Title: DETECTION OF BRIDGE ANOMALOUS BEHAVIOR AND ASSESSMENT OF THEIR IMPACT ON STRUCTURAL PERFORMANCE

Authors: Pilate Moyo
Piotr Omenzetter
James Mark William Brownjohn

ABSTRACT

In-service civil infrastructure experience short-lived and transient changes in strain from time to time resulting from ground movements, development of cracks, heavy traffic, accident impacts, etc. With the advent of instrumented structural monitoring and analytical tools it is now possible to capture and examine these events. In this paper an approach based on wavelet analysis is adopted for identification of the events whereas intervention analysis concepts are used for assessing their effects on structural behavior and performance. The data studied are strain time series recorded by a structural health monitoring system installed in a major bridge at construction and service stages.

INTRODUCTION

Bridges constitute significant, expensive and critical components of any country's transportation system. They also have a long service life and are rarely replaceable once erected. Many countries have recognized the importance of maintaining the health of their bridge stocks and have introduced bridge management systems that are usually based on visual inspection. While such management systems provide a useful platform for repair and maintenance programs, they also present drawbacks that include high manpower demands, inaccessibility of some critical areas of the bridge during inspections and lack of information on actual loading. As a result, some problems related to the structural performance of a bridge may go unnoticed until they become serious or expensive to repair. Shortcomings of inspection based management systems on one hand, and developments in signal processing tools and availability of affordable instrumentation on the other hand have motivated the development of

---

School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore – cjames@ntu.edu.sg (J. M. W. Brownjohn)

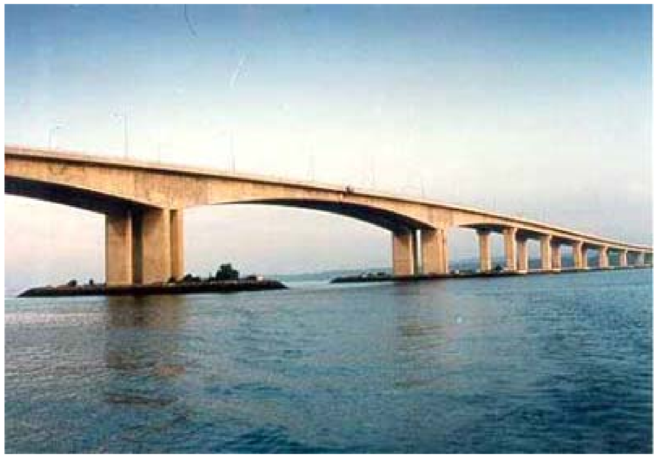

Figure 1. Singapore-Malaysia Second Link

instrumented monitoring systems. In this paper, attention is paid to analysis of long-term continuous monitoring of static performance data.

Structural health monitoring (SHM) is defined here as the continuous monitoring of a structure's response to the loading environment in order to diagnose the onset of anomalous structural behavior. This may involve continuous measurement of effects such as strains, stress, temperature, humidity, wind and accelerations, due to construction, environmental, traffic and dead loads, and the analysis of these data to detect and characterize unusual structural behavior.

The subject of the monitoring program described in this paper was The Singapore-Malaysia Second Link, a post-stressed box girder bridge, completed in 1997, and carrying a dual carriageway with three lanes on each carriage (Figure 1). A SHM system was installed during construction in order to monitor the bridge's short-term and long-term behavior [1]. The SHM system includes a set of temperature sensors, stress cells, strain gauges and accelerometers distributed in three segments of one of the spans.

The strategy adopted for identifying anomalous structural behavior during the bridge's operation stage involves learning from data recorded at the construction stage. Known, identifiable events such as post-tensioning and concreting may be associated with possibly similar events that may occur during service life such as ground movements, heavy traffic, settlement of supports, changes in the weather and loss in post-tensioning force. Changes arising from short-lived sudden events such as ground motions and heavy traffic could be similar to post-tensioning effects during construction, while changes arising from short-lived gradual events such as settlement of supports could be similar to casting events. Hence, by identifying such events during the bridge's service life one can make a knowledgeable guess about the cause.

