SHM MEASUREMENT STABILITY AND COMPENSATION METHODS

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This article discusses the issue of measurement stability in the context of short-term and long-term bridge monitoring. It further presents methods used to compensate for temperature induced variations, including an approach that employs mathematical morphology techniques more commonly applied to image processing applications. Through the use of these methods, it is shown that undesirable temperature induced effects present in recorded strain signals can be removed, thus stabilizing the measurements and enhancing important detail in the signals.

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1 INTRODUCTION

A key advantage to the use of structural health monitoring is its ability to compile a quantitative record of the performance and state of a structure over long periods of time. Such monitoring makes extensive use of traditional electronic data acquisition (DAQ) equipment to collect and store strain, displacement, acceleration, and/or temperature measurements. While the use of electronic data collection systems for civil engineering applications is common, their use in the monitoring of in-service structures poses unique challenges that do not arise during traditional laboratory based testing of structural components.

The difficulty with using DAQs for SHM comes about from the very way in which the equipment obtains its measurements. Fundamentally, the DAQ employs the electro-mechanical properties of a sensor or gauge to convert a physical effect into an electrically measureable effect. For example, in the case of strain gauges, changes in the applied strain produce a change in the physical geometry of the gauge, thus altering its electrical resistance. The DAQ equipment measures this change in resistance by comparing the relative (differential) voltage appearing across the gauge resistor (R_G) to that appearing across reference resistors (R) within the instrument, using the Wheatstone Bridge circuit shown in Figure 1 (Kenny (2005)).

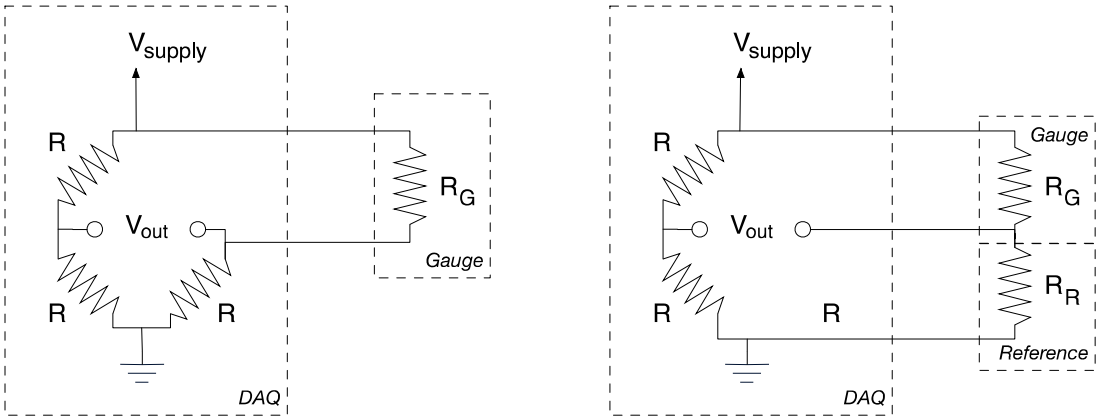

Figure 1. Quarter-bridge circuit (left) showing gauge resistor (R_G) and internal DAQ resistors (R). Half-bridge circuit (right) showing the addition of the compensating reference resistor (R_R).

This approach is complicated by the fact that the value of each of these resistors varies with temperature, and in some cases non-linearly (Vishay (2007)). In a laboratory setting where the gauge and DAQ are maintained at a consistent temperature, the only significant affect on the measured gauge resistance, and therefore measured strain, is the actual strain in the material at the gauge location. However, in the case of SHM systems deployed on in-service structures, the environmental temperature of the gauge and/or the DAQ instrument varies over time, producing a perceived change in strain due to temperature alone. Further complicating this situation is the fact that the instrument and the strain gauge may be at quite different temperatures. The instrument is normally installed on a structure in a standard electrical cabinet. These cabinets provide only rudimentary temperature control to keep the operating temperature of the electronics above 0°C in cold climates, such as during winter months in central Canada. At the same time, the gauge may be experiencing environmental temperature extremes of –30°C or more.

