Temperature Effect on Vibration Properties of Bridge Structures

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In civil engineering structures, modal changes produced by environmental conditions, especially temperature, can be equivalent to or greater than the ones produced by damage. Therefore, it is necessary to distinguish the variations in structural properties caused by environmental changes from those caused by structural damages.

temperature effect | modal properties | damage identification

1. Introduction

Structure can be damaged during service, resulting in structural failure and collapse, which may pose a major risk to human life. Therefore, the identification of structural damage in civil engineering plays an important role. In essence, structural damage refers to reductions in characteristic structural parameters. Therefore, structural damage can be evaluated based on changes in modal parameters [1][2][3]. Vibration-based identification techniques can be used to detect the severity and location of damage to structures. However, due to environmental factors, different data sets measured at different times may yield different monitoring results [4][5][6][7][8][9][10]. Numerous sets of field monitoring data and theoretical analyses show that structural modal parameters are not only related to structural properties but are also susceptible to ambient factors, especially temperature variations [11]. Changes in the structural response caused by temperature variation can cover up change in the structural response caused by structural damage. The integration and interpretation of various data types are essential for the effective use of SHM systems for structural state assessment and damage detection [12].

Some researchers have studied the mechanism of the effect of temperature variation on natural frequency. For example, Hu et al. [13] monitored a prestressed-concrete box girder bridge on the A100 Highway in Berlin and reported on the bridge’s general condition and potential damage. They observed nonlinear influences of temperature on natural frequencies and used the multiple linear regression method to characterize the nonlinear relationship between temperatures and natural frequencies. Kromanis and Kripakaran [14] applied a novel calculation technique to bridge structure performance monitoring so that the temperature-induced response in the process of measurement interpretation could be quantified. They proposed a regression-based method to generate a numerical model to capture the relationship between the temperature distribution and the structural response based on the distribution measurement data collected during the reference period. The use of a laboratory truss and a concrete footbridge showed that this method could accurately predict the thermal response.

When the environment's influence on changes in dynamic structural characteristics is not properly considered, vibration-based structural damage detection methods may produce false positive or negative damage signals [15]. Therefore, eliminating the modal variability caused by temperature interference is essential in vibration-based damage detection [16]. Gu et al. [17] developed a two-step damage detection method combining novelty detection and a multi-layer neural network, which was intended to avoid false alarms in the implementation of vibration-based structural damage identification methods due to varying temperatures. This method distinguishes the natural frequency changes caused by damage from the changes caused by temperature. A simply supported beam and finite element model based on an experimental grid structure were used for numerical research to simulate different degrees of stiffness reduction under different temperature conditions, which verified the detectability and robustness of this method. Yang et al. [18] proposed a phase-shifting method based on the Fourier series expansion fitting method to mitigate the influence of the time-lag effect. They computed the phase difference between temperature and response strain data at each decomposed order, and the total phase difference can be obtained by weighted summation. The authors reported that this method could effectively reduce the time-lag effect, leading to a sound understanding of the temperature load and its effect.

The existing structural damage detection methods can be divided into data-based and model-based methods. The most commonly used data-based methods are machine learning, deep learning, support vector machine, principal component analysis, etc. The main advantage of these methods is that there is no need to build a finite element model, and the collected dynamic signals are used directly. Therefore, modeling errors can be avoided. However, a disadvantage is that a large amount of data is required, which makes data processing difficult. At the same time, the severity of damage cannot be quantified in most cases. The model-based method mainly includes the meta-heuristic optimization-based model updating method, the wavelet-based method, and the Bayesian inference-based model updating method. Those methods can more accurately determine the location and severity of damage, compared to the data-based methods. Nevertheless, their disadvantage is also obvious: these methods need to establish a benchmark finite element model, which introduces some errors.

2. The Effects of Ambient Temperature on the Structural Dynamic Properties

2.1. Theoretical Analysis

2.1.1. Probabilistic Methods

Due to the influence of environmental and artificial factors, the data collected in several vibration tests are not completely consistent because the measured data contain uncertainties. This may lead to incorrect damage identification results if these uncertainties are not appropriately addressed [19][20][21][22][23][24]. Therefore, some researchers have used probability-based methods to address the effect of temperature on vibration properties and to consider temperature uncertainties. Bao et al. [12] proposed a Bayesian-based damage detection technique in which structural parameters and temperature were variables of modal properties (frequencies and mode shapes).