Operation of SHM systems generates large volume of data, such as stress, strain, accelerations, from which identification and localization of abrupt and transient changes by simple visual examination is neither easy nor efficient. To overcome this problem an approach based on wavelet analysis has been developed for identifying abrupt and transient changes from static strain data acquired by the SHM system. The strain data considered is a time series of static strains recorded at hourly intervals in selected locations of the bridge. The procedure described takes advantage of time-frequency localization, compact support, smoothness and band pass filter properties of wavelet functions. These properties enable wavelet transforms to reveal intrinsic abrupt and gradual changes that may not be visually identifiable.

Having identified the occurrence of an anomalous event, it is of interest to determine whether there is any evidence of change in structural behavior and performance associated with the event. An approach to this problem is to consider components of strain in a simple time-series model, associated with anomalous events. The strain can be broadly divided into elastic strain and inelastic strain. Elastic strain is reversible, that is, it dies out once loading has been removed from a structure. On the other hand, if the strain is inelastic the structure suffers an irreversible strain change, or permanent deformation. Irreversible strain can reduce the limit state capacity of a structure and may result in serviceability problems if a strain change is large enough. In new, healthy structures, exposing the structure to certain levels of irreversible strains may not impair structural performance immediately, however accumulation of these strains may have a long-term impact. Therefore maintaining a database of these strains and their effect on the structure is essential for future condition assessment. Thus it is important to get some indication of which of the components of instantaneous strain dominate strain changes due to random impacts that occur in a structure from time to time. For this, impact assessment procedures proposed by Box and Tiao [2], also known as intervention analysis, will be adopted. Procedurally they are well suited for assessing the impact of unusual events on structures in that intervention analysis requires the occurrence of an event in a time series to be known, and the assessment is concerned with estimating the magnitude and nature of an impact.

THEORY

Wavelet analysis for identification of anomalous events

The basic idea of wavelet analysis is to represent general functions in terms of simple building blocks at different scales and positions. In most practical signal processing application, data decomposition is carried out using the discrete wavelet transform. Given a discrete signal in time $y(t)$ ($t = 1, 2, \ldots T$; T being the size of a sample), we may decompose it as follows [3]:

$$y(t) = \sum_{k=1}^{K} c_{J,k}\phi_{J,k}(t) + \sum_{j=1}^{J}\sum_{k=1}^{K} d_{j,k}\psi_{j,k}(t) \tag{1}$$

where $\phi_{J,k}(t)$ and $\psi_{j,k}(t)$ are discrete scaling and wavelet functions respectively. They are derived through translation and dilation from the basic scaling function $\phi(t)$ and the mother wavelet $\psi(t)$:

$$\phi_{j,k}(t) = 2^{-j/2}\phi\left(2^{-j}t - k\right), \quad \psi_{j,k}(t) = 2^{-j/2}\psi\left(2^{-j}t - k\right) \tag{2, 3}$$

Coefficients $c_{J,k}$ and $d_{j,k}$ are termed scaling and detail coefficients, respectively, and are defined through the linear transforms:

$$c_{J,k} = \langle \phi_{J,k}(t), y(t) \rangle, \quad d_{j,k} = \langle \psi_{j,k}(t), y(t) \rangle \tag{4, 5}$$

where $\langle \cdot, \cdot \rangle$ denotes inner product.

If the signal $y(t)$ varies smoothly with time, as is true in the case of measured static strains in the bridge, sudden, abrupt changes will cause discontinuity in the signal variation. Daubechies [4] showed that detail coefficient, d_{jk}, at the lowest scales j in the neighborhood of the abrupt change is significantly higher than others. Therefore sudden changes in signal can be detected by checking the magnitudes of wavelet coefficients against a critical value. A good initial approximation of this critical value is a modified version of the universal noise threshold proposed by Donoho and Johnstone [5]:

$$\lambda = 2\sigma\sqrt{\log T + \log\log T} \tag{6}$$

where σ is the standard deviation of detail estimation error, which can be assessed as follows [6]:

$$\sigma = median\left(\left|d_{J-1,k} - median\left(d_{J-1,k}\right)\right|\right)/0.6745 \tag{7}$$

More details on the use of wavelet analysis for finding anomalous events from strain measurements of the bridge can be found in a forthcoming paper by Moyo and Brownjohn [7].

