Proceedings of the ASME 2010 Conference on Smart Materials, Adaptive Structures and Intelligent Systems
SMASIS2010
September 28 – October 1, 2010, Philadelphia, Pennsylvania, USA

SMASIS2010-3839

FATIGUE LIFE MONITORING OF METALLIC STRUCTURES BY DECENTRALIZED RAINFLOW COUNTING EMBEDDED IN A WIRELESS SENSOR NETWORK

Sean O'Connor
Department of Civil and Env. Engineering
University of Michigan
Ann Arbor, MI, USA

Junhee Kim
Department of Civil and Env. Engineering
University of Michigan
Ann Arbor, MI, USA

Jerome P. Lynch
Department of Civil and Env. Eng.
University of Michigan
Ann Arbor, MI, USA

Kincho H. Law
Department of Civil and Env. Eng.
Stanford University
Stanford, CA, USA

Liming Salvino
Naval Surface Warfare Center
Carderock Division
West Bethesda, MD, USA

ABSTRACT

Fatigue is one of the most widespread damage mechanisms found in metallic structures. Fatigue is an accumulated degradation process that occurs under cyclic loading, eventually inducing cracking at stress concentration points. Fatigue-related cracking in operating structures is closely related with statistical loading characteristics, such as the number of load cycles, cycle amplitudes and means. With fatigue cracking a prevalent failure mechanism of many engineered structures including ships, bridges and machines, among others, a reliable method of fatigue life estimation is direly needed for future structural health monitoring systems. In this study, a strategy for fatigue life estimation by a wireless sensor network installed in a structure for autonomous health monitoring is proposed. Specifically, the computational resources available at the sensor node are leveraged to compress raw strain time histories of a structure into a more meaningful and compressed form. Simultaneous strain sensing and on-board rainflow counting are conducted at individual wireless sensors with fatigue life prediction made using extracted amplitudes and means. These parameters are continuously updated during long-term monitoring of the structure. Histograms of strain amplitudes and means stored in the wireless sensor represent a highly compressed form of the original raw data. Communication of the histogram only needs to be done by request, dramatically reducing power consumption in the wireless sensing network. Experimental tests with aluminum specimens in the laboratory are executed for verification of the proposed damage detection strategy.

INTRODUCTION

Structural failures where fatigue damage has been cited as the root cause are widespread throughout modern history spanning from the Versailles train crash in 1842 [1] to the more recent destruction of China Airlines Flight 611 in 2002 [2]. Since fatigue is known to be a progressive material degradation, consideration of fatigue in a structural health monitoring (SHM) system is necessary. In quantifying fatigue damage by strain-time monitoring, a reliable fatigue life monitoring system can prove to be an invaluable tool that can improve structural management methods (i.e., inspection and maintenance) and potentially predict pending structural failure. In order for a fatigue monitoring system to be reliable, it first requires the ability to monitor all possible locations where fatigue induced cracking may occur. As it is nearly impossible to monitor all structural members, areas most susceptible to damage, particularly regions with high stress concentrations should be selected for monitoring. This may still require a dense network of sensors engaged in long-term monitoring. As a result, massive amounts of measured strain time history data are accumulated.

Numerous wireless sensing platforms have emerged in the last decade for SHM [3]. Wireless sensors combine the functionality of data acquisition, embedded data analysis, and wireless data transmission within a single device. Among their many advantages, wireless sensing channels can be installed at a fraction of the cost of a wired channel. This allows dense sensor networks to be affordably deployed throughout large structural systems. This affordability increases the reach of the system to a larger set of users since cost is almost always a main parameter when deciding to monitor a structure or not. Another advantage of wireless sensors is that they are capable of processing data locally. Directly transmitting massive amounts of raw strain data via wireless sensing would consume the limited communication bandwidth available and result in significant power consumption during communication. In this study, the embedded computing available on-board wireless sensors will be taken advantage of for SHM purposes, specifically for fatigue assessment. Decentralized computation of rainflow counting in a wireless sensor network will allow one to process measured data at individual sensors, convert that data into individual cycles of specific mean and amplitude, and produce a more meaningful and compressed form of the original time history data. This data is continuously updated and sits ready for transmission only when requested by system end-users. Huge power savings are realized by this point, as the wireless radio is responsible for consuming more power than any other hardware component [4].

A strategy for fatigue life estimation by a wireless sensor network installed in a structure for autonomous health monitoring is proposed. A method is required for both cycle counting and damage accumulation. In the proposed embedded system, strain data is continuously stored and processed for cycle identification by rainflow counting. Rainflow counting condenses the irregular load history into a sequence of constant amplitude events. Cycles of strain amplitude and mean are input to a strain-life relation and assigned a life value, which ultimately represents the amount of damage done by that particular cycle. Damage incurred by each individual cycle is accumulated through the use of the Palmgren-Miner linear damage hypothesis. In an effort to verify the accuracy of the embedded procedure, an aluminum bar specimen is cyclically loaded in a closed-loop electrohydraulic load frame. A strain gage attached to the aluminum specimen provides strain-time data to both a wired and wireless data acquisition system. Data acquired by wired means is processed off-line after testing as one whole data set. In contrast, data acquired wirelessly is processed on-line by a wireless sensor and stored on-board in a cumulative manner. Results from both wired and wireless systems are then compared.