Compensating for the temperature induced strain often involves the addition of a reference gauge that is paired with each active strain gauge. The reference gauge takes the place of one of the reference resistors within the DAQ instrument. This compensated (half-bridge) arrangement is shown on the right of Figure 1. The reference gauge is bonded to the same structural component as the measuring gauge, but in an orientation that is not subject to the structural strain of the active gauge. The expectation is that temperature induced strains will affect both the active and reference gauge equally, cancelling the effect of temperature on the measurement. However, using a reference gauge paired with each active gauge increases installation, component, and cabling costs.

In the case of the Red River North Perimeter Bridge in Winnipeg, Canada, an alternative compensation method was attempted. This involved the use of a single reference gauge on a separate input channel, wired in the quarter-bridge arrangement. All active gauges on the structure were also wired using the same arrangement. It was expected that by observing the behaviour of the reference channel that the temperature effect could be determined and subsequently removed from the active channels. In practice, however, there was no clear relationship between the response of the reference channel and the compensation that would need to be applied to correct the active

channels. As a result, alternative methods of post-processing were investigated in an effort to remove the unwanted temperature effects within the strain signals.

2 STRAIN MODEL

In order to properly compensate for the unwanted components of the active strain signals, it is necessary to formulate a relationship between the true structural strain and the strain measured by the DAQ instrument. Based on observation of the record measurements it was determined that there were two main factors present in addition to the structural strain. These are the temperature induced strain and a zero-offset in the recorded strain signal. This leads to the recorded strain equation 1.

$$S_O(t) = S_S(t) + f(T(t)) + Z_{off} \quad (1)$$

Here S_S (t) denotes the structural strain, f $(T(t))$ is a time-varying function of temperature, and Z_{off} is the zero-offset strain. The presence of each of these signal components can be seen in the recorded strain signal of Figure 2. From this figure it is clear that there is an overall background trend, which in this instance is decreasing in time. In addition, the measurements begin at an approximate strain level of –222με, rather than zero. This zero offset may be due to a combination of incorrect calibration of the acquisition system, aging of the circuit components or gauge, or the accumulated temperature induced strain. Finally, the structural strain can be seen in the detail of the signal. In this case there are five prominent strain peaks in the latter portion of the plot. However, these are partially obscured by the unwanted background effects.

3 SIGNAL FILTERING USING MATEMATICAL MORPHOLOGY

Several attempts were made to remove the unwanted signal components using techniques such as high-pass filtering and signal envelope detection. These were found to provide unsatisfactory results due to an inability to determine generally appropriate filter parameters and by distorting the signal. The method ultimately employed involves the use of mathematical morphology to identify the baseline trend in the signal, which is

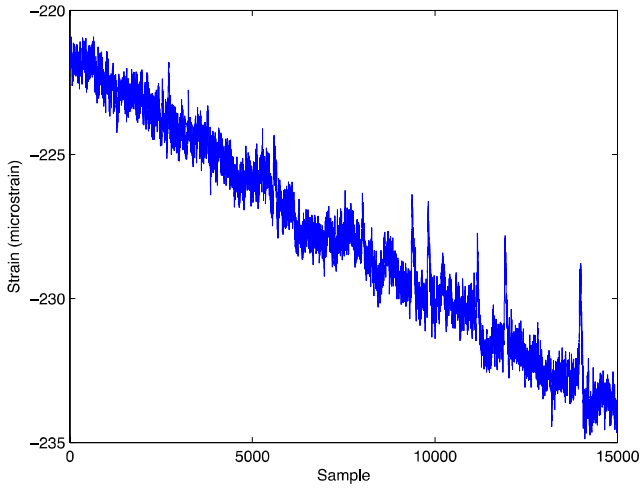

Figure 2. Recorded strain showing temperature induced background trend and zero offset.

then removed.