Intervention analysis for assessment of anomalous event impact

Having identified the occurrence of an anomalous event, it is of interest to assess whether the event results in any change in structural performance. In this study, the impact assessment is carried out using the intervention analysis procedures [2]. A Box-Jenkins model is a transfer function model between output $y(t)$, input $x(t)$ and noise $e(t)$, of the type [8]:

$$y(t) = B(q)/F(q)\,x(t) + C(q)/D(q)\,e(t) \tag{8}$$

where $B(q)$, $C(q)$, $D(q)$ and $F(q)$ are polynomials in the delay operator q^{-1}.

The basic concept of intervention analysis is the assessment of how exogenous event occurring at known time affects a stationery time series process. Using the Box-Jenkins model, the time series can be represented by an autoregressive moving average (ARMA) model $C(q)/D(q)e(t)$, that describes the normal behavior of the system, and the effect of an extraneous event, that can be modeled in terms of a deterministic input $x(t)$ using a transfer function $B(q)/F(q)$. The deterministic input series, $x(t)$, serves to indicate the presence of an external event and is often represented by a step function $w(t)$ or pulse function $u(t)$ (see Figure 2). By selecting an appropriate transfer function, the effect of the intervention event can be

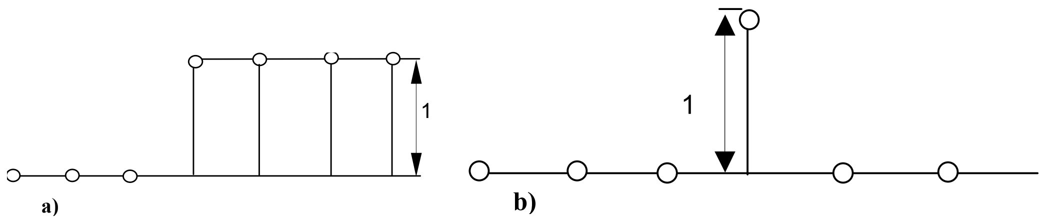

Figure 2. Deterministic input time series for intervention analysis: a) step function, b) pulse function.

considered as abrupt and permanent, gradual and permanent or abrupt and temporary. The respective models corresponding to these three effects are as follows:

$$x(t)=w(t),\quad B(q)=\omega q^{-1},\quad F(q)=1 \tag{9}$$

$$x(t)=w(t),\quad B(q)=\omega q^{-1},\quad F(q)=1-\delta q^{-1},\quad 0<\delta\le 1 \tag{10}$$

$$x(t)=u(t),\quad B(q)=\omega q^{-1},\quad F(q)=1-\delta q^{-1},\quad 0<\delta\le 1 \tag{11}$$

where ω is the magnitude of change and δ is the rate of change of the signal with time.

The strategy for impact assessment employed in this paper is as follows. The first step is building an ARMA model. Since the ARMA model describes stochastic behavior of a time series and intervention events are additional external disturbances, only the data before the onset of external events should be used in constructing ARMA model. It is also assumed that the form of the time series ARMA model remains the same after the event. Once an ARMA model for the time series has been identified an appropriate Box-Jenkins model must be selected to assess the impact of the event. A procedure for selecting a representative intervention model is to proceed as follows. First parameters for an abrupt temporary intervention model are estimated. If the estimated value of the rate of change parameter δ is close to unity, then the strain change is largely permanent. Next, parameters for a gradual, permanent change are estimated. If the parameter δ is too small, then a gradual impact is ruled out and the only remaining impact would be an abrupt permanent change.

APPLICATION

The procedures for identification of anomalous events and assessment of their impact were applied to the hourly measured static strain data of The Singapore-Malaysia Second Link. Attention is paid to strain data recoded during and after construction of the bridge. The causes of some events that occurred during the construction phase are known (e.g. post-tensioning, concreting of segments and shifting of form traveler) and their impact can be more easily understood and anticipated. Thus, analysis of construction stage events serves for validation of the proposed SHM strategies and lays a groundwork for knowledgeable examination of future events occurring when the bridge is in service.

