 40 years of the bridge and an annual inspection for the last 10 years. Using the above equation the manual

inspection calculation will result in a total of \$900,000 for 50-year inspections.

II. Event-based with BVMS (Wired/Wireless Accelerometers Alternative)

The cost is based on two factors: the equipment cost and the inspections needed.

1. Equipment Cost

The equipment replacement is an important factor since they are subject to failure due to their life span. This is analyzed in a Best, Expected, and Worst case scenario based upon the life span of the equipment used.

A. Event-Based Wired Accelerometers Alternative

The total equipment cost for the Wired Accelerometer Alternative is calculated with the following equation:

$$TSWdC=(AQ*CA)+IST+(Cb*L*Cc)+CDAU+S+CS+QI$$

TSWdC: Total set wired Cost

AQ: Quantity of accelerometers needed

CA: Cost per unit of Accelerometers

IST: Installation Cost

Cb: Cables for power and communication

L: Length

Cc: Cost of cables per unit of length

CDAU: Cost of Data Acquisition Unit

S: Cost of Software

CS: Cost of Communication System

QI: Quality check Inspection Cost

B. Event-Based Wireless Accelerometers Alternative

The total equipment cost for the Wireless Accelerometer Alternative is calculated with the following equation:

$$TSWIC=(AQ*CA)+IST+(Mcp*Cm)+CDAU+S+CS+QI$$

TSWIC: Total set wireless Cost

AQ: Quantity of accelerometers needed

CA: Cost per unit of Accelerometers

IST: Installation Cost

Mcp: Micro-controllers and power

Cm: Cost of micro-controller

CDAU: Cost of Data Acquisition Unit

S: Cost of Software

CS: Cost of Communication System

QI: Quality check Inspection Cost

2. Inspection Cost

The number of inspections needed was calculated based on historical data that was shown in previous sections. A total cost for inspections was calculated for the 50 years life span based on the following equation:

50 year inspection cost = (Total inspection cost)*(Number of inspections needed)

Using historical data of 17 different bridges, the number of repairs identified in the bridges' lifespan were categorized into Best, Expected and worst categories (figure 10). This categorization is to capture the variability in bridges' behavior, since not all bridges have the same characteristics.



Figure 10: BVMS Inspection Cost for 50-years

3. Total Cost of Event-based Alternatives

The total cost for the two Event-Based alternatives were calculated based on the following common equation: Total Life-Cycle Cost = (50 years Inspections Cost)+(50 years Equipment Cost). The 50 years Equipment Cost was calculated according to the following equation: 50 years Equipment cost = (Number of set replacement)*(price per set).

The following graphs explain the prices for Event-Based alternatives (Wired Accelerometers Alternative and the Wireless Accelerometer Alternative) with best, expected and worst costs compared to the cost for the current manual process.



Figure 11: Cost comparison between the Event-Based Wired Alternative and the Periodic with Manual Inspection

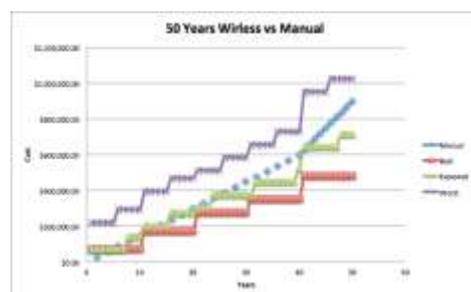


Figure 12: Cost comparison between the Event-Based Wireless Alternative and the Periodic with Manual Inspection

Business Case

Based on the data obtained from costs calculated life cycle costs, it can be concluded that the Event-Based BVMS has reduced the cost and caused savings of 45% of the current manual inspection in the wired accelerometers alternative and 48% in the wireless accelerometer alternative.

System Lasts	5 years	8 years	10 years
50 years monitoring	Worst	Expected	Best
Event Based Inspection			
Wired	\$900,000-\$1,064,000 = -\$164,000 %118	\$900,000-\$687,000= \$213,000 %23.7	\$900,000-\$502,000= \$398,000 %44
Wireless	\$900,000-\$1,018,000= -\$118,000 %113	\$900,000-\$658,000= \$242,000 %26.9	\$900,000-\$479,000= \$421,000 %46.8
Periodic Inspection			
Manual	\$900,000.00	\$900,000.00	\$900,000.00

Table 1: Total cost for the proposed alternatives

The worst case is when the Event-Based system lasts for 5 years, the expected case is when it lasts 8 years, and the best case is when it lasts 10 years. The Wired alternative suggests cost savings in the expected and best case scenarios from 27%-47% when compared to the current manual inspection cost. However, in the worst-case scenario, both alternatives are higher in cost than the current manual inspection process at 118% for the wired alternative and 113% for the wireless alternative. Furthermore, the manual inspection has one constant cost that does not change depending on the type of cost, the time period, or how long the system lasts.

Additionally, analyzing just the manual inspection cost for the expected case, Event-Based reduces the cost by 77% for both the wired and wireless alternative. Since the manual inspection after the alarm is exactly the same for both wired and wireless alternative, the cost saving the manual inspection is also the same for both solutions.

Recommendations and Conclusions

The event-based system is recommended due to the fact that it allows for savings of up to 59%, and the need for manual labor and equipment is significantly reduced. This will allow for swift manual inspections, when needed, since the bridge inspectors will be aware of the location of the deficiency, and will only need to make preparations for inspecting a specific part of the bridge, which will reduce time and the need for manual labor. Out of the two event-based alternatives, the wireless alternative is more preferable since it will not require the installation of wires for the power source and communication. The wireless system is very dynamic and can be manipulated for any bridge with small modifications.

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