Connecticut Permanent Long-Term Bridge Monitoring Network Volume 7: Lessons Learned for Specifications to Guide Design of Structural Health Monitoring Systems

Prepared by: Richard E. Christenson, John T. DeWolf,
Stephen Prusaczyk

August 14, 2014
Report Number CT-2256-8-13-9

SPR 2256

Connecticut Transportation Institute
University of Connecticut
Storrs, Connecticut

Prepared for:
Connecticut Department of Transportation

James A. Fallon, P.E.
Manager of Facilities and Transit
Bureau of Engineering and Construction

Disclaimer

This report does not constitute a standard, specification or regulation. The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the views of the Connecticut Department of Transportation or the Federal Highway Administration.

Technical Report Documentation Page

1. Report No.
CT-2256-8-13-9

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle

Connecticut Permanent Long-Term Bridge Monitoring Network
Volume 7: Lessons Learned for Specifications to Guide Design of Structural Health Monitoring Systems

5. Report Date
August 14, 2014

6. Performing Organization Code
SPR-2256

7. Author(s)
Richard E. Christenson, John T. DeWolf, Stephen Prusaczyk,

8. Performing Organization Report No.

9. Performing Organization Name and Address

University of Connecticut
Connecticut Transportation Institute
270 Middle Turnpike, U-5202
Storrs, Connecticut 06269-5202

10 Work Unit No. (TRAIS)

11. Contract or Grant No.
SPR-2256

12. Sponsoring Agency Name and Address

Connecticut Department of Transportation
2800 Berlin Turnpike
Newington, CT 06131-7546

13. Type of Report and Period Covered

1999 - 2013

14. Sponsoring Agency Code
SPR-2256

15. Supplementary Notes
This study conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract

This report proposes a set of specifications for bridge structural health monitoring that has resulted from the experiences gained during the installation and monitoring of six permanent long-term bridge monitoring systems in Connecticut. As expected in bridge health monitoring research, numerous challenges have been identified and resolved during the course of this project, and this knowledge is passed on in the form of proposed data specification for bridge structural health monitoring sensor data.

17. Key Words
Bridge monitoring, data qualification, error quantification

18.Distribution Statement
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161. The report is available on-line from National Transportation Library at http://ntl.bts.gov

19. Security Classif. (of report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
33

21. Price
N/A

Form DOT F 1700.7 (8-72)

Reproduction of completed page authorized

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

Table of Contents

Title Page ... i
Disclaimer ... ii
Technical Report Documentation Page ... iii
Metric Conversion Factors ... iv
Table of Contents ... v
Abstract ... 1
Introduction ... 3
Objectives and Scope of Study ... 5
Proposed Specifications ... 5
Data Anomalies ... 7
Aliasing and Filtering ... 11
Quantization ... 13
Measurement Noise ... 14
Conclusion ... 17
Lessons Learned in Bridge Monitoring ... 19
1. Data Anomalies ... 19
2. Aliasing ... 21
3. Quantization Error ... 22
4. Measurement Noise ... 23
Acknowledgements ... 25
References ... 26

LIST OF FIGURES

Figure 1. Intermittent Noise Spikes from Sikorsky Bridge System ... 9
Figure 2. Periodicy Observed on Bigfoot Bridge System ... 10
Figure 3. Filtering Issues ... 13
Figure 4. Quantization of Cromwell Bridge System and Picture of Bridge ... 14
Figure 5. Inherent Noise Levels in Sikorsky Bridge System Accelerometer 1 Span 1 ... 15
Figure 6. Potential Noise Due to Cable Lengths Sikorsky Bridge Accelerometer 1 Span 1 ... 16

Connecticut Permanent Long-Term Bridge Monitoring Network
Volume 7: Lessons Learned for Specifications to Guide Design of Structural Health Monitoring Systems

Abstract: This report proposes a set of specifications for bridge structural health monitoring that has resulted from the experiences gained during the installation and monitoring of six permanent long-term bridge monitoring systems in Connecticut. As expected in bridge health monitoring research, numerous challenges have been identified and resolved during the course of this project, and this knowledge is passed on in the form of proposed data specification for bridge structural health monitoring sensor data.

Bridge structural health monitoring involves the collection and analysis of systematic measurements obtained from installed sensors on the bridge. While there are many quality certification systems available for civil engineering systems, e.g. American Society for Testing and Materials (ASTM), typical bridge monitoring specifications do not explicitly address performance requirements. As the applications of bridge structural health monitoring become more varied and advanced, it will become necessary to ascertain the quality of measured data in order to check its suitability for new and varied applications.

The quality of measured data has a direct impact on the results obtained from data analysis in structural health monitoring. The quality of measured data for a bridge monitoring system should meet three basic criteria: First, measured data should be devoid of anomalies, such as signal clipping, intermittent noise spikes, temporary signal dropouts, and spurious trends. Second, the errors, including aliasing and quantization, and system noise should be within an acceptable range. Lastly, the measured data should satisfy required assumptions, such as stationarity and normality.

Data qualification is defined as validating the quality of measured data and quantifying errors and noise to ensure the measured data sufficiently satisfies the above-mentioned criteria. Despite the tremendous impact data qualification has on bridge health structural monitoring, data qualification to provide a basis for bridge monitoring data specifications has not been formalized . This paper proposes measures of data qualification that can be used as a foundation for data specifications in bridge structural health monitoring. This paper will use data collected from monitored bridges in the Connecticut Long Term Bridge Monitoring program as examples.

This report concludes with a section on lessons learned from the monitoring of six bridges in the State of Connecticut.