Analysis of a known event during construction stage

The event chosen for examination is associated with post-tensioning of a bridge segment. Figure 3a shows part of the strain time series that contains an abrupt change of strain that resulted from post-tensioning. The event occurs at time $t = 241$ of strain record. Considering events such as post-tensioning to be severe, a second threshold can be defined for the wavelet details to isolate these severe responses. This second threshold level was empirically found using coefficients associated with post

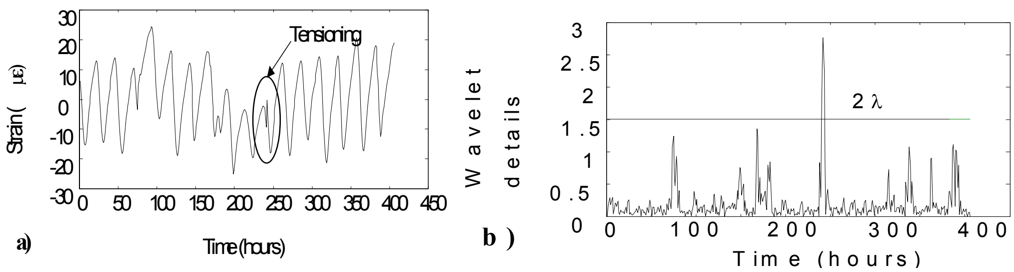

Figure 3. Tensioning of a bridge segment during construction: a) strain time series, b) wavelet detail coefficients at lowest scale

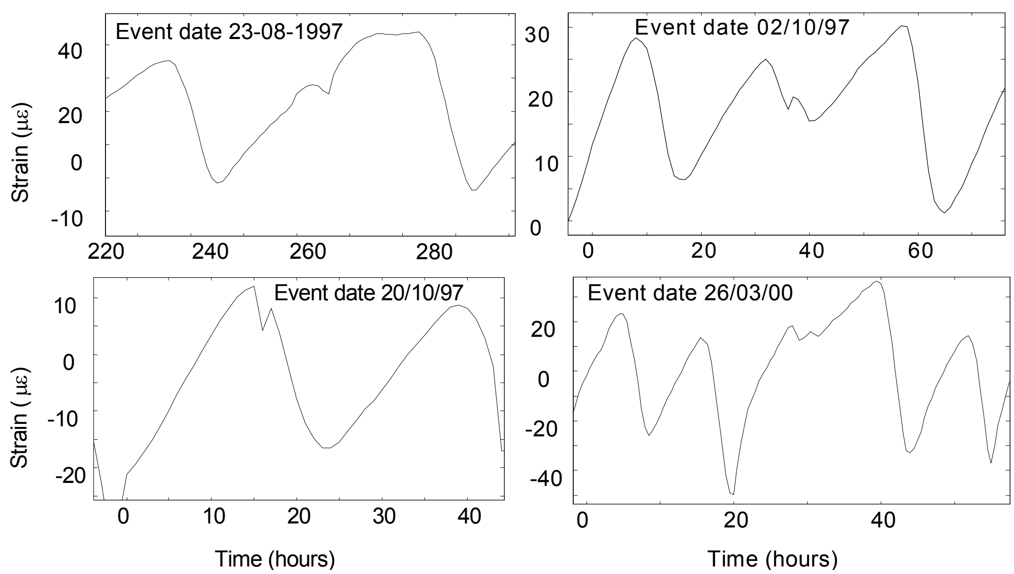

Figure 4. Abrupt events identified during post-construction stage.

Table I. Impact assessment of unknown events identified during post-construction stage.

Event date	Temporary abrupt		Permanent gradual		Permanent abrupt	Selected Model
	ω (με)	δ	ω (με)	δ	ω (με)	
23/08/97	3.52	0.98	4.35	0.38	3.04	Permanent abrupt
02/10/97	3.80	0.99	4.46	0.57	-	Permanent gradual, will reach 10.1 με
20/10/97	-7.07	0.04	-	-	-	Temporary abrupt
26/03/00	-2.30	0.46	-2.41	0.11	-2.52	Temporary and permanent abrupt; effective drop 0.22 με

tensioning events to be approximately 2λ, where λ was defined in equation 6. Figure 3b shows wavelet details at the lowest scale that clearly exceed the threshold level of 2λ when the post-tensioning takes place.

