# Lowcost Structural Health Monitoring Scheme Using MEMS-based Accelerometers

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***Abstract*— Vibration analysis is the great need and can be used in many practical applications, especially in monitoring the status of machines, bridges and other construction works. This paper presents a low-cost structural health monitoring scheme using MEMS-based accelerometers. The purpose of this scheme is to achieve the high performance system for bridge monitoring with low cost. The system can operate in two modes, real-time and offline. In the real-time mode, embedded real-time short-time Fourier transform programs on the 3-DOF accelerometers were performed for the monitoring and alert. In the offline mode, the analysis of bridge models was utilized based on DIAMOND tool for further analyses and evaluations. Initial results show that the system is suitable for practical applications.**

***Keywords-vibration, monitoring, MEMS, accelerometer.***

## I. INTRODUCTION

One of the principles of monitoring system is vibration analysis method [1]. Analysis of vibration can detect damage of the construction and location of these points of damage. Vibration analysis can also be used to determine the degradation of the construction work after a long time in use. In practice, signals in time domain is not often in form of periodic but often a very complicate form. This means that the vibrations are caused by many vibration components. In other words it is a combination of many different sources of vibration. A vibration analysis is only possible when data are sufficiently reliable to use, so the device used to collect data is important. There are three types of devices can be used to measure and monitor vibration: the moving probe, the velocity meter and accelerometer. Each measuring device has limited and specific applications in which the accelerometer is the best method to determine the force from the vibration sources. Moreover, the accelerometers have been widely used with low-cost thanks to the strong growth of MicroElectronicMechanical System (MEMS) technology.

In this paper, we have proposed a low cost, efficient monitoring system for bridge. This system operates in two modes that are real-time and offline. In the real-time mode, an embedded real-time spectrum program was performed for the monitoring and alert. In the offline mode, the DIAMOND tool was utilized for further analyses and evaluations of the bridge's status. The low cost target can be archived with cheap accelerometers, cheap DSPIC micro-controller, and free DIAMOND tool from LANL institutes.

## II. PROPOSED STRUCTURAL HEALTH MONOTORING SYSTEM

The proposed scheme was show in Fig. 1. The monitoring process can be spitted into two modes: real-time (short term) and offline (long term). In real-time mode, this paper presents a real-time vibration monitoring system based on a 3-DOF (degrees of freedom) MEMS accelerometer. A real-time STFT (Short Time-Fourier Transform) programs was written for the monitoring and alert. With the long term monitoring, the output data of the monitoring system will be updated regularly, serves to monitor the status of bridges over time and environmental impact. DIAMOND, a free MATLAB toolbox [2], was integrated to our scheme in order to utilize several techniques for experimental modal analysis and damage identification.

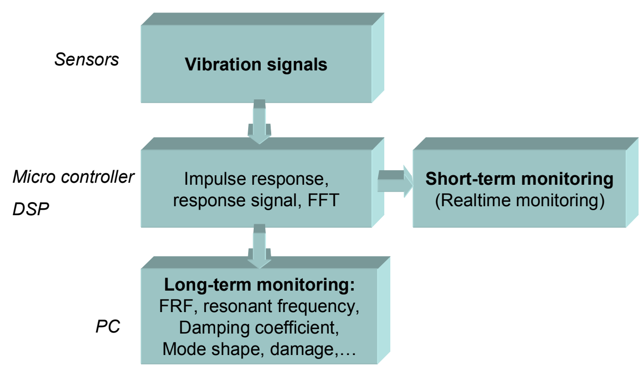


Figure 1. Diagram of the proposed system

The experimental and statistical vibration methods are promising for SHM applications. Measurements are performed on the surface of the construction. The damage will be investigated as distinct changes between typical construction's status and the current one.

## III. SHORT TERM MONITORING

There are still problems with MEMS based the sensors which are necessary to be solved before use. The performance of accelerometers is affected by measurement errors that are classified into deterministic errors and stochastic errors. To eliminate the deterministic errors, we can specify them quantitatively by calibrating the device. It is, however, more complex in determination of the stochastic errors [6].

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The Allan variance is statistical measure to characterize the stability of a time-frequency system [4]. The power spectrum density method can only extract white noise standard deviation. In contrast, using the Allan variance, several other error parameters can be comprehensively derived.