FATIGUE LIFE MONITORING PROCEDURE

Rainflow Counting

The fatigue life monitoring process begins by identifying cycles within a complex load history. A number of cycle counting methods are used to reduce irregular load histories into a collection of constant amplitude events such as rainflow counting [5], range-pair counting [6], and racetrack counting [6]. Rainflow cycle counting has shown to be among the superior methods for cycle counting of irregular loads. In the rainflow method, cycles are identified in a manner in which closed hysteresis loops are identified from the stress–strain response of a material subject to cyclic loading. As shown in Fig. 1, closed hysteresis loops can be identified from the strain-time history shown. Ranges A-D, B-C, E-F, and G-H, would represent cycles counted under rainflow counting techniques.

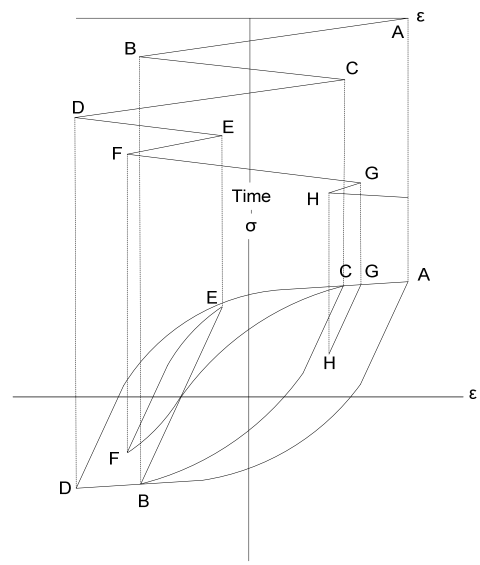


Figure 1: Rainflow cycle analysis via closed loop identification

Rainflow counting, however, is originally intended to be carried out once the entire strain history is known since counting starts and ends at the maximum peak or valley. Due to the limited memory in wireless sensors, it is not possible to wait until the entire load history has been realized before fatigue accumulation can be calculated. Rather, a rainflow counting algorithm suitable for on-line data processing must be selected [7, 8].

One rainflow counting method in particular, the 'one-pass' rainflow counting algorithm [7] , addresses this issue by not requiring the entire load history. This method, which is used for embedment in this study, is a vector-based counting algorithm first demonstrated by Downing, et al. [9] and modified by Okamura, et al. [10] to account for half cycles. The embedded rainflow counting algorithm starts by arranging sampled strain time history measurements into a single vector. From the set of strain data, peak and valley points inherent in cyclic measurements are identified and stored. The typical rainflow counting procedure is then performed on the set of peaks and valleys, identifying closed hysteresis loops and logging those ranges as cycles. For each cycle, both the strain amplitude and mean strain are recorded. This rainflow counting procedure identifies the same cycles as the traditional rainflow procedure that uses the entire strain time history. This fact makes the 'one-pass' rainflow counting procedure very attractive for continuous real-time monitoring of fatigue life using smart wireless sensors.

Histogram Design

The 'one-pass' rainflow counting technique can be operated in a real-time manner for continuous monitoring of fatigue life. The compression of a strain time history from sampled points to cycles though, is not enough to monitor fatigue in the long term. Further data compression is realized by accumulating identified cycles of mean and amplitude into a histogram similar to the one shown in Fig. 2. A fixed size histogram allows for *a priori* allocation of the available memory integrated with the wireless sensor, allowing for the

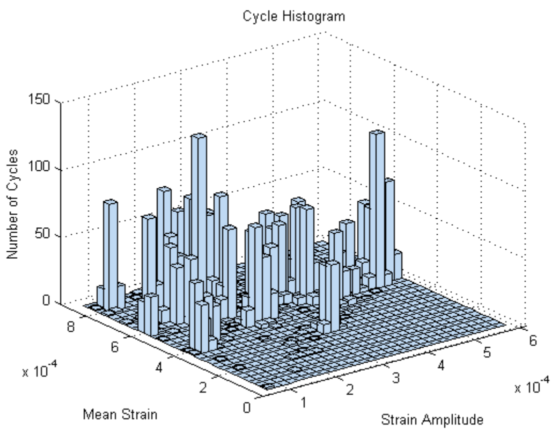


Figure 2: Histogram of cycle accumulation

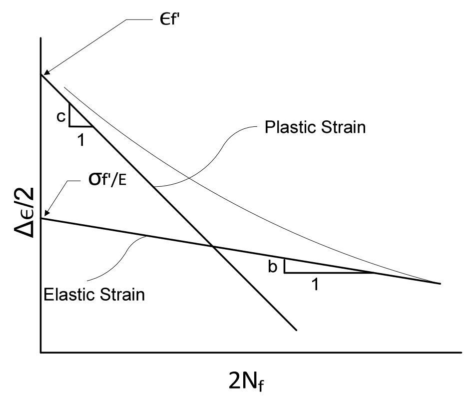


Figure 3: Strain-life curve

near perpetual accumulation of fatigue cycles and thus continuous "real-time" fatigue life monitoring. Considerations of bin sizing in the mean and amplitude axes will be of importance in terms of mean and amplitude accuracy, as well as in terms of the scarce memory consumed.

