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Support vector regression for anomaly detection from measurement histories

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ABSTRACT

This research focuses on the analysis of measurements from distributed sensing of structures. The premise is that ambient temperature variations, and hence the temperature distribution across the structure, have a strong correlation with structural response and that this relationship could be exploited for anomaly detection. Specifically, this research first investigates whether support vector regression (SVR) models could be trained to capture the relationship between distributed temperature and response measurements and subsequently, if these models could be employed in an approach for anomaly detection. The study develops a methodology to generate SVR models that predict the thermal response of bridges from distributed temperature measurements, and evaluates its performance on measurement histories simulated using numerical models of a bridge girder. The potential use of these SVR models for damage detection is then studied by comparing their strain predictions with measurements collected from simulations of the bridge girder in damaged condition. Results show that SVR models that predict structural response from distributed temperature measurements could form the basis for a reliable anomaly detection methodology.

1. Introduction

Bridges are valuable assets of the national highway infrastructure and their maintenance and management imposes a significant cost on the economy. In the UK, local authorities and Network Rail [1] estimated that they would require over £1.95 billion for the repair and strengthening of their bridge stock. The Federal Highway Administration (FHWA) [2] in the USA noted that almost 24% of the country's bridge stock was classified as structurally deficient or functionally obsolete in 2011. Therefore there is significant interest among the bridge engineering community in innovative technologies and approaches that reduce lifecycle costs of asset management. Current assessment procedures rely primarily on visual inspections, which have the following drawbacks:

- They often fail to detect early-stage damage [3]; repairs undertaken at an advanced stage of deterioration are generally expensive and cause significant traffic disruption.
- They seldom provide sufficient data for accurately characterising structural behaviour [3]. Consequently, estimates of structural capacity are typically conservative and impose unnecessary strengthening and replacement costs.

Monitoring systems have the potential to overcome these limitations by enabling early detection of the onset of damage, and accurate evaluation of asset condition and behaviour.

In the last decade, Structural Health Monitoring (SHM) systems have been deployed more frequently on bridges with the objective of tracking their real-time performance [3]. For example, three long-span bridges – Tsing Ma bridge, Kap Shui Mun bridge and Ting Kau bridge, are continuously monitored using over 800 permanently-installed sensors as part of the Wind and Structural Health Monitoring System (WASHMS) by the highways department in Hong Kong [4]. Wireless sensors that take advantage of energy-harvesting technologies are expected to further simplify the installation of future monitoring systems, and the storage and transmission of collected data [5–7]. These developments are envisaged to form the underpinning technologies for smart infrastructures [8] of the future that continuously sense their environment and provide real-time asset condition for effective management. However, this transition is greatly dependent on the development of fundamental methodologies for processing and interpreting the deluge of measurements generated by sensing systems.

The inverse engineering task of defining the state of a system from indirect measurements is often referred to as structural system identification [9]. System identification techniques [10] can be broadly classified into two categories: (i) model-based methods and (ii) data-driven methods. Model-based methods identify one

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or more behaviour models of the structure that are representative of measured structural behaviour. Since models are directly useful for structural assessment, these methods have been extensively studied by researchers in structural health monitoring (SHM). Many have focused on the evaluation of modal parameters such as mode shapes, frequencies and damping from vibration-based monitoring (VBM) [3,11]. Model-based methods have also been investigated for interpreting static measurements [12,13]. In particular, multi-model strategies [14,15] that explicitly account for modelling and measurement uncertainties have been developed and successfully illustrated for analysing measurements from static load tests of full-scale bridges [16]. However, challenges still remain, the most difficult being the quantification of the effect of variations in ambient conditions [11] and in particular, temperature variations which are known to greatly affect structural response [11,17,18]. Recently, Kulprapha and Warnitchai [19] showed that behaviour models could be developed for predicting the thermal response of a multi-span pre-stressed concrete bridge from distributed temperature measurements. However, model development and simulation is often time and resource-intensive and thus not suited for analysing large volumes of measurements [20].