The basic idea of the Allan variance is to take a long data sequence and divide it into segments based on an averaging time $\tau$ to process. Let give a sequence with N elements $y_k$ , $k$= 0,1,…, $N$-$1$. Then, we define for each $n=1,2,3,...,M \leq N/2$ a new sequence of averages of subsequence with length $n$:

$$x_j(n) = \frac{y_{nj} + y_{nj+1} + ... + y_{nj+n-1}}{n}, \qquad j = 0,1,..., \left[\frac{N}{n}\right] - 1 \quad (1)$$

If the sampling time is $\Delta t$ , the time span within an averaged sequence of length $n$ is $\tau = n\Delta t$ . The Allan variance, for a given subsequence length $n$, is defined as:

$$\sigma_a^2(\tau, N) \overset{\Delta}{=} \frac{1}{2\left(\left[\frac{N}{n}\right] - 1\right)} \sum_{j=0}^{\left[\frac{N}{n}\right]-2} (x_{j+1}(n) - x_j(n))^2 \cdot \quad (2)$$

Table 1 shows the estimated noise coefficients for the accelerometers. Note that the source errors are not only caused by the sensors but also the circuit that accelerometer assembled on (see Fig. 2). These parameters are useful for analyzing and processing the obtained data.

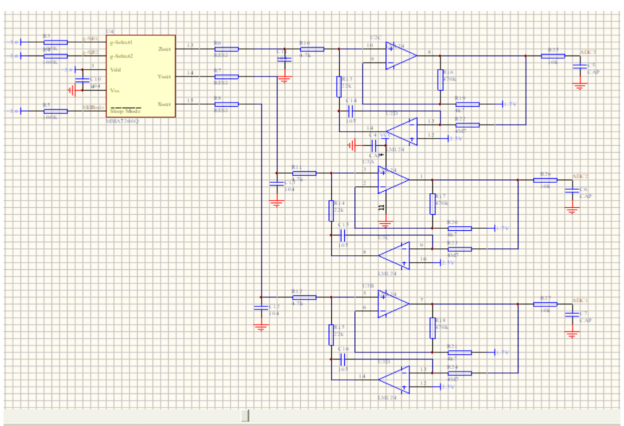


Figure 2. The accelerometer and the controlled circuit assembled on the board

In real-time mode, this paper presents a real-time vibration monitoring system based on a 3-DOF (degrees of freedom) MEMS accelerometer (see Fig. 3). The accelerometer was mounted onto a monitored object in order to acquire the vibration data. Continuous voltage signals in three channels were brought directly to an Analog to Digital Converter (ADC) unit that integrated in a DSPIC30F4013 chip.

TABLE I

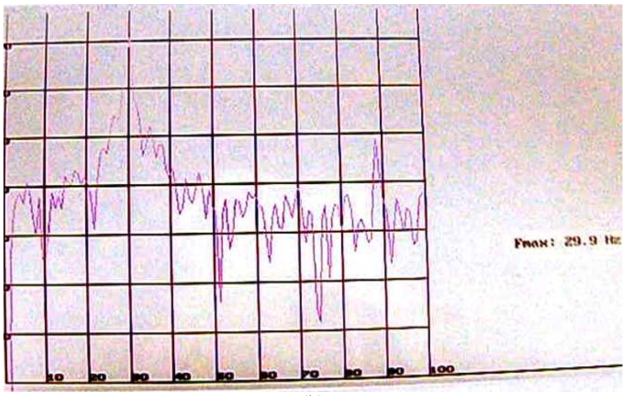
IDENTIFIED NOISE COEFFICIENTS USING ALLAN VARIANCE.

| | Quantization noise $Q_z$(m/s) | White noise Q(m/s/$\sqrt{s}$ ) | Flicker noise B(m/s$^2$) | Random walk K (m/s$^2$/$\sqrt{s}$ ) | Trend R(m/s$^3$) |
|---|---|---|---|---|---|
| X | 1,352*10$^{-5}$ | 4,734*10$^{-5}$ | 4,155*10$^{-5}$ | 1,161*10$^{-5}$ | × |
| Y | 1,400*10$^{-5}$ | 5,169*10$^{-5}$ | 4,713*10$^{-5}$ | 7,588*10$^{-6}$ | 5.0685*10$^{-7}$ |
| Z | 1,339*10$^{-5}$ | 5,688*10$^{-5}$ | 4,025*10$^{-5}$ | 9,197*10$^{-6}$ | 7.4025*10$^{-7}$ |

Figure 3. 3-DOF Piezoresistive accelerometer testing on the shaker, vibrated signal is then transmitted to µ-controller.

A real-time STFT programs was written for the monitoring and alert (see Fig. 4). Fig. 4 shows the vibration experiment in lab, the shaker is vibrated at 29,6 Hz and our real-time program show the good spectrum result at 29,9 Hz. The little difference can be understood as the resolution of STFT.


(a)



(b)

Figure 4. The testing STFT was computed for real-time monitoring

## IV. Long Term Monitoring

For long term monitoring, the modal analysis (MA) and damage identification methods were applied by utilizing DIAMOND tool [2]. It is a free toolbox embedded in MATLAB environment. Thus, we are able to utilize this software into our monitoring system.

