Full length article

Data-driven approaches for measurement interpretation: analysing integrated thermal and vehicular response in bridge structural health monitoring

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ABSTRACT

A comprehensive evaluation of a structure's performance based on quasi-static measurements requires consideration of the response due to all applied loads. For the majority of short- and medium-span bridges, temperature and vehicular loads are the main drivers of structural deformations. This paper therefore evaluates the following two hypotheses: (i) knowledge of loads and their positions, and temperature distributions can be used to accurately predict structural response, and (ii) the difference between predicted and measured response at various sensor locations can form the basis of anomaly detection techniques. It introduces a measurement interpretation approach that merges the regression-based thermal response prediction methodology that was proposed previously by the authors with a novel methodology for predicting traffic-induced response. The approach first removes both environmentally (temperature) and operationally (traffic) induced trends from measurement time series of structural response. The resulting time series is then analysed using anomaly detection techniques. Experimental data collected from a laboratory truss is used for the evaluation of this approach. Results show that (i) traffic-induced response is recognized once thermal effects are removed, and (ii) information of the location and weight of a vehicle can be used to generate regression models that predict traffic-induced response. As a whole, the approach is shown to be capable of detecting damage by analysing measurements that include both vehicular and thermal response.

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1. Introduction

Bridges are important transportation links, and their uninterrupted operation is vital for a functioning economy and society. Current procedures for their structural management are based largely on visual inspections that can be unreliable and highly subjective [1,2]. Furthermore, since detailed visual inspections are expensive requiring significant engineer time, they are performed sporadically. For example, in the UK, principal inspections that require engineers to examine each bridge component by getting within touching distance are typically performed only once every 6 years [3]. Consequently, concerns affecting bridge performance are often identified at an advanced stage, thereby requiring expensive structural interventions that are disruptive to the operation of transport networks. Such reactive approaches to bridge management also leads to huge maintenance backlogs that greatly undermines the capacity of the transport infrastructure. In the UK, the maintenance backlog for works on the 57,000 bridges, which are owned and operated by the local highway authorities and estimated to be worth £24 billion, was over £2.4 billion or about 10% of their value as per 2007 estimates [4]. In the USA, according to data submitted to Federal Highways Administration in 2015, 58,791 bridges (9.6% of the bridge stock) were classified as structurally deficient [5] and the total costs of their rehabilitation were predicted to be $31 billion. There is therefore great interest among the bridge engineering community in deploying sensing technologies, which can provide reliable, continuous data streams about bridge loading and response, as a useful complement to visual inspections [6–9].

The main challenge in sensing-based bridge management is in relating collected measurements to structural performance.

Response time histories can be complex to analyse for a variety of reasons. They contain a certain degree of noise due to sensor characteristics. Outliers arising from occasional sensor malfunction or data acquisition issues are also often present. However, more important is the fact that the structural response and hence the measurements are strongly affected by the various loads on the structure including environmental factors and vehicular traffic. Previous research has shown that environmental loads, which vary both diurnally and seasonally, leave a strong signature in the response time histories [10]. Specifically, temperature effects on bridge response can exceed those of other environmental and operational loads [11]. Traffic induced-response appear as short spikes superimposed on thermal response [12]. For example, Fig. 1 (left) shows time histories of the horizontal movement measured at the expansion joint of the River Exe Bridge. Spikes in the horizontal movement are induced by heavy vehicles crossing the bridge. Fig. 1 (right) is a zoomed-in view of a portion of the displacement time-history that corresponds to the passage of a heavy truck over the bridge. Consequently, simple approaches for detecting damage that ignore how the response is affected by the various loads are not useful for real-life structures. For example, the concept of detecting damage by using threshold bounds on individual measurements seldom works since the effect of damage on structural response is often much smaller than the change in response due to diurnal and seasonal temperature variations [13].

Data-driven techniques that exploit patterns arising from spatial and temporal correlations in measurements are well-suited to deal with the above-mentioned complexities in measured response time histories. Since these techniques do not rely on a physics-based model of the structure, they can be more effective than model-based methods for dealing with the potentially large volumes of measured data. Data-driven techniques usually require a training data-set comprising measurements representing baseline conditions of a bridge. The techniques extract features representative of normal structural behaviour from the training data-set and then compare these features with those extracted from new measurements to detect changes in structural behaviour [14].