Damage Accumulation

Strain-life methods which account for mean strain effects are used here to predict fatigue life. First, the total strain amplitude can be expressed as the sum of an elastic strain amplitude and a plastic strain amplitude, each represented linearly against cycles to failure on a log-log plot. Total strain amplitude versus cycles to failure, N_f, before mean stress (or mean strain) correction [11] is written as

$$\frac{\Delta\epsilon}{2} = \frac{\sigma_f{}'}{E}(2N_f)^b + \epsilon_f{}'(2N_f)^c \tag{1}$$

where $\frac{\Delta\epsilon}{2}$ = strain amplitude

$\sigma_f{}'$ = fatigue strength coefficient

E = modulus of elasticity

$2N_f$ = reversals to failure

$\epsilon_f{}'$ = fatigue ductility coefficient

b = fatigue strength exponent

c = fatigue ductility exponent

The constants b and c represent the slopes of the elastic and plastic strain. Similarly, $\frac{\sigma_f{}'}{E}$ and $\epsilon_f{}'$ are the y-axis intercepts of the elastic and plastic strain curves in Fig. 3.

Eq. (1) is applicable if dealing with full cycles with zero mean strain. However, several researchers have proposed modifications to the strain-life relationship of Eq. (1) to account for mean stress effects including Morrow [12], Manson and Halford [13], and Smith, Watson, and Topper [14]. These relations all have their own advantages, but require the mean stress in order to evaluate the number of cycles to failure. A modification to the strain-life relation using mean strain instead of mean stress would be better because we directly measure strain and not stress. The need to track stress-strain around a hysteresis curve to determine mean stress is taken out of the picture, making the embedded process easier to implement. One such empirical relationship between total strain range, $\Delta\varepsilon$, and cycles to failure is adopted herein [15]. This empirical relationship which accounts for mean strain instead of mean stress is written as

$$\Delta\epsilon = \frac{2(1-R)\epsilon_f{}'}{\left[(4N_f-1)(1-R)^a+(2)^a\right]^{1/a}} \tag{2}$$

where $R = \epsilon_{min}/\epsilon_{max}$ if $|\epsilon_{max}| \geq |\epsilon_{min}|$

$R = \epsilon_{max}/\epsilon_{min}$ if $|\epsilon_{max}| < |\epsilon_{min}|$

$\Delta\varepsilon = \epsilon_{max} - \epsilon_{min}$

Here, a is equal to $-1/c$. The fatigue ductility coefficient, $\epsilon_f{}'$, fatigue strength exponent, b, and fatigue ductility exponent, c, determined for the strain-life relationship are used both directly and in computing material constant, a. These parameters are best evaluated by performing cyclic testing in the laboratory. When fatigue data is not available or easily obtained, these parameters can be estimated from static properties or by using other estimation methods.

In this study, the empirical fatigue law of Eq. (2) will be used. To estimate the model parameters (fatigue ductility coefficient, $\epsilon_f{}'$, fatigue ductility exponent, c, and fatigue strength exponent, b), the uniform material law by Baumel and Seeger [16] is used. For aluminum and titanium alloys, the strain-life equation is estimated as

$$\frac{\Delta\epsilon}{2} = 1.67\,\frac{\sigma_b{}'}{E}(2N_f)^{-.095} + 0.35(2N_f)^{-0.69} \tag{3}$$

where σ_b = yield stress

While we will not be using Eq. (3), we can however extract the fatigue ductility coefficient, $\epsilon_f{}'$, fatigue ductility exponent, c, and fatigue strength exponent, b from it. With knowledge of these constants, the material constant, a, can be estimated and Eq. (2) can be written in its final form as

$$\Delta\epsilon = \frac{2(1-R)0.35}{\left[(4N_f-1)(1-R)^{-0.4}+(2)^{-0.4}\right]^{1/-0.4}} \quad (4)$$

In this form, the mean strains and strain amplitudes obtained through rainflow counting are sufficient for determining the fatigue life, N_f, of an instrumented component. Although it is possible to embed a mean stress procedure, it will require more work for the wireless sensor and may be unnecessary as the prediction proposed in Eq. (4) has been shown to compare extremely well with data received from alloys tested under a variety of different tensile and compressive mean strains [17].

