Proceedings
of the
SEM Spring Conference on Experimental and Applied Mechanics

and

Experimental/Numerical Mechanics in Electronic Packaging III

Houston, Texas

June 1-3, 1998

Published by the Society for Experimental Mechanics, Inc.

REAL-TIME ASSESSMENT OF FATIGUE DAMAGE TO STRUCTURES

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ABSTRACT. In industrial environments, failures of system components can lead to unsafe operation, environmental damage, and significant loss of revenue. When specific components of the system are critically designed, analysis and instrumentation can be combined to assess operation. After analyzing the potential strain fields in a structure, strain gages may be installed at key locations to measure dynamic strain during operation or use of the structure. Fatigue analysis can be performed on the acquired data to determine if failures are likely. From these data, operational parameters and/or system design can be altered to maintain safe and reliable operation.

This procedure can result in high channel counts, producing large amounts of data and can quickly overwhelm the analyst. Furthermore, one is not always assured of obtaining data during times of high strain. Therefore, a system to continuously acquire and evaluate the data while presenting only the most useful information is required.

Such a system using off-the-shelf acquisition and PC hardware has been developed and has been in use for a number of years. A method for counting stress-cycles in real-time will also be presented. A procedure for estimating the amount of damage (usage) that has already occurred will be shown. The concept of a "Fatigue Concern Indicator" will also be introduced.

1. INTRODUCTION

Structural failures in an industrial environment were detected by the facility operations personnel. Although cracks were detected prior to catastrophic failure, the failures resulted in significant loss of revenue and could have posed significant safety and environmental hazards. After repairs were made and normal operation was resumed, data were acquired to quantify the cause(s) of the failures. The data indicated that unexpected events were occurring in the process that were generating abnormally large forces. These forces resulted in fatigue failures of critical structural components.

To develop both long-term and short-term solutions to the problem, several key issues were addressed, including:

- the amplitude of the generated forces,
- the frequency at which events occurred,
- trends (to determine if force amplitudes were increasing),
- strain amplitudes in critical components, and
- which process variables could be altered (if any) to immediately reduce forces without compromising process throughput.

Additionally, it was desired to develop statistical databases over an extended time period. These data could help provide an estimation of the amount of damage already experienced by structural components, as well as estimates of forces and damage that could be experienced in the future. Previously, data were acquired using standard acquisition methods. However, the amount of data that were required rendered such collection and interpretation methods obsolete.

Therefore, a data acquisition system was developed to provide continuous acquisition and monitoring. Capabilities for real-time analysis were included to limit the information to a manageable amount.

2. SOFTWARE SPECIFICATIONS

The acquisition system was required to obtain sufficient data to fully characterize an event, while discarding data when an event was not occurring. A captured event would be ranked by severity criteria and stored in one of several forms. "Interesting" events were required to be saved in their entirety (all digitized points for all channels). Less interesting events could be reduced to a few key criteria for each channel. Previous data showed that in this case, events would generally occur at intervals of one to 30 minutes. However, some events occurred in groups separated by as little as a few seconds. Therefore, uninterrupted data acquisition was required while the ranking and storage functions occurred.

Previous data showed that each major event (an "interesting" event) had a duration of approximately 50—60 seconds, including several seconds of data immediately prior to the onset of an event. The preliminary data also showed that to ensure that the peak amplitudes were measured, a sampling rate of not less than 500 Hz was required. For a maximum of 40 channels, an event time of 60 seconds, and a sampling rate of 500 Hz, the software would be required to manipulate 1,200,000 digitized data points per event.

To capture an interesting event, some method of determining its onset was needed. Evaluation of previous data suggested the use of two trigger types: a "level-dwell" and a "peak—peak" trigger.

The level-dwell trigger requires an amplitude level to be exceeded for a specified amount of time. A peak—peak trigger computes the maximum peak-to-peak value that occurs during some pre-defined time interval. For either trigger type, parameters can be adjusted so that only an "interesting" event should produce a trigger.

As events were handled, several other functions were desired, including:

- real-time data display from any channel;
- data trending for 4-hour, 12-hour, and 24-hour periods (to assist with process control);
- statistical information from the beginning of the monitoring period (the "epoch"), for the most recent 10 – 15 events, and for the largest 10 – 15 events; and
- computation of the fatigue life used ("usage factor") during that event.

