The 3rd International Conference on Structural Health Monitoring of Intelligent Infrastructure
Vancouver, British Columbia, Canada
November 13-16, 2007

TRACKING THE EFFECTS OF CHANGING ENVIRONMENTAL CONDITIONS ON THE MODAL PARAMETERS OF TAMAR BRIDGE

James MW Brownjohn
Vibration Engineering Section, United Kingdom

Peter Carden
Vibration Engineering Section, United Kingdom

Abstract

A widely encountered difficulty when monitoring structures is the separation of abnormal changes from normal changes. Abnormal changes arise from degradation of structural elements and undesirable changes in boundary conditions. Normal changes arise from the effects of changing environmental conditions such as wind and temperature, which, for example, may cause the structure to move on its bearings.

This paper describes preliminary results from a study on Tamar Suspension Bridge which is providing data to study the correlation of environmental variables with changes in its modal parameters. The Bridge has been instrumented with a permanent monitoring system and the modal parameters of the bridge are extracted continuously and autonomously using a stochastic subspace identification technique. Parameters are being used as data for an autoregressive exogenous model, with the environmental conditions providing the exogenous input. The primary aim of this approach is to reduce the number of false positive alarms while still retaining the monitoring system's sensitivity to abnormal changes. The procedure is briefly described here, but results cannot be presented until Spring 2007 after a few months of continuous operation.

INTRODUCTION

The Tamar Bridge (Fig. 1) is a vital transport link over the River Tamar carrying the A38 trunk road from Saltash in Cornwall to the city of Plymouth in Devon. The bridge is owned, operated and maintained by the two local authorities, and has relied solely on toll income to cover all capital and operating costs.

The original bridge, opened in 1961, was designed by Mott Hay and Anderson as a conventional suspension bridge with symmetrical geometry, having a main span of 335m and side spans of 114m, and with anchorage and approach spans the overall length is 642m. Unusually for a suspension bridge of this era, the towers were constructed from reinforced concrete, and have a height of 73m with the deck suspended at half this height. The towers sit on caisson foundations founded on rock. Main suspension cables are 350mm in diameter and each consists of 31 locked coil wire ropes, and carries vertical locked coil hangers at 9.1m intervals. The stiffening truss is 5.5 metres deep and composed of welded hollow boxes.

Figure 1. Tamar Bridge.

The bridge was the subject of a strengthening and widening exercise [1], completed in December 2001, necessary because after nearly four decades of use, it was found that it would not be able to meet a new European Union Directive that bridges should be capable of carrying lorries up to 40 tonnes. Since restricting use of such vehicles would damage the local economy, the bridge needed to be strengthened or replaced. The upgrading included the following major components:

- 18 new nominally 100mm diameter locked-coil cables were installed and stressed to supplement the original suspension system, primarily to help carry the additional dead load of the new cantilever lanes and associated temporary works.
- The composite main deck was replaced by a three-lane orthotropic steel deck.
- Single lane cantilevers were added to each side of the truss.
- Continuity of the main span with the Plymouth side span via an articulated link at the Plymouth Tower was replaced by continuity of the cantilevers around the Plymouth tower. The main span and Saltash side spans remain disconnected.

MONITORING SYSTEM

In order to monitor the behaviour of the bridge during and after the work, environmental and structural monitoring equipment was installed by Fugro. The sensors for this system included anemometers, a fluid pressure-based deck vertical displacement sensor, temperature sensors in the main cable and deck steelwork, load cells in additional cables and electronic distance measurement (EDM) system for tracking relative tower deflections. At present the EDM and deck level sensors no longer function.

More recently there has been concern about the longitudinal deflection of the deck and oscillations of the additional stay cables. As the beginning of a more elaborate monitoring system that will include full deflection monitoring of the deck, a set of three accelerometers have been installed close the mid span of the deck, biaxial accelerometers were installed on a selection of four additional stays and extensometers fitted across the operational expansion joint. The new monitoring system along with the original Fugro system is accessed by internet and went live at the beginning of February 2007 and now collects response data continuously. Prior to installation of the system, the bridge was studied in a full-scale ambient vibration test [2] in order to calibrate a finite element model to be used for performance diagnosis, and to allow for the deck dynamic response to be reconstructed from the three accelerometer signals.

