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Predicting thermal response of bridges using regression models derived from measurement histories

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ABSTRACT

This study investigates the application of novel computational techniques for structural performance monitoring of bridges that enable quantification of temperature-induced response during the measurement interpretation process. The goal is to support evaluation of bridge response to diurnal and seasonal changes in environmental conditions, which have widely been cited to produce significantly large deformations that exceed even the effects of live loads and damage. This paper proposes a regression-based methodology to generate numerical models, which capture the relationships between temperature distributions and structural response, from distributed measurements collected during a reference period. It compares the performance of various regression algorithms such as multiple linear regression (MLR), robust regression (RR) and support vector regression (SVR) for application within the proposed methodology. The methodology is successfully validated on measurements collected from two structures – a laboratory truss and a concrete footbridge. Results show that the methodology is capable of accurately predicting thermal response and can therefore help with interpreting measurements from continuous bridge monitoring.

1. Introduction

Rising expenditure on bridge maintenance has led to significant interest in sensing technology and in its potential to lower lifecycle costs of bridge management. Current bridge monitoring systems greatly simplify the collection, storage and transmission of measurements, and such systems are increasingly installed on bridges around the world. Notable examples are the Stonecutters bridge in Hong Kong [1] that is continuously monitored using over 1200 sensors and the St. Anthony Falls bridge in Minnesota, USA [2] that has over three hundred sensors. Monitoring systems on these structures continuously measure a number of bridge parameters related to the structures' response and its environment. The management and interpretation of the collected data, however, poses a great challenge to bridge engineers.

Data interpretation techniques currently employed in practice are often simplistic and tend to be unreliable. For example, the approach typically adopted to analyse measurements from bridge monitoring is to check whether collected measurements exceed pre-defined threshold values and to send email or text notifications to bridge engineers when such situations occur. However, specifying threshold values such that a monitoring system is sensitive to damage while not producing excessive false alarms is seldom possible. The development of robust and reliable strategies for measurement interpretation is therefore increasingly accepted as central to the practical uptake of structural health monitoring (SHM) [3,4]. Such strategies are also envisioned to be a fundamental element of the future "smart" infrastructures [3,5,6] that are expected to take advantage of recent advances in wireless sensing [7] and energy harvesting technologies [8].

Response measurements (e.g., strains) taken from bridges comprise the effects of several types of loads including vehicular traffic and ambient conditions. Hence an important step in measurement interpretation is characterising the influences of the individual load components on collected measurements. This research addresses the challenge of accounting for the thermal response in measurements collected during quasi-static monitoring of bridges. Previous long-term monitoring studies have illustrated that daily and seasonal temperature variations have a great influence on the structural response of bridges [1,9], and that this influence may even exceed the response to vehicular traffic. Catbas et al. [10] monitored a long-span truss bridge in the USA and observed that the annual peak-to-peak strain differentials for the bridge were ten times higher than the maximum traffic-induced strains. Measurements from long-term monitoring of the Tamar Bridge in

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the UK showed that thermal variations caused the majority of the observed deformations in the structure (Koo et al., 2012). While this paper is concerned mainly with quasi-static measurements, temperature variations are also known to have noticeable effects on the vibration characteristics of bridges. Cross et al. [11] investigated temperature effects on the dynamic response of Tamar bridge and showed that ambient temperature significantly influences seasonal alterations in the structure's fundamental frequency. Ni et al. [12] and Hua et al. [9] showed that the modal properties such as frequencies are highly correlated with ambient temperatures for the Ting Kau bridge. These studies highlight the importance of temperature effects on long-term structural behaviour. In the context of monitoring, they also emphasise the need for systematic ways of accounting for temperature effects in the measurement interpretation process.

Existing measurement interpretation techniques can be broadly classified into two categories [4] – (1) Model-based (physics-based) methods and (2) Data-driven (non physics-based) methods. Model-based methods rely on behavioural models (e.g., finite element (FE) models) that are derived from the fundamental physics of the structure. Their application to interpreting measurements from continuous structural health monitoring is limited due to their larger computational requirements and the difficulty in generating reliable behaviour models that are representative of the structure [10,13]. In contrast to model-based methods, data-driven methods operate directly on measurements and require minimal structural information. They especially show promise for anomaly detection due to their capability for recognising and tracking patterns in measurement time-series. Data-driven methods use available measurements to first establish baseline criteria for structural behaviour, i.e., to define conditions that identify with normal structural behaviour. For example, measurements collected shortly after a bridge is built or refurbished could help determine baseline conditions. Subsequent measurements are assessed in real-time to detect deviations from these conditions. This research aims to develop computational approaches for evaluating the thermal response of bridges that are suitable for subsequent embedment within data-driven methods for measurement interpretation.