3. ACQUISITION TECHNIQUES

A primary requirement of the data acquisition portion of the application was that the system should continuously acquire data, regardless of other computations (GUI operation, statistical analysis, etc.) that might be occurring. A technique called circular double buffering was developed to accomplish this task [3,6]. This technique utilizes the DMA (direct memory access) controller in the PC to transfer data from the acquisition hardware directly into memory, without requiring action from the CPU. Therefore, even though data are being acquired, the CPU is free to accomplish other tasks. Additionally, this technique allowed for pre-triggered data to be acquired (i.e., data prior to trigger detection).

4. EVALUATION OF DAMAGE

The acquisition system described provided high quality strain data that completely characterized the events. However, it is difficult to develop guidelines for "excessive" strain amplitudes. For example, it is not generally known whether a few large amplitude events are more destructive than many smaller amplitude events. Therefore, the concept of fatigue life is utilized to provide a more complete evaluation of the data that are acquired.

For a material exposed to cyclic stresses of a known amplitude (S_a), an S-N curve [4] may be used to predict the number of cycles (N) before failure may occur. However, for transient events, stress cycles occur at many different ampliutdes. Obviously, it becomes difficult to determine an allowable number of cycles for multiple ampliutde events. In such cases, the usage factor can provide an estimate of damage for a given event.

The usage factor is an accumulator of stress cycles that cause fatigue damage. When the material has experienced no stress cycles, it has a usage factor of 0. As cycles occur, the usage factor increases. When the usage factor acumulates to a value of 1.0, failure can be expected.

The procedure to compute a usage factor (U) is outlined below.

1. Obtain Principal stresses, $\sigma_1, \sigma_2, \sigma_3$.
2. Compute Stress Differences, $S_{1,2}$, $S_{2,3}$, $S_{3,1}$.
3. Count the number of cycles occurring for each Stress Range (S_r).
4. Determine the allowable number of cycles (N_i) for the material from the value of each Stress Range from an appropriate S-N Curve.
5. The contribution to the total Usage for each Stress Range (U_i) is $\frac{1}{N_i}$.

4.1. Obtaining Principal Stresses

In an unknown strain field, values for principal stress may be obtained using three strain gages laid in a rosette. Principal stresses may be computed from the measured strain values with an equation developed for the particular geometry of the rosette. However, if the strain fields are known (through FEA or other analyses) and the strain gages are properly applied, principal stress values may be inferred directly from two gages applied to the structure surface. This approach reduces processing requirements, and decreases the number of strain channels that must be provided.

Orienting the strain gages such that ε_1 was aligned along the axis of principal strain and ε_2 was mounted orthogonal to ε_1, the principal stresses can be computed using equations 1and 2.

$$\sigma_1(t)=\mathrm{SCF}_1 \frac{E}{1-\upsilon^2}\left[\varepsilon_1(t)+\upsilon\varepsilon_2(t)\right] \qquad (1)$$

$$\sigma_2(t)=\mathrm{SCF}_2 \frac{E}{1-\upsilon^2}\left[\varepsilon_2(t)+\upsilon\varepsilon_1(t)\right] \qquad (2)$$

4.2. Computing Stress Differences

As described in [1,5], fatigue evaluations are made using Stress Differences. The largest of the stress differences will be used in the fatigue calculations. Because of the gage orientation used, the stress differences are specified by:

$$S_{1,2}(t)=\sigma_1(t)-\sigma_2(t) \qquad (3)$$

$$S_{3,1}(t)=-\sigma_1(t) \qquad (4)$$

4.3. Counting Cycles

After equations 3 and 4 have been applied to every sample in a captured event, a cycle-counting algorithm [2] is applied. Note that the resulting histories contain a large number of values. Many of these values represent cycles that will not contribute to the usage factor (since the peak—peak value may be below the endurance limit).

Using a technique termed Thresholding [6], these cycles can be discarded prior to the counting procedure to reduce computation time. For the specific example investigated here, this technique reduced the number of points passed to the cycle counting algorithm from 30,000 to approximately 500. The cycle counting procedure thus becomes much less computationally intensive.

The result of the cycle counting and thresholding operation is a table containing k stress ranges, each having n complete cycles.

4.4. Compute Usage Factor

Fatigue curves for most common materials can be piecewise curve-fit to an equation of the form:

$$S_a = \frac{A}{N^b} \quad . \qquad (5)$$

For the ASME fatigue curve for carbon steel, A and b are defined in the table below for ranges of N.