An experiment was carried out on a two-story portal frame, and the model uncertainty, measurement noise, and temperature effect were considered to verify the method's effectiveness.

Basseville et al. [25] proposed two extensions of the statistical parameter damage detection algorithm based on null space residuals associated with output-only subspace identification, which accounted for the temperature effects. The first extension was based on the use of a thermal model to derive a temperature-adjusted null space, and another involved the application of the thermal model and statistical nuisance rejection technique. Both methods were illustrated in laboratory test cases in a climate chamber. Wang et al. [16] introduced a Gaussian mixture model to cluster the temperature and frequency data into different subsets and deduced a new representative temperature for the bridge temperature field. In addition, they established a more accurate baseline correlation model. The authors reported an engineering application in a cable-stayed bridge, demonstrating the validity of eliminating the temperature-induced change in modal frequency based on long-term monitoring data.

2.1.2. Artificial Intelligence Methods

With the continuous development of artificial intelligence, this technique has been applied to various aspects of research [26][27][28][29][30][31][32]. In a study on the effect of temperature on vibration properties, Hsu and Loh [33] extracted the underlying environmental factors using an auto-associative neural network based on the structural system's identified or measured target features under varying environmental conditions. They reported that this technique could deal with non-increasing characteristics (stiffness) and non-decreasing characteristics (the damage index after introducing damage) without directly measuring ambient factors. Torzoni et al. [34] reported an effective damage localization strategy using vibration and temperature data to consider the influence of temperature fluctuation on the structural response. By allowing a limited number of predefined damage scenarios, temperature data were used as a condition, and deep learning technology was used as a supervised classification to deal with damage localization tasks. They tested the capability of this procedure to locate the damage through two case studies and showed a relatively high accuracy even in a rather small local stiffness properties reduction situation.

Zheng et al. [35] proposed a new method to reduce the influence of temperature variation on the dynamic modal characteristics of bridges. They used a probabilistic-based machine learning method (the Gaussian process model) to learn the correlation between the modal characteristics of the monitored bridge and the corresponding temperature variations based on field sensor measurements. Then, the authors simulated a numerical example to prove the effectiveness of this method in mitigating temperature variations or other ambient impacts in vibration-based structural health monitoring. Zhou et al. [15] used the back-propagation neural network (BPNN) technique to establish the correlation between damage-sensitive modal characteristics and temperature. With the correlation model, the measured modal characteristics under different temperature conditions were normalized to the same reference temperature state to eliminate the effect of temperature. Then, the normalized modal characteristics were applied to structural damage identification.

2.1.3. Optimal Algorithm Methods

Many researchers have studied optimization algorithm methods since they are simple and can be calculated quickly. Huang et al. [36] investigated a non-destructive global damage identification method based on a genetic algorithm (GA), which was used to identify the severity and location of damage to a structure under the influence of temperature variation and noise. The method's effectiveness was verified in several scenarios of damage to three-span continuous beams and two-span steel trusses, and it showed good robustness under random noise levels.

Meruane and Heylen [37] studied a damage detection method that was able to deal with temperature variations. In their study, the objective function correlated mode shapes and natural frequencies, and a parallel genetic algorithm handled the inverse problem. Since the elastic modulus of materials is temperature-dependent and the algorithm updated the temperature and damage parameters together, the temperature effects and real damage events could be distinguished. The authors then simulated the I-40 bridge and a three-span bridge to verify the method.

2.1.4. Other Methods

In addition to the above three methods used to study the effect of temperature on vibration properties, some scholars have adopted different methods to study this issue. For instance, Gillich et al. [38] employed adjustment coefficients to eliminate the effect of temperature, which were individually developed for each mode of vibration. Then, the authors proposed a damage assessment method based on multi-modal analysis, which allowed the assessment of beam axial force damage caused by temperature variation. Under the condition of variable temperature, numerical simulation and experimental tests were carried out on the beams with fixed ends to verify the practical applicability of the method for adjusting the coefficient.

Manoach et al. [39] presented a numerical and experimental study of the vibration of a damaged laminated beam under dynamic loads and temperature variations. Based on the analysis of Poincaré maps of the damaged and healthy plate, the early proposed non-heating plate damage detection criterion was modified, and the damage detection of beams under high temperature was tested. The importance of considering the actual temperature in damage detection was shown. Xia et al. [40] investigated the variations in structural vibration characteristics versus the structure's non-uniform temperature field. A thermodynamic model was used to estimate the temperatures of different structure components at different times. This study provided a novel way to quantify the influence of ambient effects on structural vibration features.