The first step in intervention analysis is selection of an appropriate time series model for the strain data. Here, an autoregressive model (AR) is used, i.e. $C(q)=1$ in the general model. The partial auto-correlation analysis was used to determine the AR model using the first 240 observations. The analysis reviled that AR model of order 25 can describe the time series with sufficient accuracy.

The subsequent impact analysis yielded the following results: $\omega = 13.2\ \mu\varepsilon$ ($\mu\varepsilon$ = microstrain = 10^{-6}) and $\delta = 0.99$ for the temporary abrupt impact model, $\omega = 7.13\ \mu\varepsilon$ and $\delta = 0.18$ for the gradual permanent impact model, and $\omega = 11.88\ \mu\varepsilon$ for the permanent abrupt impact model. The decay parameter for the abrupt temporary impact, $\delta = 0.99$, is close to one, indicating that the effect of the event would not decay to pre-intervention level too quickly. This is confirmed by the rate of change parameter for the gradual permanent change, which is close to zero. These parameters suggest that the intervention model should be an abrupt permanent change of magnitude $\omega = 11.88\ \mu\varepsilon$. This should be expected since post-tensioning force remains permanently after locking the strands at the ends.

Analysis of unknown events during post-construction stage

Figure 4 shows some unusual events identified from the post-construction data. The impact analysis results of the identified events are listed in Table I. Note that if the rate of change parameter for an abrupt temporary model is close to zero no other models are tested as this strongly suggests a temporary, rapidly decaying impact. Negative values of the parameter ω indicate loss in post-tensioning force proportional to the magnitude of the parameter, while positive values signify an increase in compressive strain. It is interesting to note that most of the tension effects are accompanied by significant recovery of strain. A plausible reason could be the effect of post tensioning which pulls the structure together.

CONCLUSIONS

This paper describes procedures used for identification of abnormal events from strain data recorded by a monitoring system installed at a major bridge and assessment of their impact on structural performance. To capture anomalous events, wavelet decomposition of the strain signal is used due to its ability to distinguish and localize abrupt changes. For assessment of the identified events' impact on the bridge structure the intervention analysis is adopted. The intervention analysis classifies impacts as temporary or permanent. The selection of an appropriate impact model for a particular event is based on the logical relationship between the impact models. The reliability and effectiveness of the approach was checked using post-tensioning events recorded during the construction of the bridge. The method was then applied to examine captured, unknown events during post-construction stage, yielding assessment of their significance.

REFERENCES

1. Brownjohn, J. M. W. and Moyo, P. 2000. "Monitoring of Singapore-Malaysia Second Link during Construction," in *Proceedings of 2nd International Conference on Experimental Mechanics*, Singapore, November 29-December 1 2000, pp. 528-533.
2. Box G. E. P. and Tiao, G. C. 1975. "Intervention Analysis with Applications to Economic and Environmental Problems," *Journal of the American Statistical Association*, 70(349), pp. 70-79.
3. Kaiser, G. 1994. *A Friendly Guide to Wavelets*, Birkhäuser, Boston, USA.
4. Daubechies, I. 1992. *Ten Lectures on Wavelets*, Society for Industrial and Applied Mathematics, Philadelphia, USA.
5. Donoho, D. L. and Johnstone, I. M. 1994. "Ideal Spatial Adaption by Wavelet Shrinkage", *Biometrica*, 81, pp. 425-455.
6. Donoho, D. L. and Johnstone, I. M. 1995. "Adapting to Unknown Smoothness via Wavelet Shrinkage," *Journal of American Statisticians Association*, 90, pp. 1200-1124.
7. Moyo, P., Brownjohn, J. M. W. 2002. "Detection of Anomalous Structural Behavior Using Wavelet Analysis," *Journal of Mechanical Systems and Signal Processing*, (to appear).
8. Ljung, L. 1987. *System Identifications: Theory for the User*, Prentice Hall, Englewood Cliffs, New Jersey, USA.