The fatigue life corresponding to each cycle is an indication of the amount of damage imposed on the material due to that specific cycle. In this way, we can start to accumulate and monitor damage. The damage summation of each cycle is done using the Palmgren-Miner linear damage hypothesis originally proposed by Palmgren [18] and later modified by Miner [19]. The Palmgren-Miner rule is written as

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} \quad (5)$$

where D = accumulated damage

k = total number of cycles in a loading spectrum

$i = i_{th}$ applied stress/strain level

n_i = number of cycles at stress/strain level i

N_i = fatigue life at stress/strain level i

This method implies that failure occurs when the summation of cycle ratios, $\frac{n_i}{N_i}$, is equal to 1. It should be noted that by using strain-life methods, we are predicting initial racking instead of complete failure. Further monitoring of fatigue damage (i.e., after the initiation of cracking) requires crack propagation methods.

The value residing in each bin of the accumulated cycle histogram represents the number of cycles at a specific strain amplitude and mean. The position of each bin determines the fatigue life of that particular bin, since it represents the strain amplitude and mean strain required for the strain-life relation. In the embedded implementation, cycles incurring damage below a specified threshold result in their elimination from the analysis. Signal noise will generate high amounts of low amplitude cycles, which when accumulated over an excessive amount of time, may falsely contribute to the expended life of the material. Although certain materials have no defined fatigue limit, this liberty is assumed safe as noise level amplitudes are far below reasonably assumed estimations for fatigue limits of these materials. It is important to use damage as the parameter for which cycles are counted or eliminated from analysis. Very small amplitude cycles at very high mean stress may result in relevant fatigue damage, and should not be eliminated from analysis.

EXPERIMENTAL VALIDATION OF DECENTRALIZED RAINFLOW COUNTING

Narada Wireless Sensor

The Narada wireless sensing unit shown in Fig. 4 was developed at the University of Michigan [20] and is used in this study for embedment of the 'one-pass' rainflow cycle counting algorithm. The Narada uses an Atmel Atmega128 microprocessor with 128kB of external SRAM for data storage and computation. The external memory allows for the unit to store up to 64,000 data points at one time. Wireless communication is realized via a Chipcon CC2420 IEEE802.15.4-compliant wireless radio, making the unit exceedingly versatile for developing large, scalable wireless sensor networks. This unit utilizes a four channel, 16-bit Texas

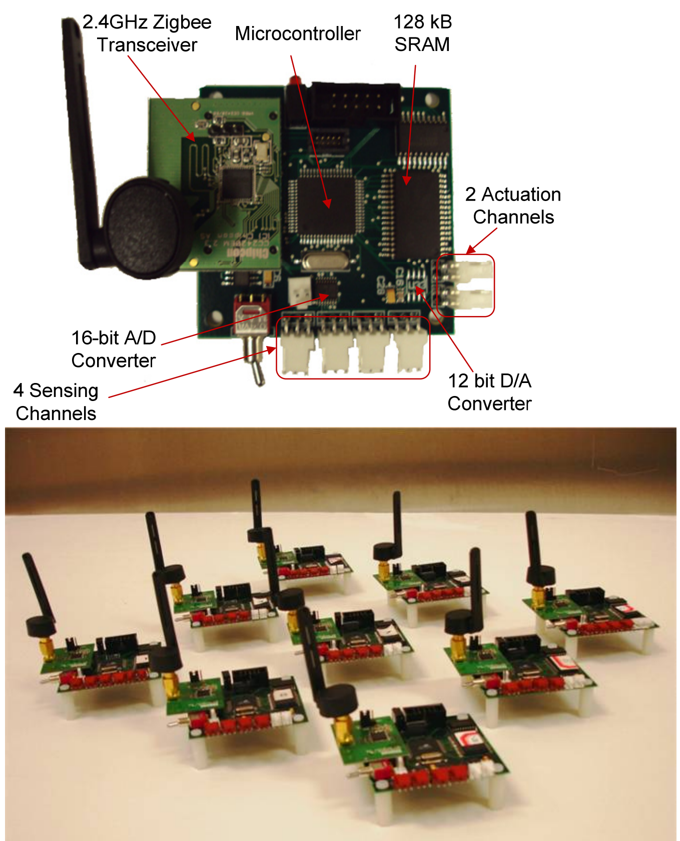


Figure 4: Narada Wireless Sensing Unit

Instruments ADS8341 ADC for data acquisition, and a two channel, 12-bit Texas Instruments DAC7612 digital-to-analog converter (DAC) for actuation capability.

Specimen Material & Preparation

For this study, specimen material 6061-T6 aluminum alloy is used; mechanical and physical properties can be found in Mil-HDBK-5H [21] and ASM Material Data Sheet [22]. The specimen being tested is a 17 in by 3 in by 1/8 in thick bar. A 10 mm strain gage was used (Tokyo Sokki Kenkyujo Co., Ltd. TML PFL-10-11-1L 120Ω) at the mid-section of the bar. Bonding areas were removed of grease and oils and lightly polished before adhering strain gages.

