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Robust ultrasonic damage detection under complex environmental conditions using singular value decomposition

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ABSTRACT

Guided wave ultrasonics is an attractive monitoring technique for damage diagnosis in large-scale plate and pipe structures. Damage can be detected by comparing incoming records with baseline records collected on intact structure. However, during long-term monitoring, environmental and operational conditions often vary significantly and produce large changes in the ultrasonic signals, thereby challenging the baseline comparison based damage detection. Researchers developed temperature compensation methods to eliminate the effects of temperature variation, but they have limitations in practical implementations.

In this paper, we develop a robust damage detection method based on singular value decomposition (SVD). We show that the orthogonality of singular vectors ensures that the effect of damage and that of environmental and operational variations are separated into different singular vectors. We report on our field ultrasonic monitoring of a 273.05 mm outer diameter pipe segment, which belongs to a hot water piping system in continuous operation. We demonstrate the efficacy of our method on experimental pitch–catch records collected during seven months. We show that our method accurately detects the presence of a mass scatterer, and is robust to the environmental and operational variations exhibited in the practical system.

1. Introduction

Guided wave ultrasonics is an attractive monitoring technique for damage diagnosis in large-scale plate and pipe structures. Guided waves propagate with low attenuation and can interrogate large areas with only a small number of sparsely distributed, low-voltage transducers [1–3]. Ultrasonic guided waves are characterized by a dispersive and multi-modal nature, which complicates the received ultrasonic signals and makes it challenging to extract information about the damage [4].

Due to the complexity of guided waves, many damage detection methods rely on baseline comparison to remove static, background information. In these scenarios, a set of baseline records is collected when the structure is known to be intact. The differences between any new records and the baseline signal can then used to monitor for structural damage [5]. Alternatively, structural damage can be detected by analyzing the cross-correlation coefficients, a measure of similarity, between a baseline and each new time-record [6].

However, ultrasonic waves are vulnerable to changes in environmental and operational conditions (EOC) [7] that are inevitable in the normal operation of civil and mechanical structures. Such changes of EOCs may affect the mechanical properties of the medium in which the ultrasonic waves propagate, and produce changes in the received wave signals. Therefore, the baseline information is generally not static over time. In active pipes, for example, ultrasonic waves are often influenced by variations in temperature, pressure, and flow rate. These effects complicate analysis and mask damage-related information [8].

Among the common EOCs to affect ultrasonic monitoring systems, temperature is the most ubiquitous and widely studied. Researchers have developed many algorithms to compensate for temperature variations. Optimal baseline selection methods were first developed in [9], which avoid temperature variation by comparing the new record with a library of baselines collected at

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different temperature. Researchers then developed local peak coherence [5,10], and optimal signal stretch methods [11,12], assuming temperature change has a stretching effect on the signal. With that assumption, the amount of temperature change can be determined by comparing new records with stretched version of a baseline signal. One can then stretch the new record so that it is comparable to the baseline records. The estimation of stretching factors can also be done in the scale transform domain to achieve higher resolution and efficiency, as shown in [13]. Other researchers argue that having a fixed baseline or baseline set may be not sufficient in a dynamic environment, and developed a continuously growing baseline temperature compensation method to avoid collecting a comprehensive library of baselines before the monitoring phase [14]. As demonstrated in both laboratory and practical experiments, these temperature compensation methods can be used to adjust each record and improve our capability to detect damage.

Fig. 1 illustrates an example of scale-transform temperature compensation [13] applied to two experimental records from an operating hot-water pipe under variable temperature, flow rate, and pressure. Fig. 1(a) and (b) show a comparison of the two signals zoomed into different fast-time intervals, where 'fast-time' refers to the time-of-flight of the ultrasonic waves, and is characterized by the sampling of voltage readings in one pitch–catch record. In contrast, we define 'slow-time' as the time scale associated with the interval (usually in minutes) in between records, and is characterized by the number of records. We can see that the signals align well at the beginning and increasingly deviate as they approach the coda, the end of the signal. We apply the scale-transform temperature compensation [13] on the dashed record with the solid trace as the baseline. Fig. 1(c) and (d) show that after temperature compensation the records are much better aligned with each other.