MA is effective for modeling the characteristics of a specific system [3]. MA is based on the theory of eigenvalues and eigenvectors of the system. By applying MA, the corresponding experiments have been done effectively and fairly simple. Consequently, the resonant frequencies, damping coefficients, and mode shapes can be estimated. There are several methods commonly used to estimate the MA parameters are Operating Deflection Shapes (ODS), Rational Polynomial Approximation (RPA), and Eigensystem Realization Algorithm (ERA). To identify the damage [4], Strain Energy Method (SEM) and Flexibility method were utilized in DIAMOND [2].

When carrying out an experiment by actively applies force to the target structure, we can measure the Operating Deflection Shape (ODS) [7]. Then, we would be able to determine parameters in the MA analysis. Obviously, the first step is to analysis obtained input signal *x(t)* and the output *y(t)*. There are several ways to excite and measure at the tested nodes such as: fix the output's position and change the input's location, fix the input's location and change the output's location, etc. Then, the signal can be transformed into the frequency domain in the form of spectral density functions $G_{xx}(\omega)$, $G_{yy}(\omega)$, and $G_{xy}(\omega)$. The frequency response function (FRF) can be computed as:

$$H_{xy}(\omega) = \frac{G_{xy}(\omega)}{G_{xx}(\omega)}. \tag{3}$$

FRFs can also display though a coherent function:

$$C_{xy}(\omega) = \frac{\left|G_{xy}(\omega)\right|^2}{G_{xx}(\omega)G_{yy}(\omega)}. \tag{4}$$

Coherent function reflects the correlation between input and output signals. If the structure is considered as a linear invariant system, this function equal to 1. If the signal is noise, this function is 0. Usually, it takes the value changes in the range 0 to 1.

It can be seen that the FRF in the Equ. 4 provide different results for each time of calculation. This is really easy to explain because there are many reasons of this variation.

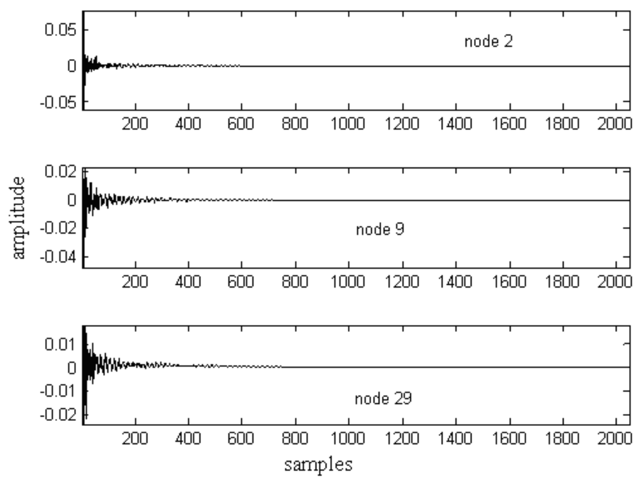



Figure 5. Response signals at near, middle, and far nodes

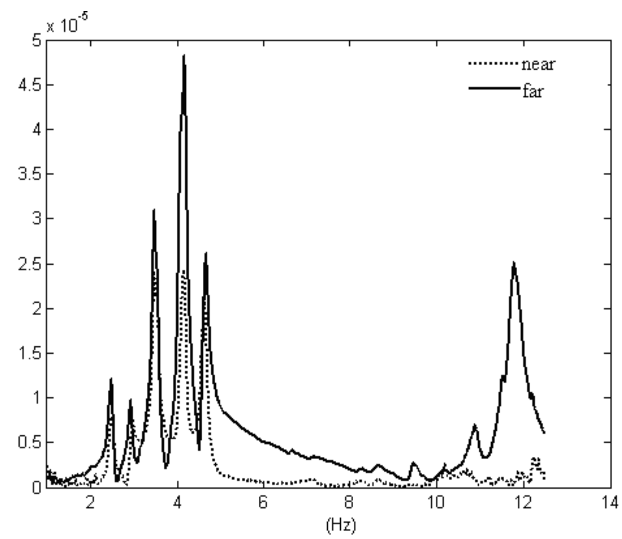



Figure 6. FRFs at near and far nodes

To illustrate the algorithm, the experimental data on a test bridge here are measured on the actual bridge in Ref [2]. Figure 5 is the result obtained on three typical output nodes. The attenuation of the amplitude varies significantly by location of the nodes. Then, the FRF was calculated as shown in Fig. 6.