A secondary aim of the monitoring system was to provide a platform for developing tools for automated real-time performance tracking, thus avoiding the need for manual data interpretation difficulties. The behaviour of the bridge expressed as dynamic response of the deck and cables and as quasi-static motion of the deck and towers depends on effects of vehicles, thermal and wind load. Effective structural health monitoring requires development of an understanding of the normal load-response characteristics as a prerequisite to detecting performance outliers. This paper describes the automated procedures being developed to track the dynamic response parameters and subsequently detect performance outliers.

PROCEDURE AND RESULTS

Figure 2 shows a typical auto power spectral density from a vertical accelerometer on the deck of Tamar Bridge. There are a number of modes excited below about 1.5 Hz from mainly by wind. Between about 1.5 Hz and 5 Hz there is a substantial amount of energy and this corresponds to the typical frequency range associated with body bounce of vehicles. There is another band of large excitation from about 8.5 Hz to 12 Hz which is typical for vehicle excitation. The energy between approximately 14 Hz and 19 Hz is on the high side for vehicle excitation and an explanation for this part of the spectrum is under investigation by the authors. Beyond 20 Hz or so, there is no discernible structure in the spectrum.

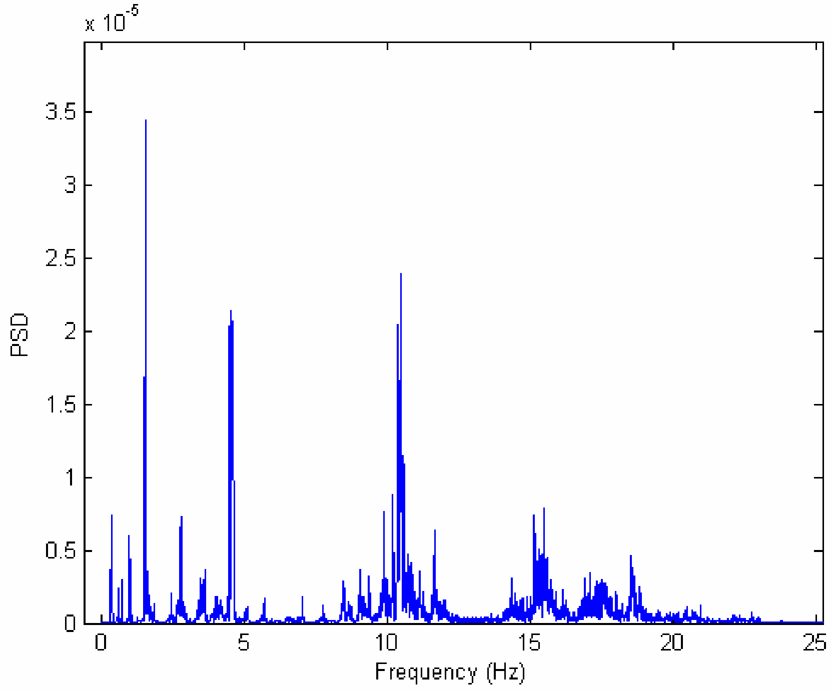

Figure 2. A typical Auto Power Spectral Density of a vertical deck accelerometer response.

For the purposes of SHM, we would like to extract modal parameters from such response histories of the bridge automatically. Various algorithms may be used, but stochastic subspace identification was chosen by the authors in this paper. The reasoning for this choice and the details of the automatic implementation of it in the SHM system are described in the next section.

STOCHASTIC SUBSPACE IDENTIFICATION

Mathematically, structural systems may be recast from continuous second order differential equations governing their behaviour into discrete state space equations. SSI is an efficient method for identifying the state space matrices from measured response data. The natural frequencies, damping parameters and mode shapes may then be extracted from these state space matrices. Major advantages of taking this approach are that it is quick and non-iterative and therefore does not suffer from convergence problems. Fundamental proofs and discussions of numerical stability are described in [3] while a succinct, though thorough, step-by-step procedure with an example application is provided in [4].