INTRODUCTION

Structural health monitoring of highway bridges has proven to be extremely beneficial for engineers, state agencies, and researchers. These systems allow for determination of structural integrity to supplement physical inspections. Physical inspections can be limited due to lack of physical access to areas on the structure, lack of manpower, or economic reasons. Also, the frequency of physical inspections is not always adequate to prevent catastrophic structural failure (*DeWolf et al. 1995, DeWolf et al. 1995 Application*). On the other hand, structural health monitoring can be used to determine the condition of the entire structure, with only a start up cost. Also, unlike physical inspections, structural health monitoring can provide inspectors with actual values for stress, accelerations, or any other parameter being measured (*DeWolf et al. 2002*). With a combination of structural health monitoring and physical inspections, the health of a bridge structure can accurately be determined. This can effectively prevent failure of highway bridges, which can cripple the economy and cause loss of life. Bridge health monitoring systems allow the collection and analysis of data, which can describe the behavior of bridges over their lifespan. This analysis can help bridge owners, such as state agencies; determine optimal bridge maintenance and replacement strategies (*DeWolf et al. 1995*). Vibration based monitoring is of particular use for damage detection and monitoring deterioration of structures (*DeWolf et al. 1991, DeWolf et al. 1998, DeWolf et al. 2002*). Vibration monitoring has been shown to effectively assess the global condition of highway bridges (*DeWolf et al. 1991 Bridge Vibration, DeWolf et al. 1992, DeWolf et al. 1995, DeWolf et al. 1995 Application).* Strain monitoring has also been effectively implemented to determine the levels of stress and structural performance of particular structural members and connections (*DeWolf et al. 1995 Application, DeWolf et al.*

1998, DeWolf et al. 2002). This type of analysis had been used to determine whether or not a bridge structure is behaving as designed (*DeWolf et al. 1998*). The analysis of bridge data can provide additional information on the structural health of the bridge and supplement bridge inspections (*DeWolf et al. 2002*). The benefits of bridge monitoring are generally recognized by the bridge engineering community with an increasing number of applications throughout the country (*DeWolf et al. 1995, DeWolf et al. 1995 Application*).

A number of different types of structural health monitoring systems have been installed and used on highway bridges (*DeWolf et al. 1995, DeWolf et al. 1995*). As observed, the applications of bridge structural health monitoring are becoming more and more varied and advanced. Bridge monitoring systems are applied to different types of bridges, employ a variety of sensor types, and acquire the data in a variety of manners.

There are numerous quality certification systems available for civil engineering systems, e.g. American Society for Testing and Materials (ASTM), American Society of Civil Engineers (ASCE), and American Association of State Highway and Transportation Officials (AASHTO). In particular, AASHTO presents the code for the structural performance of bridges. AASHTO presents engineers with the loads to be applied to bridge structures along with design considerations to be taken (*AASHTO 2009*). In 2008, the Federal Highway Administration (FHWA) implemented a Long-Term Bridge Performance (LTBP) program to better understand long-term performance of highway bridges and the associated issues (*FHWA 2011*). The design and implementation of structural health monitoring or the long term performance of bridge structures is not included in these specifications. Typical bridge monitoring specifications do not explicitly address performance requirements for these systems. This report is based on research conducted during the current phase of the long-term bridge monitoring program (*Trivedi, 2009; Trivedi and Christenson, 2009; Prusaczyk, et al., 2011; and Prusaczyk, 2011*).

OBJECTIVES AND SCOPE OF STUDY

The objective of this study was to expand the knowledge of the development and implementation of structural health monitoring systems on a series of bridges in Connecticut. In doing so, a set of specifications for highway bridge structural health monitoring sensor data is proposed. The proposed specifications are based on experiences with bridge monitoring systems installed on a variety of bridges in Connecticut over the past decade as part of a joint research program between the Connecticut Department of Transportation and the University of Connecticut. The proposed set of specifications are intended to serve as a starting point from which further discussions can be based and future bridge structural health monitoring systems can achieve their maximum potential.

PROPOSED SPECIFICATIONS

The basis for the proposed bridge structural health monitoring specifications for sensor data has been provided by the experiences of the Long Term Bridge Monitoring Program in Connecticut. Long-Term Bridge Monitoring in Connecticut is a joint research effort of the Connecticut Department of Transportation and the University of Connecticut. Since 1994, six bridges in Connecticut have been installed with bridge monitoring systems (*DeWolf et al. 2006, Olund et al. 2009, DeWolf et al. 2009*). Recently, some of the data acquisition equipment on the bridges has been updated. There are a variety of bridges being monitored, using a number of different types of sensors, and over the course of the research, a range of data acquisition systems. Both concrete and steel bridges are being monitored, with substructure types varying from box girders, traditional slab-on-girder, to truss. The sensors installed on these bridges include: foil, vibrating wire and piezoelectric strain gages; piezoelectric and capacitive accelerometers; Resistance Temperature Detector (RTD) temperature sensors; tilt meters; and linear variable differential transformer (LVDT) displacement transducers and string potentiometers. Both wired and wireless sensors are used in the research. The diversity of this monitoring program is drawn upon in the proposed specifications.

Critical to any bridge monitoring efforts is the data analysis used to identify the structural health of the bridge. The quality of measured data has a direct impact on the results obtained from data analysis in structural health monitoring. Structural health monitoring techniques, such as peak picking (*DeWolf et al. 1991, DeWolf et al. 1998*), require data undistorted in the frequency domain. Strain monitoring of structures requires data in the time domain that is void of excessive noise and data anomalies (*DeWolf et al. 1998, DeWolf et al. 2002*). As structural health monitoring analyses continue to improve and advance, the reliance on high quality data becomes more critical.