Test Procedure

Fatigue loading was done using an MTS Series 318 electrohydraulic closed loop load unit. The load unit consists of two smooth vertical columns that are joined by two stiff cross members, one being fixed with an integrally mounted hydraulic actuator. Hydraulic grips hold the specimen in place during loading. Specimens are subject to variable amplitude uniaxial tensile cyclic loading. The loading pattern consists of 100 randomly generated peaks and valleys, shown in Fig. 5. Load sets are looped continuously during testing. In an effort to compare a wired rainflow analysis with the 'one-pass' rainflow analysis embedded in the Narada wireless sensing node, the specimen strain gage was split with its output interfaced to both the wired and wireless systems as shown in Fig. 6.

Strain gage lead wires were attached to a set of two strain boards. A quarter Wheatstone bridge circuit is connected with a 120Ω strain gage to convert resistance change into a voltage signal. In order to connect the voltage signal to both DAQ systems which have different input impedances, two identical operational amplifier circuits are interfaced with both DAQ systems as shown in Fig. 6. The operational amplifier circuit also amplifies the voltage signal by a factor of 50. In the case of the wired system, data collection is done using the National Instruments BNC-2110 DAQ at a sampling frequency of 100 Hz. In the case of the wireless system, the Narada wireless sensor uses a sampling

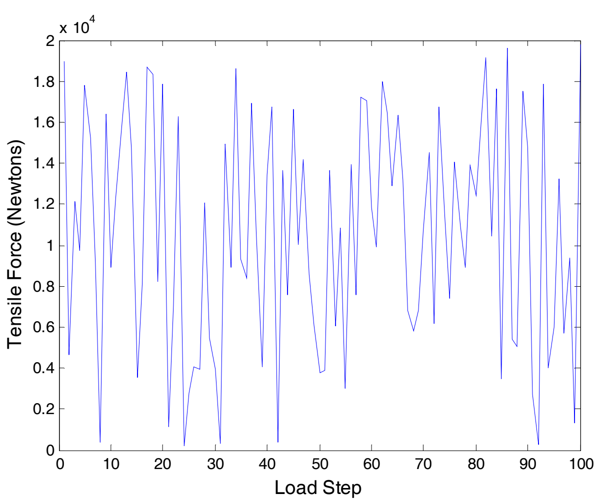


Figure 5: Load input

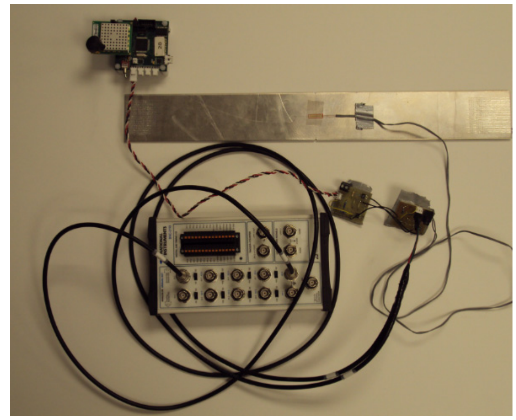


Figure 6: Dual data acquisition of strain gage

frequency of 50 Hz. Data collected from the wired system is processed by rainflow counting after testing.

Implementation of Decentralized Rainflow Counting in Narada Wireless Sensor

The embedded procedure operates in 128kB of external SRAM. External memory is divided into two 64kB halves denoted as low and high (Fig. 7). Data acquired is stored on the low side in three separate blocks with a capacity of nearly 20kB each. This allows for the acquisition and processing of data sets containing nearly 10,000 2-byte points. The three stage data acquisition guarantees the continuous acquisition of strain data in one block while fatigue life procedures (such as rainflow counting and damage accumulation) are performed simultaneously on a previously attained set of strain data.

After a stack of memory is filled, a peak picking algorithm is performed on the set of strain data. A set of only peaks and valleys are stored in a specific location on the high side of the external SRAM. The extreme condition considered for sizing memory allocation occurs when all points acquired during sampling result in peaks or valleys of the strain response signal, requiring an equally sized 20kB memory allocation. The rainflow counting procedure is carried out on the set of peaks and valleys and stored on the high side of the external SRAM. Extreme conditions here would see less than half the number of peak/valley points as the maximum number of cycles, requiring 10kB of memory allocation for strain amplitude and mean strain each.

The remaining 20kB of external SRAM on the high side is used as a continuously updated histogram. In the case where the number of cycles is represented as a 2 byte integer, 10,000 unique strain amplitude-mean strain combinations are available. Any m-by-n product of amplitude bins, m, by mean bins, n, less than 10,000 are admissible. In this test, cycles are accumulated in a 2 byte memory slot, limiting the maximum number of cycles that can be accumulated for a specific strain amplitude and mean strain to 65,535 cycles. All processing procedures carried out on the high side of the external SRAM allow for continuous strain gage data acquisition on the low side by way of an interrupt on the analog-to-digital converter. The external SRAM layout is shown in Fig. 7.