There are various flavours of SSI available and here we use covariance-driven stochastic realisation. The advantage of using covariance-driven realisation as opposed to data-driven subspace projection is that the data reduction (which is effectively a major noise filtering step) is far less memory intensive. The data-driven subspace projection utilises a QR decomposition of the data Hankel matrix and for large data sets this becomes very memory demanding. The covariance-driven realisation requires the formation of the Toeplitz matrix of the covariance of the measured output and is far less memory demanding. For on-line real time monitoring this is a substantial advantage.

$$T_{1|i} = \begin{pmatrix} \Lambda_i & \Lambda_{i-1} & \Lambda_1 \\ \Lambda_{i+1} & \Lambda_i & \Lambda_2 \\ & & \\ \Lambda_{2i-1} & \Lambda_{2i-2} & \Lambda_i \end{pmatrix} \tag{1}$$

The subscript on the Toeplitz matrix of covariances, T, refers to the subscripts of the first and last entries of the first row of the matrix. The subscript on the covariance matrix between all measured outputs, Λ, refers to the covariance lag. $T_{1|i}$ is singular value decomposed according to equation (2) and this implies the choosing of the order of the system, n.

$$T_{1|i} = USV^T = \begin{pmatrix} U_1 & U_2 \end{pmatrix} \begin{pmatrix} S_1 & 0 \\ 0 & S_2 \end{pmatrix} \begin{pmatrix} V_1^T \\ V_2^T \end{pmatrix} \rightarrow U_1 S_1 V_2^T \tag{2}$$

In theory the number of non-zero singular values will equal the order of the system, n. In equation (2) the singular value matrix is broken into S_1 and S_2. With perfect numerical accuracy and absolutely clean data, S_1 would be comprised of a diagonal of n non-zero entries and S_2 would be comprised of all zeros. In such a case, $T_{1|i}$ would decompose to $U_1 S_1 V_1^T$. However, in practice this will not happen. On rare occasions, with very good quality data and with some luck, there is a dramatic drop in the singular values which marks the order of the system. All too often this step down in magnitude of value is not present and it is up to the analyst's skill and experience to choose the correct order. Once an order is chosen, the dynamic state space matrix may be calculated, by utilising the singular values. The eigenvalues of this dynamic matrix are the poles of the system and thus yield the natural frequencies and damping estimates while the eigenvectors may be converted to the mode shape vectors. Details may be found in [4].

The construction of a stability diagram has proven invaluable in helping the analyst in choosing the correct order of the system and in distinguishing between true modal parameters and mathematical chimera. The stability diagram is formed by choosing a range of values for n and extracting the modal parameters from the dynamic matrix for each of these values. The analyst defines rules by which modal parameters may be considered stable between two different assumed orders. Figure 3 is an example of a stability diagram from data recorded on Tamar Bridge with a 6.4 Hz digital lowpass filter applied. The rules used to define a pole as being stable were:

- variation in the natural frequency of less than 1%
- variation in damping of less than 5%