The quality of measured data for a bridge monitoring system should meet three basic criteria: First, measured data should be devoid of anomalies, such as signal clipping, intermittent noise spikes, temporary signal dropouts, and spurious trends. Second, the errors, including aliasing and quantization, and system noise should be within an acceptable range. Third, the measured data should satisfy required assumptions, such as stationarity and normality. Verifying assumptions such as stationarity and normality are necessary prior to data analysis, however, this particular criteria is inherent to the bridge's loading and subsequent response and is not part of the proposed bridge structural health monitoring specifications. The proposed specifications, as discussed in this section, will address: data anomalies, including signal clipping, intermittent noise spikes, temporary signal dropouts, spurious trends, and periodicies; errors associated with aliasing and quantization; and measurement noise associated with the sensor, cabling or data acquisition hardware.

DATA ANOMALIES

The presence of data anomalies in a bridge health monitoring system should be checked and documented once the system is installed, and at regular intervals during the life of the system. The bridge monitoring system should be devoid of any data anomalies. Data anomalies may include signal clipping, intermittent noise spikes, temporary signal dropouts, spurious trends, and periodicity. While it is difficult to anticipate these anomalies, their presence can be eliminated through changes of the system or appropriate post processing of the data. These aforementioned data anomalies are indentified through the inspection of collected data in both the time and frequency domains.

One anomaly is signal clipping, which occurs when the maximum value of the sensor or data acquisition system is exceeded. This anomaly can be seen as a flat top when the signal is viewed in the time domain. Signal clipping can be avoided by properly selecting sensors and data acquisition systems that can handle the expected measurements from the bridge. If signal clipping is not prevented in the original installation of the structural health monitoring system, the sensors and data acquisition system should be replaced with a system that can handle the measurements.

Another anomaly that can occur during the collection of data from a highway bridge is intermittent noise spikes. This likely occurs when the cables connecting the components of the structural health monitoring system incur relative motion. As with signal clipping, intermittent noise spikes are noticed in the time domain of the measured data. Intermittent noise spikes are characterized by random large spikes in the time history. To avoid the presence of intermittent noise spikes, all cables in the system should be securely fixed/tied down. The connections of all cables should also be inspected to ensure a snug fit.

An example of intermittent noise spikes was observed on the Sikorsky Bridge monitoring system. The Sikorsky Bridge, pictured in Figure 1, is a five span steel plate girder bridge spanning a distance of approximately 1800 feet over the Housatonic River in Stratford/Milford Connecticut. This bridge carries the limited access traffic of The Merritt Parkway (Route 15) north and southbound. The sensors installed on this bridge include piezoelectric accelerometers, foil strain gages, LVDTs, and tilt meters. A 16-bit data acquisition unit is used to collect data from the 48 sensors installed on the bridge. Figure 1 shows the time history for an accelerometer (Accelerometer 1) located on the southernmost span (Span 1) of the Sikorsky Bridge. While the normal response of the bridge is less than 0.1g, three intermittent spikes are observed in the 10 second interval with amplitudes around 1g. This suggests that there may be an issue with the cables connecting the sensors to the data acquisition unit for the Sikorsky Bridge system.

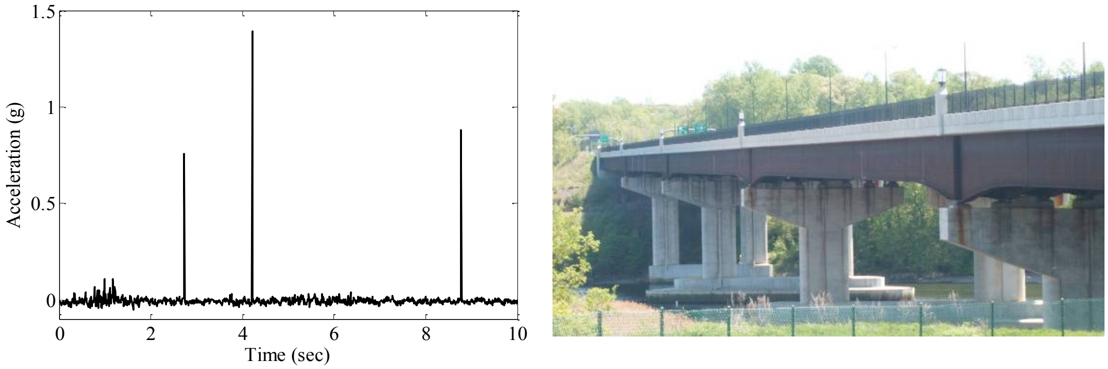

Figure 1. Intermittent Noise Spikes from Sikorsky Bridge System – Accelerometer 1, Span 1, 10-Second Time History and Photograph of Southbound Bridge

A third anomaly, temporary signal dropouts, can occur when the measured signal suddenly vanishes into the noise floor of the data for a period of time. This data anomaly can be attributed to a number of different components in a structural health monitoring system. It can be a problem with the wiring or connections of the system, or a problem with the sensors themselves. If temporary signal dropouts occur, the system should be carefully inspected for issues.

A spurious trend is a time varying change in the mean value of a set of data. When strain gages are not compensated for changes in temperature a spurious trend can occur. These temperature-caused spurious trends can be resolved by using full bridge strain sensors, or by removing any bias in the post processing of the data. Spurious trends are of significance when they do not occur because of a change in temperature. In this case, the sensor should be carefully inspected.

The final data anomaly addressed here that can be experienced in a bridge health monitoring system is a periodicy. A periodicy is a signal added to the actual signal that repeats at a regular interval. In bridge health monitoring this is likely due an improperly grounded system. This ground loop results in a 60 Hz periodic signal. The existence of a periodic signal can be most easily observed as a large spike in the frequency domain of the data set. If a periodic signal is encountered in a bridge monitoring system, the grounding of all AC electrical components should be checked.

