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Vibration-based structural health monitoring under changing environmental conditions using Kalman filtering

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ABSTRACT

A Kalman filtering based framework for structural damage assessment under changing environmental conditions is presented. The approach is based on the well-known property that the filtering residual is a realization of a white stochastic process when the filter is operating under optimal conditions. To decouple structural damage and environmental effects two additional properties of the filtering residual are employed: i) under global changes in the structure caused by environmental variations the residual remains a white process, and thus its spectral density is approximately constant; ii) local changes caused by structural damage induce peaks in the residual spectral density at the affected vibration frequencies, and thus the residual is a colored process. A Bayesian whiteness test is employed to discriminate between the two situations under finite length data conditions (damage detection), while a normalized damage measure based on the spectral moments of the residual spectral density is proposed as a quantitative damage-sensitive feature (damage quantification). The proposed approach is numerically verified in a continuous beam model of a bridge under different operating conditions, including a robustness assessment for non-uniform temperature fields. It is shown that the approach has the capability to decouple physical changes caused by structural damage and varying environmental conditions, providing robust damage measures for structural health monitoring applications.

1. Introduction

Structural health monitoring (SHM) is the process of using information obtained from an array of sensors deployed on a structural or mechanical system to infer its state of structural integrity (damage diagnosis) and to estimate its remaining useful life (damage prognosis) [1–3]. The premise of most structural damage diagnosis methods is that physical changes in a system are reflected in its dynamic properties (mainly vibration frequencies, mode shapes and damping ratios) and/or in response-based damage measures [4–6]. A limitation constraining the use of SHM approaches in applications is that structural damage is not the only cause of variations in the dynamic characteristics of structural and mechanical systems.

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In particular it has been shown that environmental effects have an important influence in the dynamic properties of structures that cannot be neglected by SHM methods [7–10]. In fact, it has been shown that variations induced by environmental effects are such that they can completely mask structural damage in applications [11–14]. This poses an obstacle for damage detection techniques since their reliability becomes questionable due to the increase in the probability of false-positive and false-negative damage estimates. Among the various environmental effects that influence structural behavior, variations in the temperature field have shown to be the one that tends to dominate in SHM applications [9]. Under these conditions SHM methods need to be able to decouple structural damage from variations in the temperature field. In other words, if the measured response and/or the estimated damage sensitive features of a structure at a given time show departure from a reference healthy state, how can we assess if the change is caused by normal fluctuations in the environment or structural damage.

Although both structural damage and fluctuations in the temperature field affect the dynamic characteristics of structures, the effects show systematic patterns that can be exploited to decouple them using vibration response measurements. In particular environmental effects tend to induce global changes that affect all the vibration properties in a somewhat uniform fashion, while structural damage tends to affect the structure locally, resulting in some vibration modes being affected significantly more than others [15]. For example, in many practical applications the overall shape of the vibration modes remain almost unaffected by variations in the temperature field, since the field is typically smooth and continuous in space and time. On the other hand, structural damage tends to induce local variations in the curvature of the mode shapes that are more pronounced in the damaged regions [16].

The difference in the sensitivity of the dynamic properties of structures to damage and temperature variations implies that their effect in response measurements can be used to solve the inverse problem of tracking back the source of the change. For this purpose different approaches have shown to be effective under different operating conditions, but mainly for homogeneous systems [17,18]. In Ref. [9] Sohn et al. developed and validated a static linear regression model using data from the Alamosa Canyon Bridge. The confidence intervals obtained were used to discriminate changes caused by environmental effects and structural damage. Regression models were further extended to account for dynamic effects using an auto-regressive exogenous ARX model [19,20]; this model takes into account thermal dynamics, i.e., the dependence of the current dynamic properties in the past time-history of the temperature field. In Ref. [19] Peeters and De Roeck validated the model using data from the Z24 bridge in Switzerland, while in Ref. [20] Moaveni and Behmanesh validated the model using data from a footbridge under different operating conditions. Another approach was proposed in Ref. [21] by Fritzen et al., where a residual is computed by comparing the response of the potentially damaged structure with a reference undamaged state; for this purpose the reference response is stored in the form of singular vectors at different temperatures. When measurements from the potentially damaged structure are gathered at a given temperature, the residual is computed by projecting to the stored reference data. This approach assumes that the subspaces spanned by the reference and damaged data are orthogonal. The use of modal filters to decouple structural damage and environmental effects was proposed by Deraemaeker et al. in Ref. [22]; the proposed approach is based on modal filters calibrated such that a peak appears in the frequency domain output of the filter in the presence of damage. In Ref. [17] Yan et al. proposed an output-only linear approach based on principal component analysis (PCA) to discriminate environmental changes from structural damage. Damage is assessed by novelty detection using the Euclidean norm or a Mahalanobis distance of residual errors; the approach assumes that the variations of temperature and damage are orthogonal. The PCA approach was further extended to account for nonlinearities using piecewise linear approximations and employing PCA for the different linear regions (local PCA) [23]. More recently a residual-based approach based on kernel PCA was proposed to account for temperature-induced nonlinearities using a non-parametric model [24]. The approach was validated using data from the Z24 bridge in Switzerland.

In this paper a statistical approach to decouple structural damage and temperature variations is presented. The approach relies on a Kalman filter model to estimate the residual error (difference between measurement and response estimate), and a Bayesian whiteness test as a damage-sensitive feature. It is well-known that when the Kalman filter operates under optimal conditions the residual is a white process, and thus the residual power spectral density (PSD) is constant [25]. The following two additional properties of the residual PSD are employed herein to decouple temperature and damage effects: i) under global changes caused by environmental variations the residual spectral density remains approximately constant; ii) local changes caused by damage induce peaks in the residual PSD, and thus the residual is a colored stochastic process. The previous Kalman filtering residual properties imply that structural damage induces a correlation in the residual process, while the residual process remains a white process under variations in the temperature field. The properties will be used to develop a framework to decouple structural damage from variations in the temperature field. The average air temperature at the structure location is assumed to be known.

To assess if a realization of the residual process qualifies (in a statistical sense) as a white process under finite length data conditions a Bayesian whiteness test is proposed, while to quantify structural damage a normalized damage index based on the spectral moments of the residual PSD is proposed. The paper is organized as follows: first, the fundamentals of the Kalman filter are briefly revised, followed by an analysis of the correlations induced in the filter residual by both structural damage and temperature variations. Then, the proposed Bayesian whiteness test is introduced for damage detection, followed by a discussion of the proposed normalized damage index introduced for damage quantification. Finally, a numerical results section illustrates the application of the framework in a continuous steel beam model of a bridge subjected to uniform and non-uniform temperature fields.