Value	500<N<20,000	N > 20,000
A	780	320
b	0.33	0.24

Equation 5 can be re-written as

$$N = \left(\frac{A}{S_a}\right)^{\frac{1}{b}} \quad . \qquad (6)$$

Therefore, if the stress amplitude is known, the allowable number of cycles before a failure can be directly computed. Conversely, the amount of usage (damage) that occurs for one cycle of this amplitude is obtained using

$$u_i = \frac{1}{N_i} = \left(\frac{A}{S_{ai}}\right)^{-\frac{1}{b}} \quad . \qquad (7)$$

and the usage for multiple cycles (n) of the same stress amplitude is

$$U_i = (u_i)(n) = \frac{n}{N_i} = n\left(\frac{A}{S_{ai}}\right)^{-\frac{1}{b}} \quad . \qquad (8)$$

For a complex time history with multiple cycles (n) of k different stress amplitudes (S_{ai} $i = 1,2,3,\ldots,k$), the total usage may be obtained by computing U_i for each S_{ai} and summing all U_i. Since there can be an infinite number of different stress amplitudes, several stress amplitudes can be grouped into a stress range (e.g., in 500 psi bands) to further simplify the calculation. Additionally, the stress ranges are converted for alternating stress ($S_r = 0.5 * S_a$). The usage factor now becomes

$$\Delta U = \sum_{i=1}^{k} n_i \left(\frac{2A}{S_{ri}}\right)^{-1/b} \quad . \qquad (9)$$

The table produced by the cycle counting algorithms can be applied to Equation 9 to produce the usage factor.

5. FATIGUE CONCERN INDICATOR

Although the usage factor estimates damage that occurs for each event, it is not the ideal choice (i.e., the most intuitive) for determining whether failures can be expected within a given time frame. As an analogy, consider the usage factor to be the fuel gage in a car. To regulate the speed of the car, one would be required to monitor fuel consumption over a time interval and compare that to known fuel economy values to determine speed. A more convenient indicator to determine rate of travel would be a speedometer.

Similarly, for usage values to be an indicator of the rate at which damage occurs, the change in usage values over some time period must be monitored and compared to a rate of usage that would produce a cumulative usage value of 1.0 at the end of the design life. A more convenient indicator would be the rate of actual usage compared to the desired rate of usage. This value is termed the "Fatigue Concern Indicator" (FCI), and is defined by

$$\mathrm{FCI} = \frac{\left(\Delta U / \Delta t\right)_{\mathrm{actual}}}{\left(\Delta U / \Delta t\right)_{\mathrm{design}}} \qquad (10)$$

FCI values less than or equal to one indicate fatigue damage is occurring at rates such that design life (Y_d) will be met. Values greater than one indicate premature failure.

The design usage rate is computed based upon the desired design life, where

$$\left(\Delta U / \Delta t\right)_{\mathrm{design}} = \frac{1}{Y_d} \quad . \qquad (11)$$

For existing systems where fatigue cycles have already occurred (U_{start}), the design usage rate becomes

$$\left(\Delta U / \Delta t\right)_{\mathrm{design}} = \frac{1 - U_{\mathrm{start}}}{Y_d} \quad . \qquad (12)$$

Note that determination of U_{start} can be problematical since it requires evaluation of accumulated damage during periods that likely have little or no data.

One method for estimating values for U_{start} is to use the monitoring system. First, a database of current events is compiled that encompasses the full range of conditions. After computing usage rates from representative events, histograms are then developed to determine the relative number of such events that occur over a particular time interval. Starting usage values can then be estimated by extrapolating the histograms over the unknown time periods. Where new material is installed, the value for U_{start} is set to zero.

6. CONCLUSIONS

The techniques utilized in development of the software provided a low-cost system that could simultaneously acquire, analyze, and display data, without losing information. Although this software was developed for a specialized application, the system could be easily adapted to a variety of situations where intermittent transient monitoring is desired. Such situations include:

- evaluation of fatigue damage to structures from intermittent loads such as damage to highway bridges from traffic,
- damage to aircraft structures due to high landing or transient aerodynamic loads,
- upsets in chemical processes, etc.,
- capture of data prior to shutdown of rotating equipment due to high vibration (e.g., instability or surge), and
- noise monitoring where L_{10} noise (short duration, high level) is a problem.

Acknowledgements *--- The work presented in this paper could not have been completed without the support of the Management and engineering/technical staff of EDI. Additionally, the author wishes to thank Norm Edwards of N.W.E Services for his assistance with the development of the usage factor calculations.*

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