In contrast to model-based methods, data-driven methods require minimal structural information and hence offer a lot of promise for real-time interpretation of measurements from continuous monitoring. These methods attempt to detect anomalous structural behaviour by evaluating whether new measurements deviate sufficiently from measurements taken when the structure is assumed to be healthy (baseline) state. For example, measurements collected soon after construction could be assumed to represent the normal condition and new measurements could be compared against this data to detect damage. Researchers have investigated many statistical techniques for interpreting quasi-static measurements including wavelet transform [21], pattern recognition [22] and autoregressive moving average models [23]. However, these methods do not incorporate the effects of ambient temperature variations and therefore detect anomalous structural behaviour only at advanced stages of damage since damage-induced changes in structural response are often masked by larger changes due to diurnal temperature variations.

Previous long-term monitoring studies have illustrated that daily and seasonal temperature variations have a great influence on the structural response of bridges [24,25], and that this influence may even exceed the response to vehicular traffic [26]. Catbas et al. [26] 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 taken from the Tamar bridge in the UK by Koo et al. [27] also showed that thermal variations were the major driver of deformations in the structure. Therefore there has been considerable interest in the SHM community on quantifying the effect of ambient conditions on structural response [28–30] and in particular, employ it for damage detection. The anomaly detection approach proposed by Posenato et al. [31,32] relies on correlations between strain measurements and seasonal temperature variations. However, this approach based on moving principal component analysis (MPCA) requires a large set of reference measurements and is also unable to detect anomalous behaviour unless damage is very severe. Laory et al. [33] later illustrated the importance of including temperature effects in the interpretation process by showing that eliminating seasonal temperature variations from the measurement histories could negatively affect the performance of MPCA. However, no previous study has yet attempted to exploit the inherent relationship between distributed temperature and response measurements for anomaly detection.

This research attempts to explicitly capture the relationship between temperature distributions and response using support vector regression (SVR) models, and exploit this relationship for damage detection. SVR essentially employs the same theoretical concepts as support vector machines (SVMs), which are a class of supervised learning methods widely used in the computing community for classification tasks. SVRs are chosen in this research due to their many successful applications for anomaly detection in diverse subjects such as computer networks, finance and medicine [34,35]. In the civil engineering domain, Ray and Teizer [36] used SVR to create blind spot maps based on the construction machinery operator's head pose; the maps could then aid in warning operators of the presence of objects in their blind spots. SVRs have also been previously used in SHM applications. Shengchao et al. [37] proposed a SVR-based fault detection method to detect anomalies in the structure of F-16 fighters without requiring prior measurements for a faulty condition. Other applications in SHM include structural integrity assessment [38] and structural system identification [39]. SVR has also been shown to effectively capture correlations between temperatures and modal frequencies [40]. However, previous studies have not examined the application of SVR for quasi-static measurements, the focus of this research.

This research aims to develop a fast and robust method for anomaly detection by taking advantage of the correlations between temperature distributions across a structure and the measured structural response. The paper first presents an approach for generating SVR models from distributed temperature and response measurements. It then describes a strategy of using such models for anomaly detection. The paper evaluates the feasibility of this methodology on measurements that are obtained from simulations of numerical models representing a bridge girder in healthy and damaged states. It will also assess the performance of the developed methodology in the presence of noise and outliers in measurements.

2. Methodology

A typical bridge management framework that employs feedback from monitoring in the decision-making process is shown in Fig. 1. The management process is iterative with results from monitoring being used to plan and prioritize interventions (e.g. repair and strengthening) and measurements from the bridge helping with condition assessment. The anomaly detection methodology that is presented in this paper is expected to form part of a suite of data interpretation techniques present within such a framework. These techniques, which may include both model-based and data-driven strategies, will supply information on real-time structural behaviour and condition.

This study will develop data-driven strategies for integrating the thermal response of bridges in the measurement interpretation process (shaded block in the measurement management module in Fig. 1). It is, in principle, a first step towards using distributed temperature and response measurements for structural performance monitoring. The objectives are to (i) demonstrate that a data-driven strategy could accurately predict the thermal response of a structure from distributed temperature measurements and (ii) such a strategy could then form the basis of an anomaly detection methodology. While the examples in the paper predominantly focus on the relationship between temperature distributions and the strains they introduce in the structure, the proposed concepts are, however, applicable in general to all types of structural response (e.g. tilt and displacement).

A flowchart of the measurement interpretation strategy presented in this paper is shown in Fig. 2. Measurements collected from sensors are first pre-processed to handle noise and remove