By decentralizing the fatigue life monitoring process, great savings in communication can be realized. Table 1

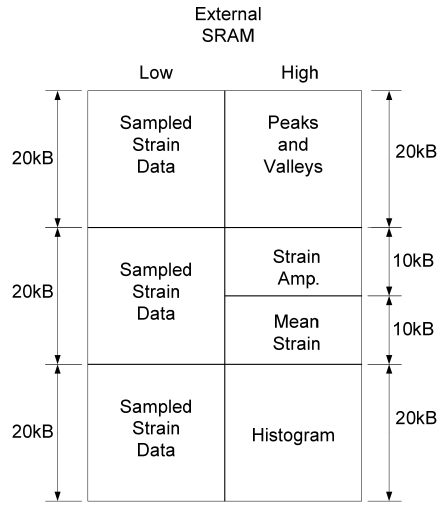


Figure 7: Memory map for embedded fatigue monitoring procedure

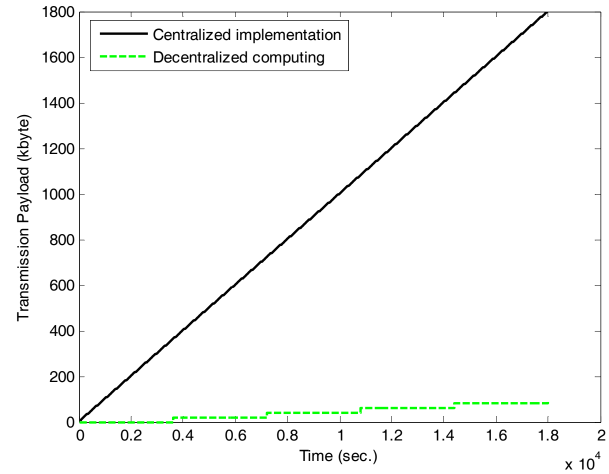


Figure 8 : Comparison of decentralized and centralized computing

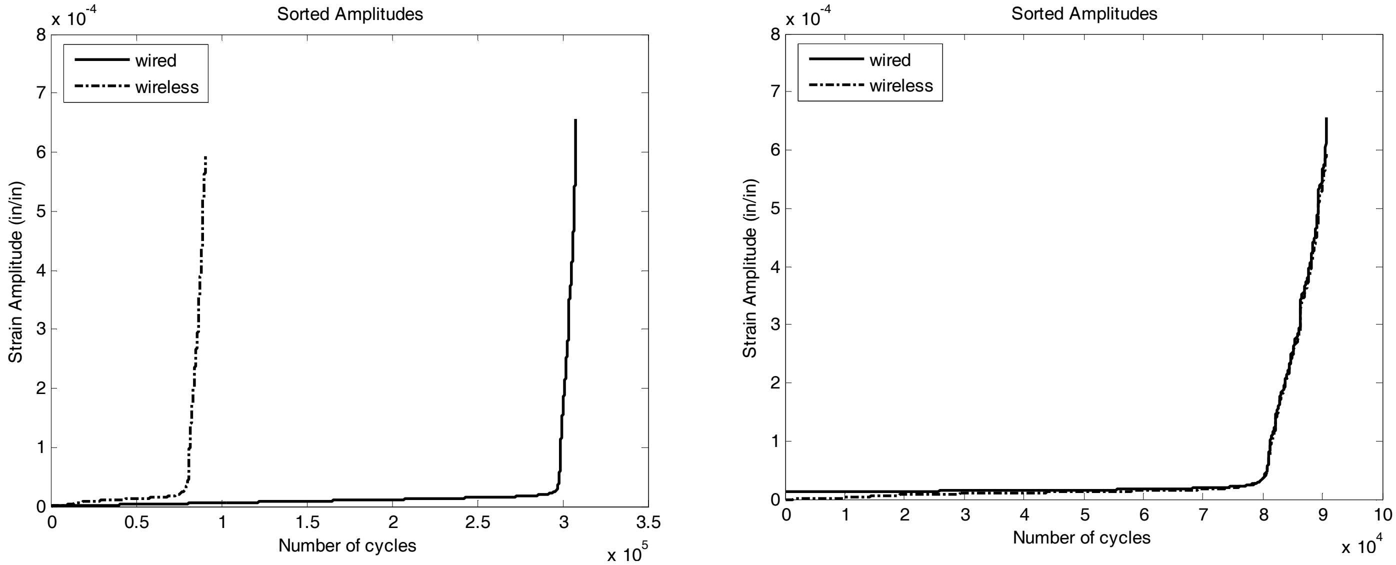
shows an analysis of communication requirements of a centralized rainflow counting implementation and a decentralized computing implementation. The example in Table 1 is consistent with 10 minutes of continuous data acquisition at a sampling frequency of 50 Hz. The decentralized implementation sends one histogram at the end of the ten minutes. A transmission reduction of approximately 67% is the result of a ten minute experiment. Fatigue life monitoring though, will require much longer periods of data acquisition and will further exploit this transmission reduction.