Data-driven methods are typically based on statistical or signal processing techniques such as moving principal component analysis [14] and wavelet transforms [15]. Existing data-driven approaches focus on the analysis of response measurements and ignore distributed temperature measurements. Omenzetter and Brownjohn [16] applied autoregressive integrated moving average models (ARIMA) to analyse strain histories from a full-scale bridge and noted that performance of the models could potentially be improved by including temperature measurements. More recently, Posenato et al. [14] exploited the correlations between response measurements due to seasonal temperature variations for anomaly detection. However, their approach was shown to be sensitive for only high levels of damage. Studies have also treated the effects of temperature variations on structural behaviour as noise superimposed on the traffic-induced response. Laory et al. [17] showed that filtering the effects of diurnal and seasonal temperature changes from response measurements may lead to information loss and hence minimize the chances of detecting anomalies. These results support the development of anomaly detection techniques that explicitly model the relationships between thermal response and distributed temperature measurements. To develop such techniques, systematic approaches for building numerical models that are capable of predicting thermal response from distributed temperature measurements are required. This research is a step in that direction.

This paper presents a generic computational approach to evaluate the thermal response of bridges from distributed temperature measurements. The premise of the approach is that a reference set of temperature and response measurements could help train regression-based models for thermal response prediction. This study compares a number of algorithms for model generation including multiple linear regression, support vector regression and artificial neural networks. The goal is to arrive at an approach that leads to robust models that are capable of providing accurate response predictions even when there are noise and outliers in the measurements.

The rest of the paper is organised as follows. The envisioned framework for incorporating thermal effects in the measurement interpretation process is first presented. The proposed approach and the various algorithms that are evaluated for model generation within the approach are then outlined. The two structures – (i) a laboratory truss and (ii) a footbridge at the National Physical Laboratory (NPL), which form the case studies in this research, are described. The performance of the developed approach is studied on measurements from these two structures. Lastly, results are summarized with important conclusions.

2. Temperature effects in bridges

Most materials expand or contract under changes in temperature. Therefore bridges and other civil structures continuously deform under temperature distributions that are introduced in them by ambient weather conditions. Temperature distributions across full-scale structures could be very complex depending upon various factors such as their geographic location, their shape and orientation, and the surrounding environment. Temperature gradients in bridges are often non-linear [18] such that they introduce thermal stresses even in bridge girders with simple supports. Potgieter and Gamble [18] showed using measurements from an existing box girder bridge that stresses and forces due to nonlinear temperature distributions are often of magnitudes comparable to those due to live loads. Bridge engineers therefore give significant importance to thermal effects and consequently, bridge designs either incorporate ways of accommodating thermal movements (e.g., expansion joints) or take into account the stresses that could be created by obstruction to thermal movements (e.g., integral bridges). Due to the difficulty in predicting the temperature distributions that could be experienced by as-built structures at the design stage, engineers typically assume linear temperature gradients as indicated by current design codes to evaluate their thermal response. The same approach is, however, not appropriate for interpreting measurements from long-term monitoring since a significant component of response measurements will be due to temperature variations. For example, consider the plot in Fig. 1 showing daily variations in bearing displacements for the Cleddau Bridge in Wales. The figure clearly shows that the displacement increases during the day as the temperature rises with dawn and then decreases later in the day with sunset. Moreover, measurements collected over a year (not shown in figure) reveal that the displacements closely follow the seasonal variations in temperatures.

The premise of this study is that temperature effects have to be factored into the measurement interpretation process for the early and reliable detection of abnormal changes in bridge behaviour. This study therefore proposes strategies for predicting and accounting for the thermal response during the measurement interpretation process. The developed strategies will support a bridge management paradigm that is schematically illustrated in Fig. 2. A bridge like any structural system exhibits responses that vary according to the applied loads. Loads could be of several types such as vehicular traffic, snow, wind and temperature. A continuous monitoring system measures the integrated structural response (e.g., strains, displacements) of the system to all applied