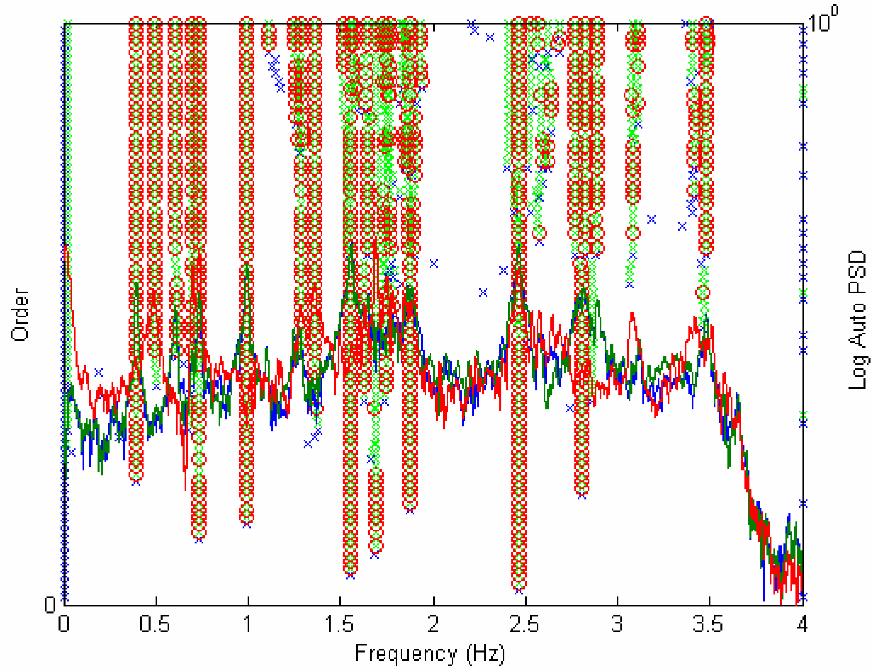

Figure 3 Typical Stability Diagram from two vertical and one horizontal accelerometers on Tamar Bridge deck. The Auto PSDs are under laid as solid lines. Red circles indicate stable poles.

Figure 3 shows long clear columns of stable poles (indicated by red circles) below about 1 Hz. This section of the diagram is relatively easy to interpret and it is straightforward to identify the first six modes (corresponding to the six columns of red circles). Above about 1 Hz the stability diagram is less easy to interpret. The columns of stable poles are more broken and less straight. There are additionally a larger number of poles, which are not considered to be stable according to the prescribed criteria. This area of the frequency spectrum coincides with the typical spectrum associated with body bounce of vehicles.

The PSD over the course of a whole day is shown in Figure 4. The energy in the evening and night time are clearly much less than during the day time in the spectral band of the body bounce which is consistent with typical traffic patterns. This leads to difficulty with automatically extracting modal parameters in the spectral regions excited by traffic. In this paper concentration is made on the lower modes excited by wind action.

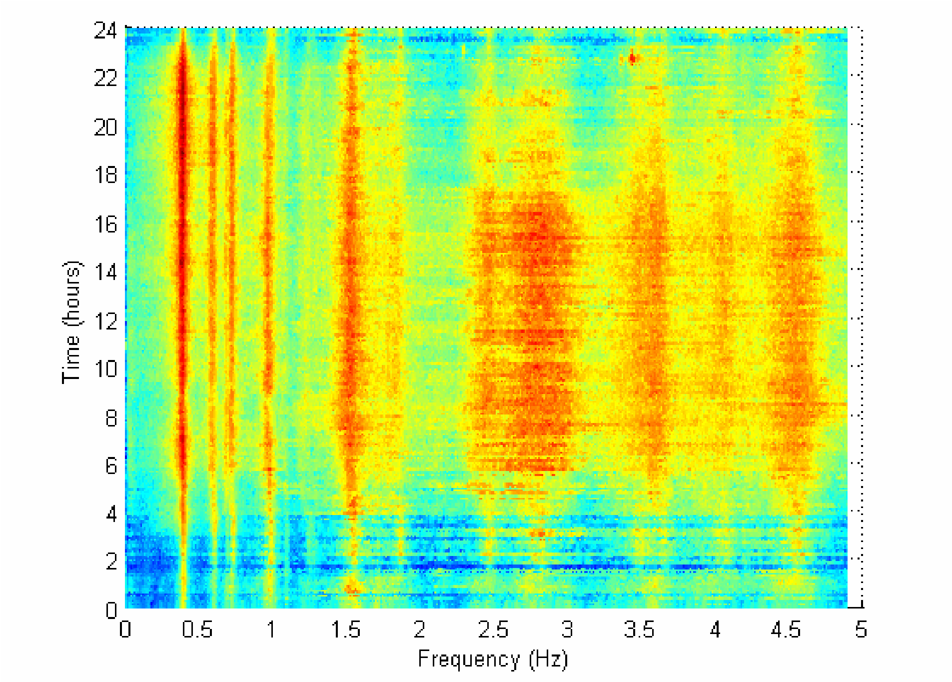

Figure 4. Auto PSD from one vertical accelerometer over a single day. Hour 0 is midnight.