An example of periodicies was observed during the recent installation of a bridge health monitoring system installed on an overpass in East Hartford, CT. The Bigfoot Bridge is a three-span, simply supported, cast-in-place post-tensioned box girder bridge connecting I-384 Westbound to I-84 Westbound in East Hartford. This bridge was constructed in 1985, and was the first bridge to be monitored in the long-term bridge monitoring project. The total span of the bridge is 234.70 m (770 ft.). The sensors installed on this bridge include 16 piezoelectric accelerometers with a ±1.5g peak amplitude and bandwidth of 0.01 to 1200 Hz; 16 foil strain gages; 12 RTD temperature sensors; and 6 tilt meters with a range of ± 3 degrees. Data is collected using a 24-bit data acquisition unit. A 60 Hz periodicy was initially observed in the measured strain gage data. An auto-power spectral density function of a foil strain gage is shown in Figure 2. The auto-power spectral density function transforms the time domain strain measurement into the frequency domain. The auto-power spectral density function is a measure of the energy content of the signal as a function of frequency. From the plot in Figure 2, it is obvious that there is significant energy localized at 60 Hz.

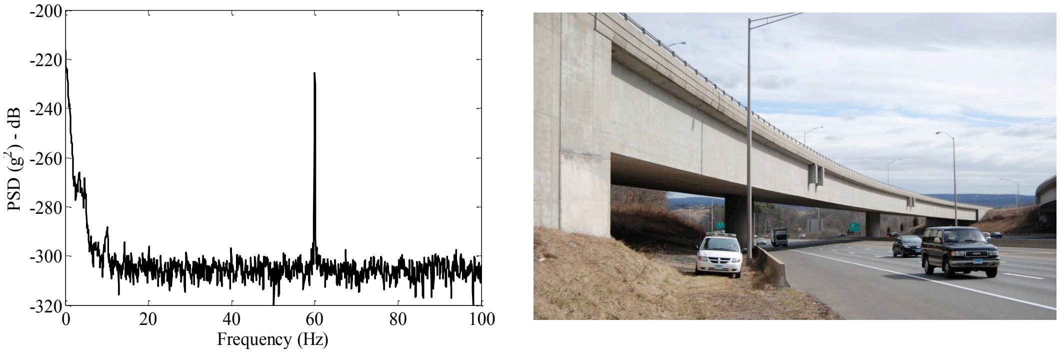

Figure 2. Periodicy Observed on Bigfoot Bridge System –
Auto-Power Spectral Density Function of Strain Measurement and Photograph of Bridge

Five data anomalies have been identified for the proposed specifications that may be encountered when working with a bridge structural health monitoring system. The existence of all or any of these anomalies should be checked initially for the system, as well at regular time intervals, and the appropriate action should be taken to eliminate any anomalies when identified.

ALIASING AND FILTERING

The potential for aliasing exists when digitally measuring analog signals. Aliasing occurs when a high frequency signal appears as a lower frequency signal. Once measured data is aliased, it is impossible to reconstruct the original signal or even tell that the sample has been aliased. It is, therefore, imperative to be proactive and prevent aliasing from occurring in the first place. This can be done by either carefully selecting the sampling rate or installing anti-aliasing filters.

In order to eliminate aliasing using the sampling rate, a rule of thumb is that data should be sampled at a rate ten times higher than the resonant frequency of the sensor. This is not an issue with certain sensors that have low resonant frequencies. For example, a tilt meter with a resonant frequency of 2 Hz should be sampled at 20 Hz. Piezoelectric accelerometers, however, can have resonant frequencies of 3500 Hz. This would require sampling the data at a rate of 35 kHz. Due to system capabilities and data storage, this may not be feasible. In such cases anti-aliasing filters can be employed. Appropriate anti-aliasing filters measure the data prior to the analog to digital conversion such that the frequency content of the measured signal larger than the Nyquist frequency (one half of the sampling rate) is effectively removed.

It is recommended that all dynamic measurements be passed through anti-aliasing filters to prevent aliasing. Current technology allows standard implementation of 8-pole filters which can effectively prevent aliasing.

The bandwidth of the filter used in an anti-aliasing filter must be carefully selected. Of first concern, as identified above, is that the bandwidth of the filter be less than the Nyquist frequency or one half of the sampling rate. Depending on the natural distortion of the specific filter used, the usable bandwidth will be some frequency less than the Nyquist frequency.

An example of an anti-aliasing filter that leads to a restricted bandwidth was experienced on the Flyover Bridge monitoring system. The Flyover Bridge, located in Hartford, Connecticut, is shown in Figure 3. This bridge is a multi-span, continuous, double steel box girder bridge with a composite concrete deck. The original data acquisition system had a two-pole low-pass filter with a cutoff frequency of 2 Hz used for anti-aliasing. With a sampling rate of 100 Hz, this filter provided sufficient anti-aliasing protection. However, the 2 Hz cutoff frequency of this filter resulted in measured data with distorted frequency content above this 2 Hz. A new data acquisition system on the bridge provides a bandwidth of 500 Hz. Figure 3 shows a plot of the auto-power spectral densities of an accelerometer (A4) located on the fourth span (Span 4) of the bridge from both the original and the current system. It is observed in the auto-power spectral density functions that the original signal was attenuated above 2 Hz. While this was not a problem for the original structural health monitoring analysis that considered only the fundamental frequency of the bridge, at 1.5 Hz, current approaches are using multiple lower frequency modes.