Figure 8 shows the transmission payload over a 5 hour period for both the centralized implementation (where raw data is continuously streamed) and the decentralized implementation (where fatigue histograms are locally updated and occasionally transmitted). Raw strain gage data increases as a linear function of time for any given sampling frequency in the centralized implementation. The number of unique strain amplitude and mean strain cycles sent by the histogram in the decentralized implementation remain fixed, and thus increase by the same amount at each request. Histograms are sent once each hour. At the end of the 5 hour example, the decentralized computation produces 1700 less kbyte for transmission than the centralized implementation, resulting in a 94% transmission reduction. Further increase in time between histogram transmissions will result in even greater transmission savings. By receiving compact amounts of meaningful data transmitted upon request as opposed to receiving vast amounts of unprocessed data transmitted frequently, faster and more efficient analysis of the structural member under observation can be conducted.

Table 1: Analysis of communication requirements of centralized and proposed decentralized fatigue life monitoring methods

Methods	Transmission payload byte
Centralized *Rainflow counting performed on central server after all time history data is received*	$N_{data} * 2\ byte$ $= 30000 * 2 = 60\ kbyte$
Decentralized *Rainflow counting conducted on wireless sensing nodes with cycle histogram sent to server*	$Histo * 2\ byte$ $= 10000 * 2 = 20\ kbyte$
	Transmission reduction = ~ 67 %

Note: Time history data length, N_{data} = 30000 points
Histogram size, $Histo$ = 10000 bins



(a) (b)

Figure 9: (a) Reordered amplitudes over entire time history (b) Wired and wireless amplitude overlay

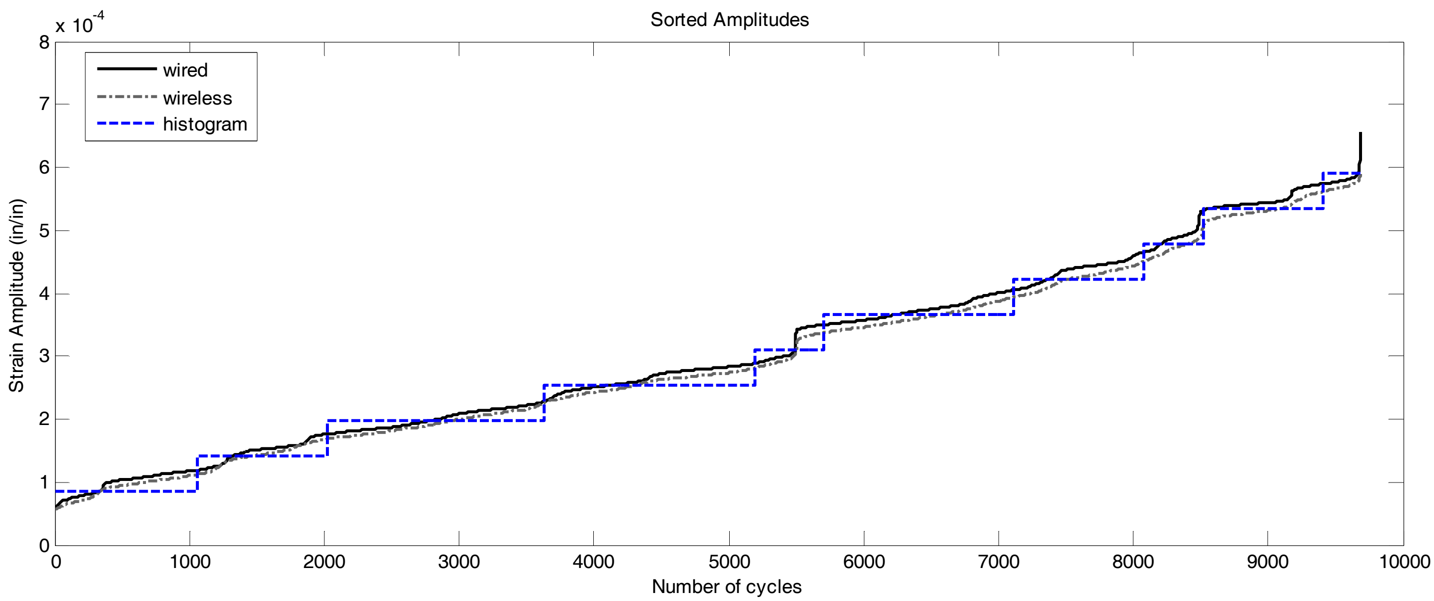


Figure 10: Close up view of relevant wired, wireless, and histogram cycle outputs