Peeters and De Roeck [5] described an automatic selection of the modal parameters by choosing only those poles that were five times stable. Thus a column with more than five red circles in Figure 3 would be selected as a physical pole of the bridge. They stated that this criterion excluded accidentally stable poles and were able to extract the first four modes of the Z24 Bridge automatically with great success. However, they had a large number of sensors on the bridge and were able to utilise mode shape information to help in selection of physical poles. In this paper no such mode shape information is available and it is shown that automatic extraction of physical poles is still possible using just three sensors.

SSI has been implemented in the monitoring system software to analyse automatically ten minute frames of the bridge response. The results of applying the two rules for selecting stable poles stated previously and using a times stable criterion of 40 over a period of 13 days in February and March 2007 is shown in Figure 5. The frequency band displayed has been limited to less than about 1 Hz. Concentration is made on only the first six modes in this paper. Higher modes are more challenging to extract automatically and are the subject of current research by the authors. The first six modes can be seen to stand out as thick bands. There are some mathematical poles scattered intermittently, especially between the fourth and fifth modes.

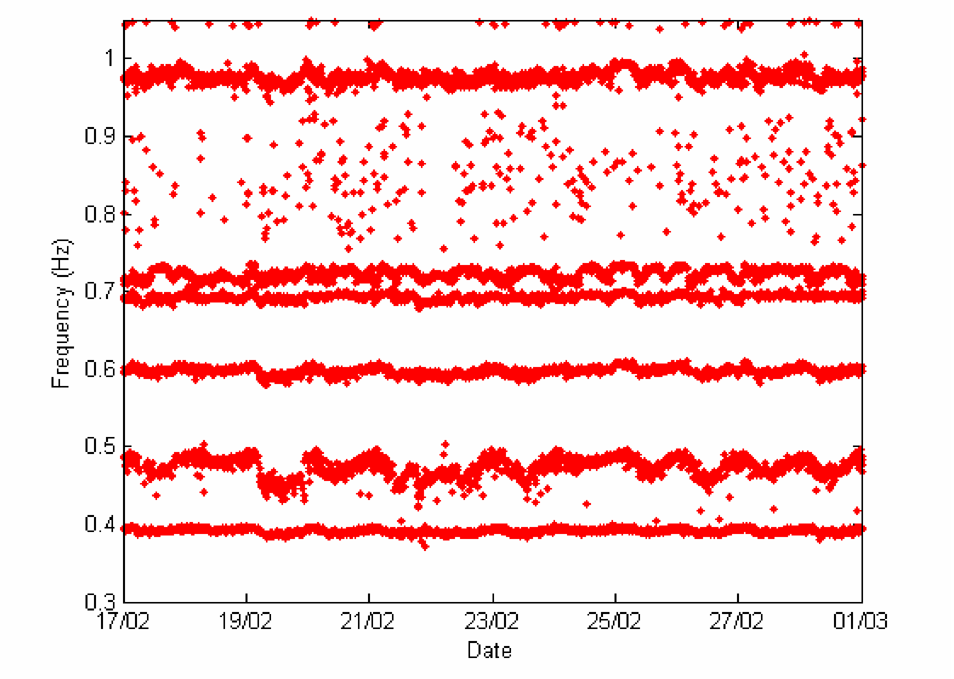

Figure 5. Automatically identified poles below 1.1 Hz.

A modal test of the bridge was conducted in April of 2006 and its mode shapes were identified [2]. This allows the association of each thick band in Figure 5 with a type of mode. The first three vertical bending modes are identified clearly and consistently at about 0.4 Hz, 0.6 Hz and just below 1 Hz. The first torsional mode is identified just above 0.7 Hz. The first lateral mode identified just below 0.5 Hz shows significant variation in time and this is being investigated by the authors.