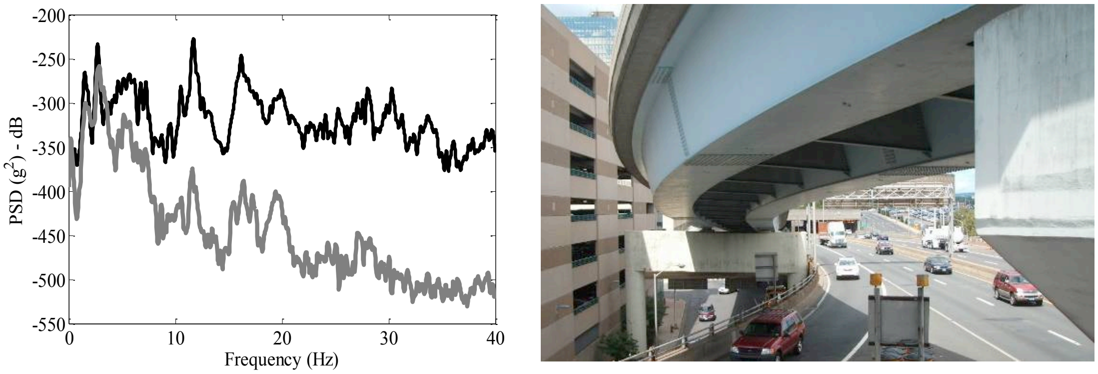

Figure 3. Filtering Issues – Accelerometer 4 on Flyover Bridge Auto-Power Spectral Density Function and Photograph of Bridge
(Original Data Acquisition (DAQ) – gray; Current DAQ – black)

QUANTIZATION

Quantization error is inherent to analog sensors and digital processing. When a continuous analog signal is saved as a digital signal, the amplitude of each sample is expressed using a finite number of bits in binary terms by the analog to digital (A/D) converter. A round-off error is created due to this conversion, which is called quantization error. The quantization error can be reduced by using an analog to digital converter with a high total number of bits. Common A/D converters available today are 24-bit. These seem to minimize quantization error sufficiently, providing accurate data results.

An example of quantization is observed between the original and current monitoring systems on the Cromwell Bridge. This bridge, shown in Figure 4, is located in Cromwell, Connecticut. The bridge carries I-91S traffic over the Mattabessett River. The bridge is a three-span, simply supported, slab-on-girder bridge. In November of 2004, the original structural health monitoring system was installed on the Cromwell Bridge. The original system consisted of 20 strain gages and a 16-bit data acquisition system. In July 2010, a new

24-bit data acquisition system replaced the original system. This improved the resolution of the sensor measurements from 1 με (microstrain) to 0.06 με. Figure 25 shows comparative time histories for strain gage 8. The original data was recorded at 10 Hz, while the new data is recorded at 1600 Hz and passed through an 8-pole Butterworth filter with a cutoff frequency of 100 Hz. Figure 4 shows the time history response of a vehicle crossing over the bridge for the original system with 1 με resolution and a vehicle crossing over the bridge with the finer 0.06 με resolution of the current system. The finer resolution can provide more accuracy of the dynamic response of the structure for both health monitoring and weigh-in-motion calculations.

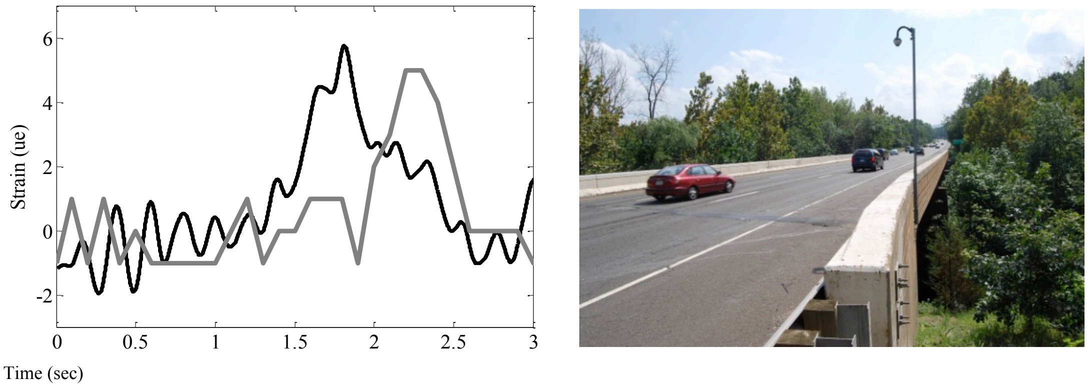

Figure 4. Quantization of Cromwell Bridge System and Photograph of Bridge (Original Data Acquisition (DAQ) – gray; Current DAQ – black)

MEASUREMENT NOISE

It is important to reduce the amount of noise in a structural health monitoring system. Noise measured in a signal may be due to the sensors, data acquisition system, means of data transmission, such as cables or any other intermediary in the system between the system and data acquisition unit.

Large levels of noise in a system can hide the actual response of the bridge being measured. This reduces the usefulness of the measurement. The amount of noise in a signal is quantified by the signal-to-noise ratio (SNR). A signal-to-noise ratio is defined as the ratio of signal power to the noise power corrupting the signal.

There are a number of ways to effectively reduce the amount of noise in a bridge health monitoring. First, sensors with a measurement range only slightly larger than the peak values to be measured should be used. Also, cable lengths should be kept as short as physically possible. Lastly, the signal being sent to the data acquisition unit should be amplified to a similar magnitude as the analog voltage input.

The previously mentioned Sikorsky Bridge system is characterized by high volumes of noise. This high level of noise can be seen below in Figure 5. This shows the acceleration recorded by Accelerometer 1 of span 1 at periods of both high and low traffic excitation. The low traffic period is meant to closely represent the noise floor, as it was impossible to completely restrict the access of traffic. The data shown below was collected from the installed system at 200 Hz.