Results

To make a comparison between a wired and wireless fatigue monitoring system, the wireless sensing system was set to transmit all cycles, giving strain amplitude and mean strain for each cycle at the end of each sampling block. Histograms were transmitted periodically during testing upon user request. Figure 9a compares wired and wireless rainflow cycle counting amplitudes, plotting all amplitudes calculated during rainflow counting, reordered lowest to highest. It can be seen that the wired system produces more low amplitude cycles than the wireless system. This can be explained as an effect of splitting the strain gage to two DAQ systems, which introduced an increase in signal noise to the wired signal. Additionally, the wired DAQ system sampled twice as fast as the wireless system resulting in more peaks and valleys to consider during rainflow counting. Figure 9b shows the amplitudes read from each system where the signal noise has been removed from the wired strain data, resulting in a more accurate comparison of the two DAQ systems; similar amplitude outputs are extracted by both systems. Figure 10 provides a closer look at the wired and wireless amplitudes that overlay in Fig. 9b. Figure 10 also includes the results recorded in the histogram during testing. For the division of the histogram bins, 327 unique amplitudes and 21 unique mean values are selected. Damage accumulation for the three sets of results is shown in Fig.11. Damage value represents the damage accumulated as calculated by the Palmgren-Miner method (namely, Eq. (5)). The maximum damage results of

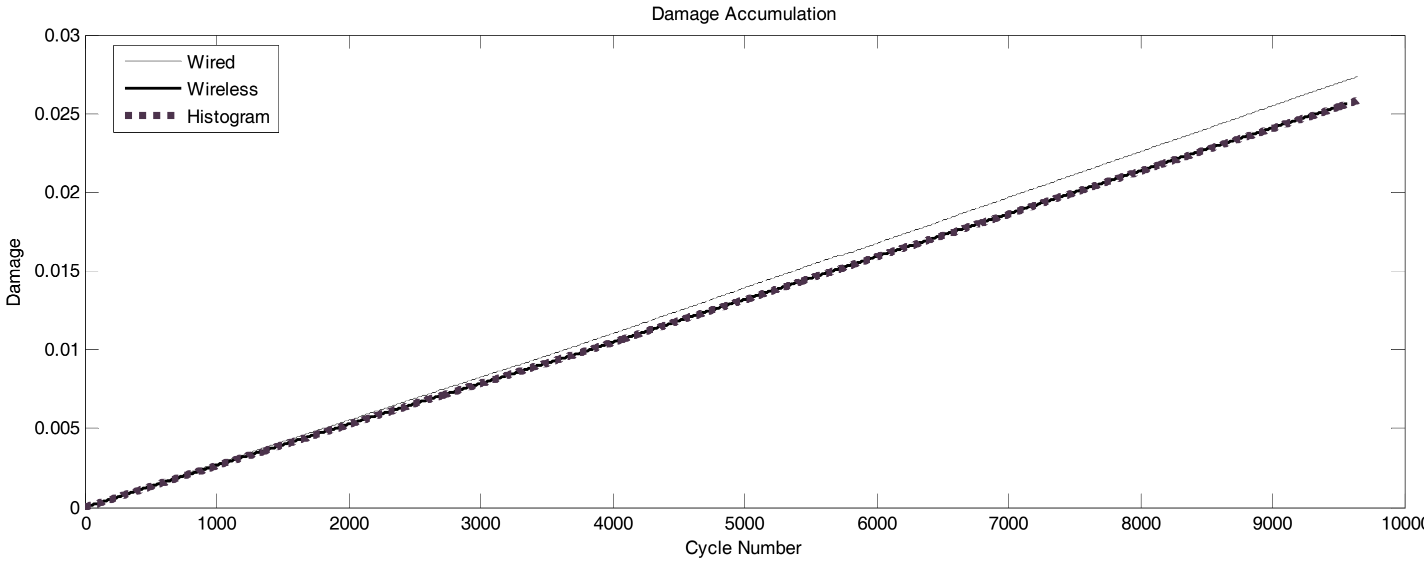


Figure 11: Damage accumulation

Table 2: Fatigue Life Results

	Total Cycles	Cumulative Damage	% difference
Wired	9642	.00273	------
Wireless	9570	.00256	6.22
Binned Wireless	9684	.00259	5.13

in Fig. 11 are listed in Table 2. Excellent agreement between the wired and wireless systems is found.

CONCLUSIONS

In this study, a strategy for fatigue life estimation by a wireless sensor network installed in a structure for autonomous health monitoring is proposed. Simultaneous strain sensing and on-board rainflow counting are conducted at individual wireless sensors and compared with wired test results. Wired data shows similar results with the wireless results, but tends to reflect higher amplitudes and more damage. It can be seen that the embedded wireless procedures reside within 5-6% difference in damage accumulation. Raw strain data acquired on the wired side showed slightly higher magnitude response than the wireless signal after being split at the quarter bridge. A comparison between all wireless cycles and the histogram representation of the wireless cycles match very strongly. Approximately 1% separates the two methods.

ACKNOWLEDGEMENT

The authors would like to gratefully acknowledge the support offered by the Office of Naval Research under Contract Numbers N00014-09-1-0567 and N00014-10-1-0613 awarded to University of Michigan and N00014-10-1-0384 awarded to Stanford University. Additional support was provided by the U.S. Department of Commerce, National Institute of Standards and Technology (NIST) Technology Innovation Program (TIP) under Cooperative Agreement Number 70NANB9H9008.

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