Data-driven techniques are adapted typically from quantitative fields such as econometrics [15] and statistics [16]. However, a few techniques such as mathematical correlation models [17] and linear approaches to modelling nonlinearities [18] have also been developed specifically for interpreting bridge monitoring data. The majority of currently available data-driven techniques are concerned with the interpretation of response time histories and are able to detect the onset of damage only in simulated measure-

ments created using numerical models of bridges that model damage as a reduction in stiffness [16]. They fail to demonstrate similar performance for measurements from real-life structures particularly when damage is located away from sensors [19] due to the presence of environmental trends that mask damage effects on response. Laory et al. [20] hence studied the removal of seasonal variations from measurements through use of a moving average filter and a low-pass filter. However, this had the negative effect of reducing damage detectability. Laory et al. [21] later combined two data-driven methods, specifically moving principal component analysis with robust regression analysis, to enhance damage detectability. However, the performance of the resulting approach has been illustrated only on measurements collected during the construction phase of a bridge.

Kromanis and Kripakaran [22] suggested a novel data-driven methodology referred to as Regression-Based Thermal Response Prediction (RBTRP) methodology for predicting thermal response, which is the main constituent of the environmental trend in measured response time histories. They demonstrated that measurements of temperature distributions can be exploited to predict accurately thermal effects in measured response. They also showed that the time histories resulting from subtracting the predicted thermal response from the measured response time histories can be analysed by anomaly detection techniques for damage detection. Other researchers have also since investigated similar methods that use both temperature and deformation measurements for damage detection. Yarnold et al. [23] showed that distributed temperature and deformation measurements can enable damage detection albeit through the use of physics-based (finite element) models. This research aims to combine the authors' previous work in predicting thermal response with a novel methodology for predicting vehicular response in order to create a damage detection approach that is capable of analysing response time histories containing both temperature and vehicular effects. There are no data-driven approaches that currently offer this capability.

This study will rely on knowledge of vehicular loads and their positions on the bridge to predict vehicular response. Technologies for measuring vehicle load and location are now well-developed. For example, coupling data from vision-based systems with data from other sensing devices can enable identification of the location, number and types of vehicles, hence, supporting the characterization of their induced response. Such concepts have already been demonstrated in many studies. Glisic et al. [24] have proposed data management principles for accessing and visualizing measurements collected with contact sensors and video streaming.
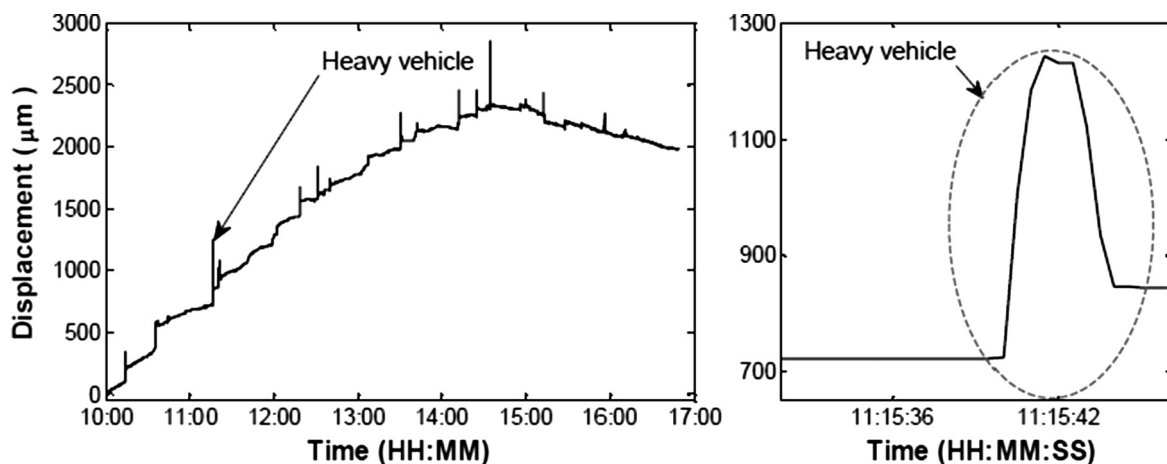

Fig. 1. The River Exe Bridge: time histories of the horizontal movement of the steel girder at the expansion joint collected over 7 hours (left) and during the passage of a heavy vehicle (right). (Courtesy: Dr David Hester and Devon County Council.)