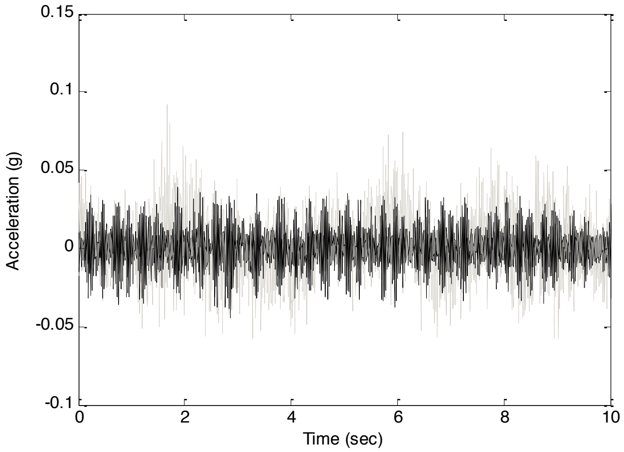

Figure 5. Inherent Noise Levels in Sikorsky Bridge System Accelerometer 1 Span 1 (Light-High Traffic Volume, Dark-Low Traffic Volume)

As seen from Figure 5, the acceleration of the bridge with high and low traffic excitation appears to be at about the same magnitude. This shows that a high volume of noise exists in the system, and is masking the actual response of the structure. The signal to noise ratio of this particular sensor is determined to be approximately 3.2, while the signal to noise ratios for all the accelerometers installed on this bridge range from 1.0 to 5.5.

When examining the high level of noise in the Sikorsky Bridge system, the extreme cable lengths was believed to be a potential source of noise. These can span distances as long as 325 ft. In order to determine the noise contribution of these cable lengths, data was collected using a portable data acquisition unit at the base station of the system and directly at the sensor. By collecting data at the sensor, researchers were bypassing approximately 125 ft. of cable.

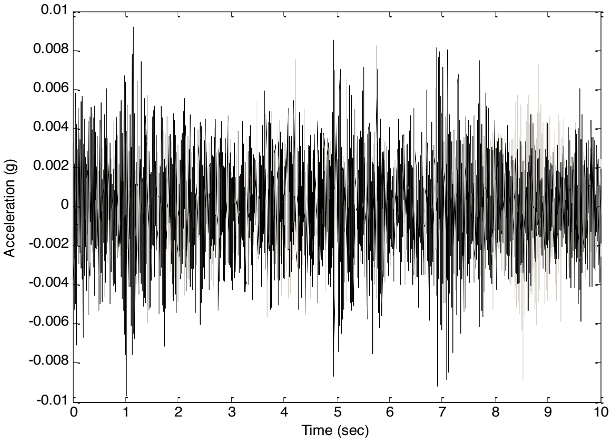

Figure 6. Potential Noise Due to Cable Lengths Sikorsky Bridge Accelerometer 1 Span 1 (Dark-At Base Station, Light-At Sensor)

From Figure 6 it is clear that the acceleration magnitudes collected at the base station and directly at the sensor are approximately the same. This plot proved to researchers that the extreme cable lengths necessary on the Sikorsky Bridge system were not a significant source of noise. Although the cable lengths did not appear to input a significant volume of noise into this particular system, as a rule of thumb, cable lengths should be kept as short as physically possible.

CONCLUSION

The previously described data anomalies along with considerations for aliasing, quantization and noise will now be used to derive a set of proposed specifications for the installation and implementation of structural health monitoring on bridge structures.

In dealing with data anomalies, the presence of any and all data anomalies experienced with the system should be checked periodically and documented accordingly. If a data anomaly is experienced, the proper action should be taken to fix the problem. To avoid signal clipping, expected measurements for strain, acceleration and any other parameter should be approximated before the installation of a permanent system. This can be done with thorough structural analysis or the installation of temporary sensors once the bridge is constructed. Once the maximum expected values are determined, sensors should be carefully selected that are able to capture the dynamic behavior of the structure. If a temporary signal dropout occurs, the most likely issue is a poor cable connection. The connections between all elements in the structural health monitoring system should be carefully inspected periodically and particularly if a signal dropout is experienced. To avoid intermittent noise spikes, all cables in the system should be adequately fixed/tied down to avoid relative motion. If intermittent noise spikes are experienced, the cables should be checked to insure adequate support. Spurious trends in strain gages can be eliminated by specifying temperature compensating strain gages. Spurious trends due to temperature variations in other types of sensors can be effectively managed in the post processing of the data. When a large spike is encountered in the frequency domain for a sensor at 60 Hz, there may be an issue with the grounding of the system. All wiring during the installation of the health monitoring system should be performed carefully and grounded properly. The structural monitoring system design documents should be reviewed, signed, and sealed by a professional Electrical Engineer to avoid electrical issues with the system.

As previously mentioned, aliasing of data can deem a set of random measurements useless. It is, therefore, essential that anti-aliasing filters be implemented on all dynamic sensors. These filters should be carefully selected so that the data collected is not distorted in regions of research interest.

Quantization error in a health monitoring system can be eliminated through the use of an analog to digital converter with a high total number of bits. Current technology allows the use of analog to digital converters with 24 bits.

By minimizing the volume of noise in a structural health monitoring system, the best quality data can be obtained and analyzed. A number of different approaches should be taken to minimize the noise in an installed bridge health monitoring system. First, the expected peak measurement values should be determined, as previously mentioned, for eliminating signal clipping. Sensors should then be selected that have a measurement range only slightly larger than these peak values. Also, cable lengths should be kept to a minimum to minimize the chances of external noise getting into the system. Noise can also be minimized by ensuring that the signal sent to the data acquisition unit is amplified to a similar magnitude as the analog voltage input. Many new data acquisition units are able to consider a small voltage range, minimizing noise from the data acquisition system.

These specifications are intended to provide a guide to the design of structural health monitoring systems for the use on highways bridges. The specifications should be updated and adapted to take advantage of advancements in technology and current practices. These conclusions are followed by a discussion of the lessons learned in bridge monitoring during the course of this research.