3.1 Mathematical morphology

The technique of mathematical morphology is commonly applied in the processing of images and involves a series of set based operations (Gonzales and Woods (2008)). In the image processing case, the source set is a set of pixel values, while in the SHM case, it is a time series of strain values. While there are several morphological operations that may be applied to these sets, the ones employed in this application are "opening" and "closing," which are themselves composed of the more basic operations of "erosion" and "dilation."

The morphological operations compute the result of applying a second smaller set, called a "structuring element," to the source set. In effect, the structuring element acts as a probe to determine various features of the source signal resulting in a transformed result set. Equations 2 and 3 provide the set notation for the basic operations of erosion and dilation respectively.

$$A \ominus B = \{ \boldsymbol{z} \mid ((B)_z \subseteq A) \} \tag{2}$$

$$A \oplus B = \{ \boldsymbol{z} \mid ((B)_z \cap A \neq \varnothing) \} \tag{3}$$

The term $\boldsymbol{z}$ indicates the location in the source set A where the structuring element B is being applied, with $(B)_z$ indicating that the structuring element is positioned with its centre at point $\boldsymbol{z}$. In the case of erosion, the point $\boldsymbol{z}$ is a member of the result set $C = A \ominus B$ if all points in B are also points in A when B is located at $\boldsymbol{z}$. For dilation, the point $\boldsymbol{z}$ is a member of the result set $C = A \oplus B$ if any point in B is also in A when B is located at $\boldsymbol{z}$.

The meaning and application of these operations is demonstrated in the example of Figure 3. Here a 3-by-3 pixel structuring element is applied to a 10-by-10 pixel image using both erosion and dilation. As can be seen, the erosion operation thins the source down to a more basic structure, while dilation fills small irregularities in the source.

The operations of opening and closing involve the successive application of erosion-dilation and dilation-erosion, respectively. These operations are expressed in set notation in equation 4 (opening) and equation 5 (closing), and illustrated in the example of Figure 3.

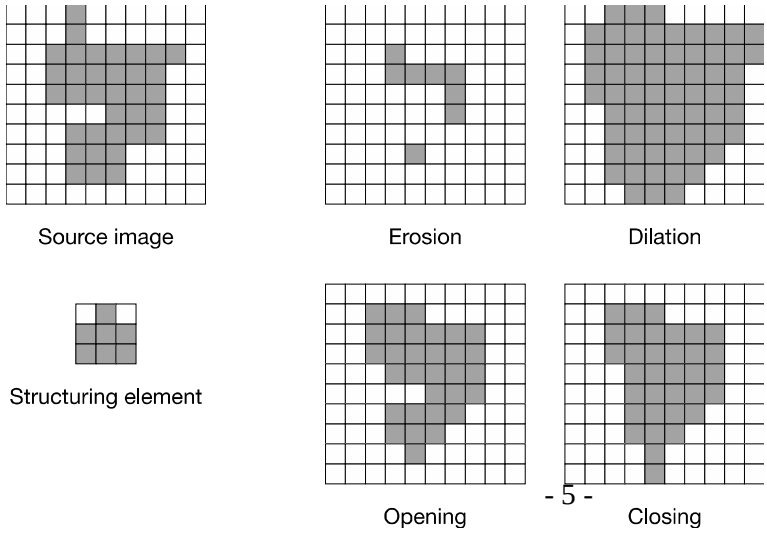

Figure 3. Results of applying morphological operators to a sample source image.

$$A \circ B = (A \ominus B) \oplus B \tag{4}$$

$$A \bullet B = (A \oplus B) \ominus B \tag{5}$$

3.2 Morphology of strain signals

The examples in the preceding section involve source data sets which are two dimensional by their very nature. By contrast, SHM signals are one dimensional time series. When considering signals of this type it is possible to express the erosion and dilation operations as equations 6 and 7 respectively (Luo et al. (2005) and Tadejko and Rakowski (2007)).

$$(f \ominus b)(x) = \min (f(x + n) - b(n)) \quad n = -M/2, \ldots, M/2;\ 0 < (x + n) \leq N \tag{6}$$

$$(f \oplus b)(x) = \max (f(x + n) + b(n)) \quad n = -M/2, \ldots, M/2;\ 0 < (x + n) \leq N \tag{7}$$

Here M denotes the length of the structuring element $b(n)$, which is applied to the source signal f of length N. When considering SHM signals, $b(n)$ is taken as a constant over its length. As a result, equations 6 and 7 may be simplified to the calculation of the min or max of f for sample points which overlap with $b(n)$.