Stretch-based temperature compensation methods have certain limitations. First, these temperature compensation methods model temperature changes as a stretching effect on the ultrasonic signals, which is only an approximation. This model does not hold for large changes in temperature. Second, the methods assume that temperature variation is uniform across the path covered by the ultrasonic records, such that the stretching effect is uniform across the ultrasonic record. Many structures are instead affected by temperature gradients. Last, temperature compensation methods generally require a set of baseline records to be collected either before or during the monitoring, which can be difficult to manage and/or update in a dynamic environment. Moreover, in a practical implementation of ultrasonic monitoring systems, temperature variation is often accompanied by other EOCs that affect the ultrasonic record. Our field experiments show that EOCs contribute to many variations of the ultrasonic records, and that temperature compensation only addresses a portion of them.

Because analytically modeling the effect of EOCs on the ultrasonic measurements is challenging, researchers have developed various data-driven methods that extract useful information from large datasets of ultrasonic records [10,15,16]. Data-driven methods extract useful features from data and then use those features to classify the status of the structure. A data-driven damage detection procedure used (explicitly or implicitly) by many researchers includes pre-processing, feature extraction, damage-sensitive feature selection, and damage classification. Detection or classification is accomplished with well-developed methods in the literature such as support vector machine [17], neural network [18], and Fisher's discriminative analysis [19]. However, reliable damage-sensitive features are usually application-specific and are difficult to find.

In this paper, we address these challenges by developing a novel damage-sensitive feature extraction and selection procedure based on singular value decomposition (SVD) to detect structural damage with ultrasonic pitch–catch records. SVD is a linear decomposition method that is widely used for dimensionality reduction, and is closely related to another latent variables methods, known as principal component analysis (PCA) [20]. We demonstrate that by applying SVD on ultrasonic records, we can separate the change produced by damage from the change caused by EOCs, without a prior knowledge of the EOC variations, and thereby robustly detect damage in a complex environment. We show its efficacy on data collected in real world piping systems experiencing significant variations in EOCs that defeat common damage detection routines.

In Section 2, we present the proposed damage-sensitive feature extraction and selection procedure. In Section 3, we describe our

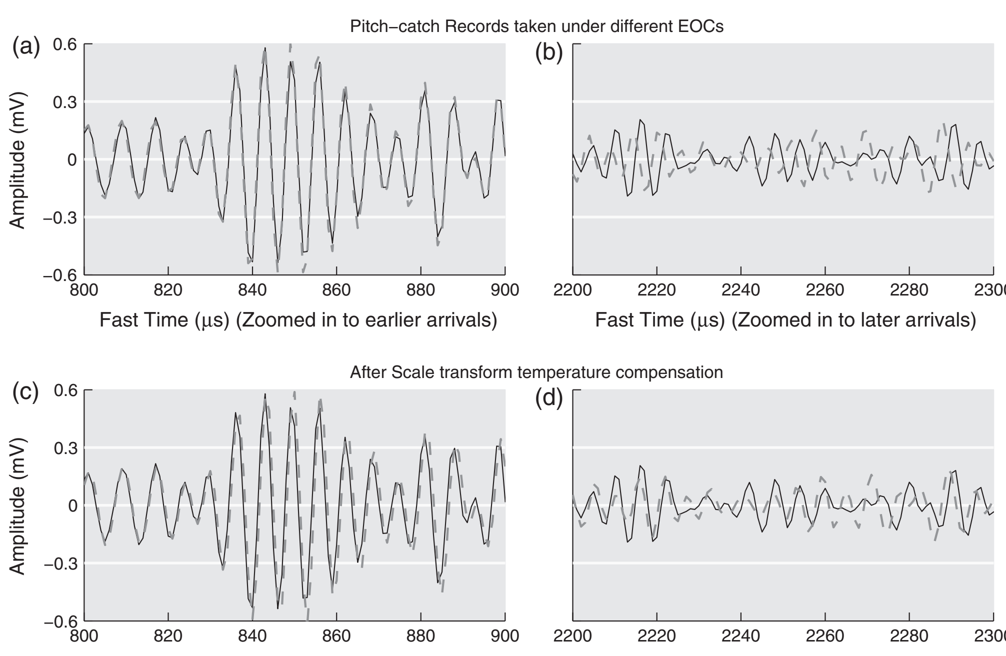

Fig. 1. (a) and (b) Two pitch–catch records collected under varying environmental and operational conditions. Record in dashed line was collected 1 h later than the record in solid line. (c) and (d) After temperature compensation, the two records are much better aligned.