LESSONS LEARNED IN BRIDGE MONITORING

As with any specialty built electronic system like this, it should be expected that during installation some issues will arise that have not been anticipated and must be addressed at that time.

To best minimize the number of issues encountered, below is a list of things to consider in any new bridge monitoring system. This list comes from lessons learned on previous bridge monitoring experiences and, in particular, from the recent system upgrades that have been ongoing over the past two years.

1. Data Anomalies

LESSON: The presence of data anomalies should be checked and documented.

Data anomalies include *signal clipping*, *intermittent noise spikes*, *temporary signal dropouts*, *spurious trends*, and *periodicity*. Data anomalies inadvertently present themselves in a bridge monitoring system – that is to say they cannot really be anticipated. These anomalies are identified through an inspection of measured data, as described below:

a) Signal clipping is where the maximum values allowed by the sensor or data acquisition system are exceeded.

LESSON: Signal clipping can be observed as flat tops in the signal in the time domain. Signal clipping is likely to occur when the measured response is larger than expected, i.e., at a level that you would not anticipate encountering. .

b) A <u>temporary signal dropout</u> occurs when the measured signal diminishes rapidly into the noise floor (zero in the absence of noise) for no apparent reason, for a period of time.

LESSON: Temporary signal dropouts can occur when there is a problem with the wiring or connectors for the sensors or perhaps with the sensor itself.

c) <u>Intermittent noise spikes</u> can occur during the acquisition of random data when the transducer cables incur relative motion.

LESSON: Intermittent noise spikes are large spikes in the data and can be detected by visual inspection of the time history record.

LESSON: All instrumentation cables should be adequately fixed/tied down to the structure to avoid intermittent noise spikes.

d) A <u>spurious trend</u> is a time varying mean value occurring in the measured data. This naturally occurs on strain sensors without temperature compensation. A spurious trend would be of particular concern for the bridge monitoring system if it was independent of the temperature variation.

LESSON: Spurious trends will happen on some sensors due to temperature and can be accommodated for in post-processing of the data.

e) <u>Periodicity</u> or <u>periodic data</u> is such that an additional signal is added to the actual signal that repeats itself at regular time intervals. In bridge monitoring this may likely arise from improper grounding of AC electric power (ground loops) and a resulting 60 Hz periodic signal. The periodicity is observed in the frequency domain.

LESSON: Equipment grounding should be double checked.

2. Aliasing

LESSON: It is important to ensure that dynamic measurements are not aliased.

Digitally measured analog signals have potential for aliasing error associated with the digitization process. Aliasing is when a high frequency signal, because of sampling, appears as a lower frequency signal – this is detrimental to bridge monitoring efforts and renders the measurement unusable.

The challenge with aliasing is that once a signal has been sampled and aliased there is no way to reconstruct the original signal or to even know that aliasing occurred. It is difficult to determine the highest frequency in the signal of a bridge response. Often times, local vibratory modes and the impact loading of vehicles entering onto the bridge may result in unexpected high frequency components to the response that are susceptible to aliasing.

LESSON: Errors due to aliasing can be effectively eliminated through appropriate sampling and filtering, as discussed below.

a) Sampling: One general approach to avoid aliasing is to sample at a rate ten times larger than the resonant frequency of the sensor. For vibrating wire strain and temperature sensors with lower resonant frequencies, this should not be a problem. However, for an accelerometer with a natural frequency around 3500 Hz, this would require sampling above 35 kHz. From a practical standpoint this sampling rate may not be achievable and/or the resulting data files may be too large for practical use.

b) Filtering: The alternative to this brute force oversampling is to remove the frequency content of original analog data signal occurring above what is called the Nyquist frequency prior to analog-to-digital conversion. This is achieved by passing the analog signal through an analog low-pass filter called appropriately an antialiasing (AA) filter. All dynamic measurements (foil strain and accelerometer) should be passed through an appropriate AA filter, ideally an 8 pole AA filter. Ensure that the as built system has AA filters on these sensors. The proposed use of National Instruments modules that have appropriate AA filters would eliminate this problem.

3. Quantization Error

LESSON: Ensure that quantization error associated with the digitization process is minimized by using an analog to digital converter in the data acquisition system with a high total number of bits (e.g. 24 bits).

Errors due to quantization and noise are inherent to analog sensors and digital processing and should be minimized. When saving a continuous analog signal as a digital signal, the continuous amplitude of each sample is expressed using a finite number of bits in binary terms by the analog to digital (A/D) converter. The round-off error associated with this A/D conversion is called quantization error. The quantization error is reduced by using an analog to digital converter in the data acquisition system with a high total number of bits (e.g. 24 bits is sufficient). The National Instruments modules proposed for use are 24 bit A/D converters.

4. Measurement Noise

LESSON: Ensure the noise resulting from the sensors and the transmission of the analog signals is minimized.

Noise in a measured signal may be due to any or all of the following:

(a) Sensors;
(b) Means of data transmission;
(c) Data acquisition system, or
(d) Any other intermediary in the system between the sensor and the data acquisition unit.

Large levels of noise can mask the actual response being measured and reduce the usefulness of the measurement. The measurement noise is quantified by the signal-to-noise ratio (SNR).

LESSON: Noise can be minimized by using sensors that have a measurement range only slightly larger than the peak values to be measured.

For example, a 5g accelerometer should not be utilized to measure a 0.05g-peak acceleration – although in some cases this may not be avoidable.

LESSON: Noise can be minimized by not using cables of excessive lengths.

LESSON: Noise can be minimized by ensuring the signal being sent to the data acquisition system is amplified to a similar magnitude as the analog voltage input.

The National Instruments strain module is able to consider a smaller voltage range, significantly improving both quantization and noise from the data acquisition system.

