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Damage detection of metro tunnel structure through transmissibility function and cross correlation analysis using local excitation and measurement

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ABSTRACT

In a modern metropolis, metro rail systems have become a dominant mode for mass transportation. The structural health of a metro tunnel is closely related to public safety. Many vibration-based techniques for detecting and locating structural damage have been developed in the past several decades. However, most damage detection techniques and validation tests are focused on bridge and building structures; very few studies have been reported on tunnel structures. Among these techniques, transmissibility function and cross correlation analysis are two well-known diagnostic approaches. The former operates in frequency domain and the latter in time domain. Both approaches can be applied to detect and locate damage through acceleration data obtained from sensor arrays. Furthermore, the two approaches can directly utilize structural response data without requiring excitation measurement, which offers advantages in field testing on a large structure. In this research, a numerical finite element model of a metro tunnel is built and different types of structural defects are introduced at multiple locations of the tunnel. Transmissibility function and cross correlation analysis are applied to perform structural damage detection and localization, based on simulated structural vibration data. Numerical results demonstrate that the introduced defects can be successfully identified and located. The sensitivity and feasibility of the two approaches have been verified when sufficient distribution of measurement locations is available. Damage detection results of the two different approaches are compared and discussed.

1. Introduction

In modern international metropolis such as New York City, Shanghai, or Tokyo, urban population has reached tens of millions. As a result, ground transportation has become increasingly insufficient for satisfying public commuting demands, while the metro system has become preferred by many for daily commuting. The health of metro tunnel structures is of

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significant importance to public safety. However, due to harsh operational and environmental conditions, metro tunnel structures may gradually deteriorate and require timely maintenance over the service life [1].

In the past decades, structural health monitoring systems have been widely adopted to monitor the behavior of structures and evaluate the safety and durability of structures. Structural health monitoring system has been progressively regarded as an effective way to reduce risks for underground structures [2]. Many damage identification techniques for detecting and locating existing damage have been developed recently, and many algorithms aim to identify damage using changes in structural vibration [3,4]. The main presumption of using vibration data is that the existence of damage changes structural stiffness, and thus changes structural modal properties that can be extracted from vibration test [5]. Following recent rapid developments in metro tunnel engineering, vibration-based structural health monitoring approach for tunnel-soil coupled system was researched. A Timoshenko beam-Transfer Matrix Method is developed to determine the relationship between the tunnel Young's modulus and the coupled resonance frequency [6]. A structural health assessment method based on torsional wave speed was proposed to determine the tunnel structure's global stiffness, and evaluate the tunnel's structural service status further [7]. Damage identification algorithms based on vibration data can provide information regarding the overall health condition of the structure, and vibration test is relatively low-cost to implement in the field.

Vibration-based damage identification techniques can be categorized into two groups: model-based approaches and non-model-based approaches [4]. Model-based approaches assume that structural response can be accurately simulated with numerical models such as FEM (finite element model). If the numerical model fails to accurately reflect the response of structure in the field, the performance in damage detection suffers. Alternatively, non-model-based approaches may avoid such difficulties and demonstrate advantages in large-scale structures. The reason lies in the challenge of acquiring an accurate finite element model for large-scale structures, even when field measurement data is available for updating and calibrating the model. Among various non-model approaches, transmissibility function and cross correlation analysis are both capable of structural damage detection and localization. Both approaches can directly utilize structural response data (without excitation measurement), which offers advantages in large structure testing.

Both theoretical development and field application using transmissibility function for damage detection and localization have been investigated by researchers. The transmissibility relationship between frequency response functions was considered by Liu and Ewins [8], where transmissibility function was defined as the ratio of frequency response functions for a chain-like multi-degree-of-freedom system. A more generalized transmissibility concept was proposed by [9] as a powerful tool for modal analysis. Translational and curvature transmissibility functions were adopted to detect and locate damage on a cantilever beam by [10]. The research demonstrated that more accurate damage detection could be achieved when high frequency range of the transfer function is used. In addition, transmissibility function were analytically derived by [11] for detecting and locating damage in linear and nonlinear structures. Two damage detection cases, a representative three-story building structure and a rotorcraft fuselage, were later applied with transmissibility function analysis by [12], where reliable damage detection was obtained in spite of certain environmental fluctuations and non-linearity in boundary condition. The work by [13] demonstrated that transmissibility function analysis was able to detect a single bolt loosening with reduced tightening torque. Furthermore, the influence of operational and environmental variability on the damage indicator was analyzed by [14]. The results showed that the accuracy and reliability of transmissibility function analysis could be improved by identifying specific frequency ranges that are more sensitive to damage and immune to sources of variability. More recently, Yi and Zhu [15,16] developed a mobile sensing system which is capable of maneuvering on the surface of ferromagnetic materials. Transmissibility function analysis was embedded in mobile sensing nodes; using data collected by mobile sensing nodes, on-board computation was successfully conducted to detect damage on a steel frame.

On the other hand, cross correlation analysis has also been studied by many researchers in the last few decades. [17] proposed that cross correlation functions between two response signals under ambient excitation have the same waveform as impulse response functions. The resonance frequencies and modal damping of the structure were estimated from cross correlation functions. The Hilbert–Huang transform of cross correlation functions was studied by [18]. The stiffness and damping coefficients of Phase-I IASC-ASCE benchmark building were identified; damage locations and severities can be identified by comparing stiffness prior to and after damage. Furthermore, a damage indicator was proposed by [19]. The indicator was defined by comparing the peak amplitude of the cross correlation function of the damaged structure versus that of the undamaged structure. Laboratory experiments on a steel portal frame were conducted to validate the damage detection approach. A prerecorded catalog of Green's function templates and a cross-correlation method was recently proposed by Heckman; brittle fracture of welded beam-column connections in steel moment-resisting frames (MRFs) was detected by using proposed method [20].

In most applications, transmissibility function and cross correlation analysis were applied to data acquired on beams, plates, frames and multistory building models. Little research has been reported on the application on underground structures. This paper describes the application of these two approaches on diagnosing damage in an underground metro tunnel. In this study, a numerical model of a metro tunnel structure is established with consideration of soil constraints. Different types of structural defects are introduced at multiple locations of the tunnel. Transmissibility function and cross correlation analysis are applied to perform structural damage detection and localization.

2. Transmissibility function and cross correlation algorithms

Damage detection algorithms based on transmissibility function and cross correlation analysis are briefly reviewed in Sections 2.1 and 2.2, respectively.