It's easy to see that the FRFs on each measurements and calculations are different. There are many reasons of this, but generally can be classified into two types are deterministic and random errors [5]. There are two common methods that can be used to reduce these errors: Monte Carlo and Bootstrap methods [8]. The Monte Carlo method assumes that there is random error in each measurement, thus, we need to take the average of multiple of FRFs before estimating the MA's parameters. The bootstrap method combine multiple of FRFs with different weight factors. Consequently, the combined FRF can be also used to estimate the MA's parameter.

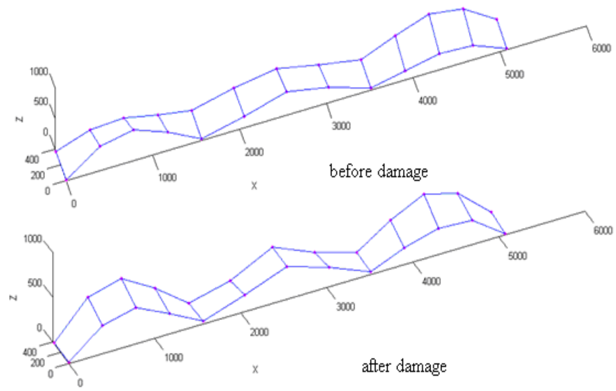


Figure 7. Mode shapes before and after damage, obtained by modal analysis.

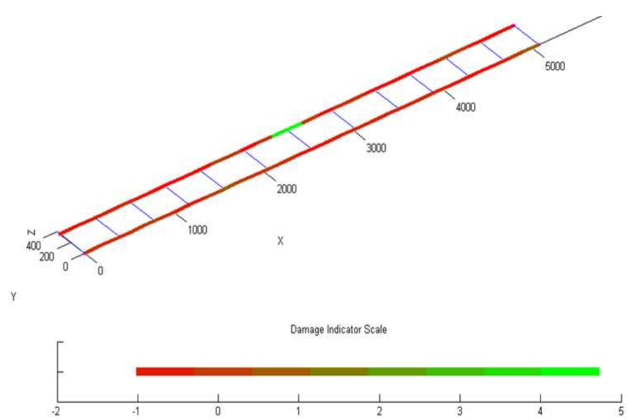


Figure 8. Damage identification at a specific node, obtained by SEM method.

Figure 7 shows the mode shapes obtain by MA method at the first resonant mode. It is easy to see the difference between of the mode shapes before and after the damage appeared on the bridge. However, using MA can identify if damage occurs, but can not indicated the location of the damage. Therefore, SEM was used to identify the damage location [9]. As a result, we were able to clearly identify the damage location (with cracks appearing) as shown in Fig. 8.

## V. CONCLUSION

This paper proposed a low-cost structural health monitoring system for bridge. The system consists of two parallel sections that are real-time monitoring and long term monitoring. The low-cost accelerometers were successfully assembled on DSPIC micro-controller for immediately warning by real-time spectral analyzing of vibrated signal. The DIAMOND software from LANL institutes would also been integrated into our proposed system for long-term monitoring. The preliminary results are helpful to the process of applying this work to practical applications.

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## REFERENCES

[1] Cornelius Scheffer, Paresh Girdhar, "Practical Machinery Vibration Analysis and Predictive Maintenance", Newnes, 2004.

[2] http://institute.lanl.gov/ei/software-and-data/diamond/

[3] George Hearn, "Modal Analysis for Damage Detection in Structures", Journal of Structural Engineering, Vol. 117, No. 10, October 1991, pp. 3042-3063.

[4] Charles R Farrar and David A Jauregui, "Comparative study of damage identification algorithms applied to a bridge: I. Experiment", Smart Materials and Structures, 1998.

[5] Scott W. Doebling and Charles R. Farrar, "Estimation of Statistical Distributions for Modal Parameters Identified From Averaged Frequency Response Function Data", Journal of Vibration and Control, Vol. 7, No. 4, 2001, pp. 603-624.

[6] Peter S. Maybeck, Stochastic models, estimation, and control, Academic Press, Vol. 1, 1994.

[7] Brian J. Schwarz and Mark H. Richardson, "Introduction to operating deflection shapes", CSI Reliability Week, Orlando, FL, 1999.

[8] Farrar, C.R. and Doebling, S.W., "A Comparison Study of Modal Parameter Confidence Intervals Computed Using the Monte Carlo and Bootstrap Techniques", Proc. of 16th International Modal Analysis Conference, Santa Barbara, CA, 1998, pp. 936-944.

[9] Sazonov, E., Janoyan, K., Jha, R., Nelson, R., Krishnamurthy, V., Gao, Z. and Fuchs, M., "Sensor network application framework for autonomous structural health monitoring of bridges", Proceedings of Structural Materials Technology (SMT): NDE/NDT for Highways and Bridges, Buffalo, NY, 2004.