In effect, the erosion operation computes a lower envelope for the data stream, while dilation computes a corresponding upper envelope. Since the opening operation involves sequential applications of erosion and dilation, it thus computes the upper envelope of the signal's lower envelope. Similarly, dilation computes the lower envelope of the signal's upper envelope. By selecting the length of the structuring element $b(n)$ to be longer than the dynamic strain events expected within the SHM data stream (ex. due to excitations from vehicular traffic on a bridge), dynamic strain activity will be retained, while background activity of a longer duration will be removed. When applied to actual streams of strain data obtained from the Red River North Perimeter Bridge in Winnipeg, Canada, a length of $M = 300$ was used.

Recall that the goal in processing the SHM signals is to remove the background trend from the meaningful dynamic activity. To accomplish this, the dynamic activity corresponding to strain peaks is first removed from the source signal by successively applying opening then closing, producing the signal $CO(t)$ (Sedaaghi (1997)). This process is illustrated in Figure 4. Similarly, negative noise peaks from the original signal are removed by first applying closing followed by opening, resulting in the signal $OC(t)$. The two signals are then averaged to obtain a combined baseline signal representing the background trend of the source signal. This trend may now be subtracted from the source signal $S_O(t)$, of equation 1, to produce the cleaned signal $S_C(t)$.

$$S_C(t) = S_O(t) - [\ CO(t) + OC(t)\ ] / 2 \tag{8}$$

Finally, the median of the cleaned signal is subtracted from that signal to produce the final structural strain signal $S_S(t)$.

Figure 5 shows the result of applying the morphological procedure to the original raw strain signal of Figure 2. Comparing these two signals clearly shows that the dynamic detail of the original signal is preserved, while the negative temperature trend and zero offset are now removed.