Figure 6 shows a zoom in of Figure 5 over a single day. Clearly not every mode is identified in each 10 minute time response recorded. The criteria for selecting stable poles and methods to extract the modes automatically when they are weakly excited are under investigation by the authors.

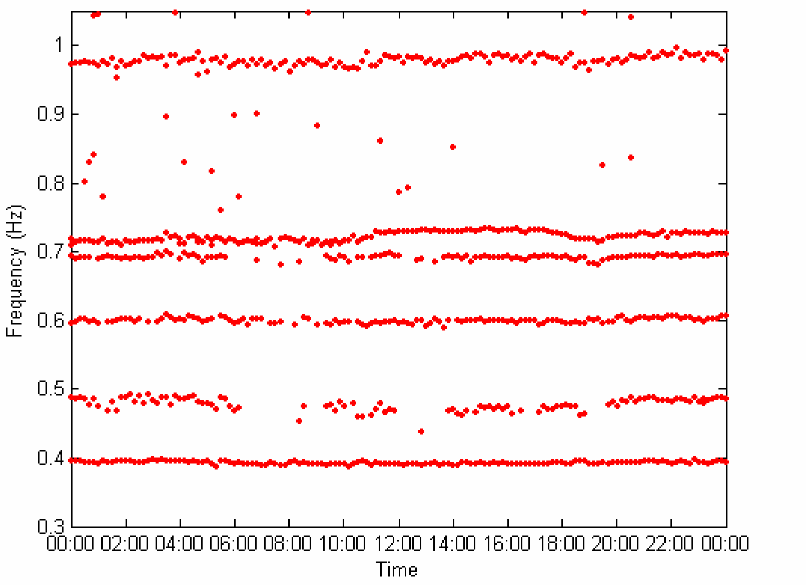

Figure 6. A zoom in on the natural frequencies extracted on 17 February 2007.

USE OF EXTRACTED MODAL PARAMETERS

It was shown by Peeters and De Roeck that Autoregressive eXogeneous (ARX) models could be fitted to long records of poles of a structure to distinguish normal variations in the structure's behaviour from changes caused by damage. The exogeneous inputs are the measured environmental variables such as temperature.

Currently (as at March 1st 2007), there are not enough data recorded from Tamar Bridge to construct meaningful ARX models. The standard deviation on the ARX parameters identified using such a short number of records would be large and also would not be based on a large enough variation of environmental parameters to avoid false alarms. Future research will look at the best exogeneous inputs to use in constructing the models, further filtering out of mathematical poles and handling times when poles of real modes are not excited enough to be identified.

CONCLUSIONS

Preliminary results from a structural health monitoring system on Tamar Bridge are presented. The natural frequencies and damping parameters of first six modes of the bridge are being extracted continuously and autonomously using a stochastic subspace identification technique programmed into the monitoring system's software. In the future these modal parameters will be used to build ARX models to distinguish normal variations of the structure's behaviour from abnormal behaviour. Future challenges include extracting modal parameters from the spectral regions excited by traffic, identifying times when modes are not sufficiently excited to be extracted reliably and identifying driving environmental parameters.

REFERENCES

1. Fish R, Gill J, Tamar suspension Bridge -strengthening and capacity enhancement. In Bridge Modification 2: Stronger and Safer Bridges Thomas Telford, London, 1997, ed B Pritchard
2. Brownjohn JMW, Pavic A, Carden P and Middleton C**.** Modal testing of Tamar suspension bridge. 25th International Modal Analysis Conference (IMAC XXV), Orlando, Florida, USA, 19-22 February ,2007.
3. Van Overschee P, De Moor B, Subspace Identification for Linear Systems, 1996 Kluwer Academic Publishers, USA, pp254
4. Peeters P, De Roeck G, Reference-Based Stochastic Subspace Identification For Output-Only Modal Analysis, Mechanical Systems and Signal Processing (1999) 13(6), 855-878
5. Peeters B, De Roeck G, One-year monitoring of the Z24-Bridge: environmental effects versus damage events, Earthquake Engineering And Structural Dynamics 2001; 30:149-171