LESSON: Reducing noise can be addressed proactively by requiring the "bridge monitoring designer" to take preliminary measurements so that the anticipated peak measurements are better known prior to the design and installation of the monitoring system.

In the lab SNRs of 100 are expected. Realistically, on a bridge, we would be satisfied with a SNR above 10. We have seen some measurements with a SNR of less than 1 (more noise than the actual signal, which is of little use). The "bridge monitoring designer" should be well aware that bridge strain and acceleration measurements can be extremely small.

ACKNOWLEDGEMENTS

This report was prepared by the University of Connecticut, in cooperation with the Connecticut Department of Transportation and the United States Department of Transportation, Federal Highway Administration. The opinions, findings and conclusions expressed in the publication are those of the authors and not necessarily those of the Connecticut Department of Transportation or the Federal Highway Administration. This publication is based upon publicly supported research and is copyrighted. It may be reproduced in part or in full, but it is requested that there be customary crediting of the source.

The support of the Connecticut Transportation Institute, University of Connecticut, is gratefully acknowledged. The authors gratefully acknowledge the Federal Highway Administration and the Connecticut Department of Transportation for funding of this project through the State Planning and Research (SPR) program, project SPR 2256. The authors would like to express our gratitude for outstanding work by Connecticut Department of Transportation employees to make this work possible. This report, prepared in cooperation with the Connecticut Department of Transportation and the Federal Highway Administration, does not constitute a standard, specification, or regulation. The authors are grateful for the work of the other graduate students who have been involved in the full monitoring project. Some have made contributions to the monitoring of this specific bridge. The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data herein. The contents do not necessarily reflect the views of the Connecticut Department of Transportation or the Federal Highway Administration.

The U.S. Government and the Connecticut Department of Transportation do not endorse products or manufacturers.

REFERENCES

American Association of State Highway and Transportation Officials. (2009). “AASHTO LRFD Bridge Design Specifications.” Washington, D.C..

DeWolf, J. T., Accorsi, M. and O'Leary, P. N. (1991). “Bridge Performance from Vibrational Monitoring.” Proceedings of the International Conference on New Dimensions in Bridges and Flyovers, Singapore, pp. 93-99.

DeWolf, J. T., O'Leary, P. N. and Bagdasarian, D. A. (1991). “Bridge Vibration Monitoring and Analysis.” Annual Meeting of the South Carolina Section of the American Society of Civil Engineers, Greenville, SC, 12 pages.

DeWolf, J. T., O'Leary, P. N. and Bagdasarian. D.A. (1992). “Failure Prevention in Bridges through Continuous Vibrational Monitoring.” Fourth International Conference on Structural Failure, Product Liability and Technical Insurance, Technical University of Vienna, Vienna, Austria, pp. 357-364

DeWolf, J. T., Conn, P. E. and O'Leary, P. N. (1995). “Continuous Monitoring of Bridge Structures.” International Association for Bridge and Structural Engineering Symposium: Extending the Lifespan of Structures, San Francisco, CA, pp. 935-940.

DeWolf, J. T. and Lauzon, R. G. (1995). "Application of Monitoring Technology to Bridge Assessment." Fifth International Conference on Structural Failure, Product Liability and Technical Insurance, Technical University of Vienna, Vienna, Austria, pp. 413-423.

DeWolf, J. T., Culmo, M. P. and Lauzon, R. G. (1998). "Connecticut's Bridge Infrastructure Monitoring Program for Assessment." Journal of Infrastructure Systems, Vol. 4, No., pp. 286-90.

DeWolf, J. T., Lauzon, R. G. and Culmo, M. P. (2002). "Monitoring Bridge Performance." Structural Health Monitoring, Vol. 1, No.2, pp. 129-38.

DeWolf, J. T., Olund, J. K., Liu, C. and Cardini, A. J. (2006). "The Long Term Structural Health Monitoring of Bridges in the State of Connecticut." Third European Workshop on Structural Health Monitoring, Granada, Spain, pp. 372-378.

DeWolf, J. T., Cardini, A. J., Olund, J. K. and D'Attilio, P. F. (2009). "Structural Health Monitoring of Three Bridges in Connecticut." Transportation Research Board 88th Annual Meeting, Washington DC, January 11-15, 2009.

Federal Highway Administration. "About - LTBP: Long-Term Bridge Performance Program." Web.07Jan.2011.http://www.fhwa.dot.gov/research/tfhrc/programs/infrastructure/structures/ltbp/about.cfm

Olund, J. K., Cardini, A. J., D'Attilio, P., Feldblum, E. and DeWolf, J. T. (2006). "Connecticut's Bridge Monitoring Systems." NDE Conference on Civil Engineering, St. Louis, MO, pp. 173-179.

Prusaczyk, S., Christenson, R. E., DeWolf, J. and Jamalipour, A. (2011). "Proposed Data Specifications for Bridge Structural Health Monitoring Sensor Data." Structures Congress & Exposition, Las Vegas, NV.

Prusaczyk, S. (2011). "Data Qualification for the Connecticut Bridge Monitoring Network." Thesis presented to the Graduate School, University of Connecticut, Storrs, Connecticut, in partially fulfillment of the requirements for the Master of Science Degree.

Trivedi , H. (2009). "Development of a Data Qualification and Error Quantification Procedure for Bridge Monitoring Systems in Connecticut." Thesis presented to the Graduate School, University of Connecticut, Storrs, Connecticut, in partially fulfillment of the requirements for the Master of Science Degree.

Trivedi, H. and Christenson, R. E. (2009). "Data Qualification and Error Quantification for Bridge Monitoring Systems in Connecticut." International Workshop on Structural Health Monitoring, Stanford University, Stanford, CA.