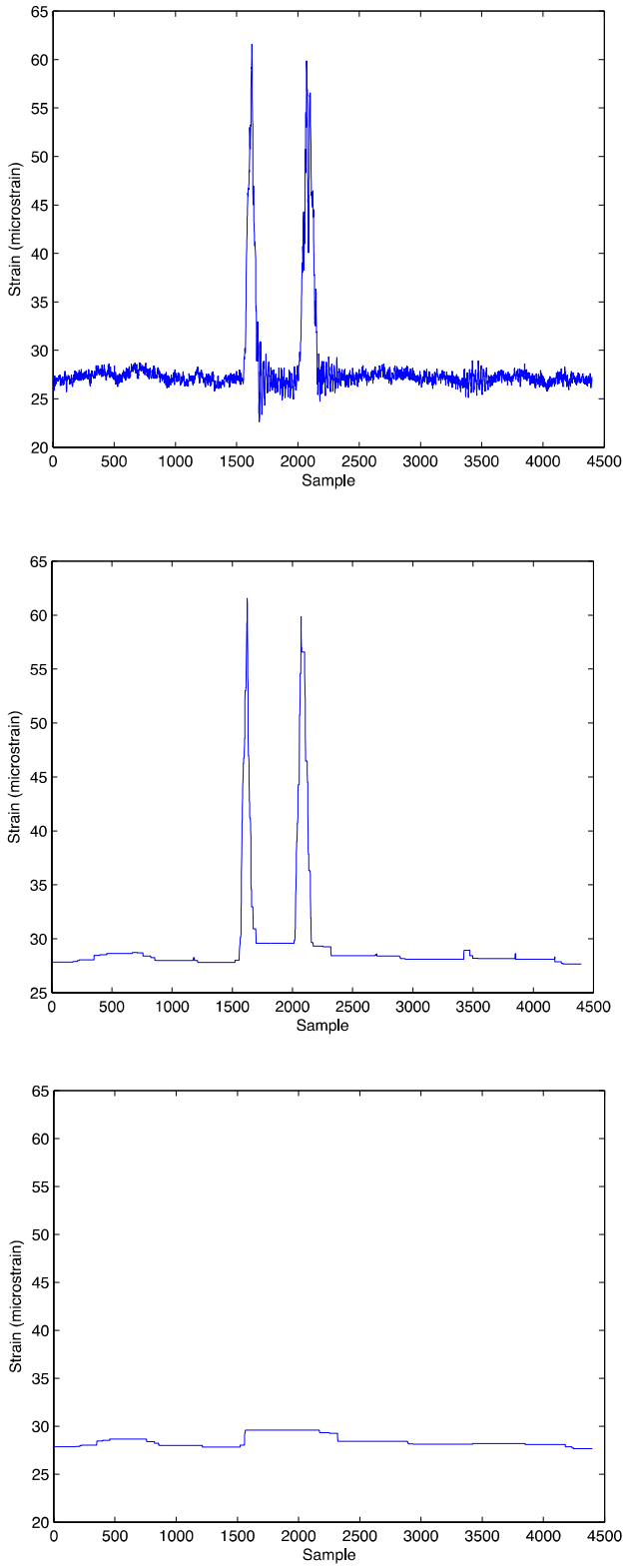

Figure 4. Result (bottom) of applying closing (middle) then opening to the source signal (top).

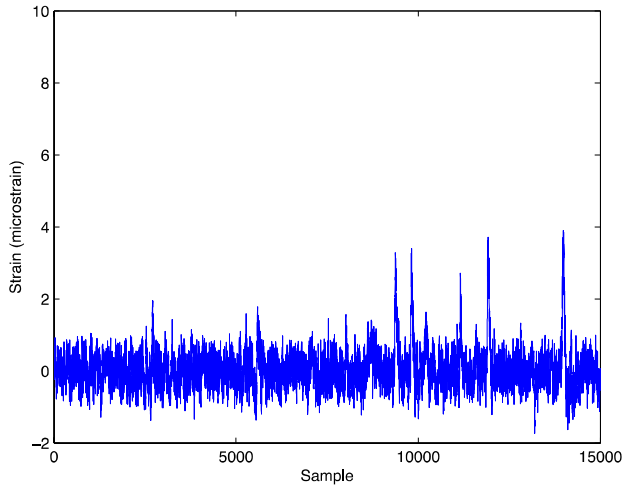

Figure 5. Corrected strain signal with background trend and zero-offset removed.

4 COMPARISON WITH TRADITIONAL COMPENSATION METHODS

As noted in the introduction, the normal method for compensating for thermally induced strain variations is to pair each active gauge with a corresponding reference gauge in the half-bridge circuit arrangement of Figure 1. This method is effective in removing short-term measurement variations, since it is expected that the resistance of both gauges in the pair will react identically to changes in temperature, given that they are located adjacent to each other on the structure. Any mismatch in their resistance would be corrected in the initial calibration procedures for the DAQ. Over the long-term, however, the nominally measured strain may drift away from zero as either the individual gauges or internal resistors forming the Wheatstone bridge age disproportionately. This is an extremely long-term effect and can be readily removed.

However, in situations where the reference gauge and active gauge do not share the same temperature environment, or where the quarter bridge arrangement is used instead (as in our case), employing morphological filtering can provide effective correction to the recorded strain signals.

5 CONCLUSIONS

This article reports our success in applying techniques of mathematical morphology to remove unwanted temperature and zero offset effects from SHM data streams that arise when data acquisition equipment is deployed on in-service civil structures, such as bridges. This approach provides a simple means of cleaning SHM signals, thus permit further comparative analysis of a structure's dynamic response over extended time periods. This approach was demonstrated using actual strain data obtained from the Red River North Perimeter Bridge in Winnipeg, Canada.

6 ACKNOWLEDGEMENTS

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