Zhu et al. [41] presented a feature extraction method to uncover the effects of temperature on bridge responses, which combined mode decomposition, data reduction, and blind separation. They also evaluated the effect of the extraction of the temperature-induced response on damage detectability using moving principal component analysis (MPCA). A truss bridge model was numerically analyzed to evaluate the thermal feature extraction method. The numerical results showed that this method was able to realize the separation of the temperature response.

2.2. Experimental Research

2.2.1. Quantitative Analysis

In the literature on the investigation of the effect of temperature on vibration properties, some scholars have focused on building theoretical models employing measured experimental data to quantify the impact of temperature on vibration properties. Based on a six-month monitoring experiment program, Cury et al. [42] established a model of the influence of temperature on the modal frequency of a PSC box girder bridge on the A1 highway in France. Then, they introduced a neural network to establish a regression model for quantifying the influence of temperature on modal parameters (frequencies and vibration modes). He et al. [43] studied a PC beam bridge in Oklahoma, developed an efficient temperature loading model to predict the temperature-induced response of the bridge, and formulated the criterion of the temperature loading effect in condition assessments based on reliability. They proposed a probabilistic model based on a uniform distribution of the temperature field and temperature gradient. This model was able to help engineers to predict the thermal behavior of PC bridges in Oklahoma, USA. They [44] also estimated the movement and stress under temperature loading with a three-dimensional (3D) finite element model and compared it with the monitoring counterparts.

Montassar et al. [45] studied the thermal effects of the inclined elastic stay cables' static and dynamic mechanical properties in cable-stayed structures. They proposed a nonlinear analytical method to calculate the variation in tension in stay cables under the influence of uniform temperature variations. They also investigated the influence of temperature variations on the free undamped vibration of stay cables. The validity and effectiveness of this method were verified by comparing the model results with measured data from the stay cables of the Rades-La Goulette cable-stayed bridge in Tunisia. Li et al. [46] focused on the boundary conditions' effects on the dynamic behavior of a suspension bridge. They proposed an analytical model to perform a sensitivity analysis of a bridge's modal parameters related to the stiffness of the expansion joints located at both ends of the bridge. They concluded that the boundary conditions significantly affected the low-order modal parameters of the suspension bridge. Moaveni and Behmanesh [47] studied the influence of ambient temperature variation on updating the finite element model of the Dowling Hall Footbridge. The footbridge had a continuous monitoring system that recorded the vibration and temperature of the bridge once an hour or when a large vibration was triggered. The authors then estimated a static polynomial model to "remove" the temperature effects from the identified natural frequencies. The proposed approach successfully minimized the effects of changing ambient temperature on the FE model updating of the Dowling Hall Footbridge.

Xia et al. [48] investigated the temperature distribution and the related response of a long-span suspension bridge—the 2132 m Tsing Ma Bridge—through numerical analysis and field monitoring. Under appropriate assumptions, fine finite element models of the bridge deck, section frame, and bridge tower were established to facilitate thermal analysis. They found that the combination of numerical analysis and field monitoring data provided a thorough understanding of the temperature behavior of long-span bridges. Zhou et al. [49] monitored the Ting Kau Bridge in Hong Kong for 770 h and constructed an appropriate neural network input to simulate the modal changes caused by temperature. The principal components of the average temperature, effective temperature, and temperature were constructed as inputs of the neural network to model the correlation between modal frequency and ambient temperature. They found that the temperature profile characterized by effective temperature was insufficient to establish a good correlation model between modal frequency and temperature.

Zhu et al. [50] investigated the relationships between temperature-induced stress and standard temperature variations by monitoring a 108 m-long steel truss bridge for two years. They provided a simple formula to model the relationship between temperature-induced strain and the temperature distribution. The accuracy of the proposed formula was verified using field monitoring data for box-shaped and H-shaped components. Their research can provide a simple and relatively general solution for temperature-induced strain prediction for steel truss bridges. They [51] also initially used the elastic beam theory to explore the relationship between temperature variation and temperature-induced responses.

2.2.2. Qualitative Analysis

In addition to the quantitative analysis of the effect of temperature on vibration properties, some scholars have paid more attention to the quantitative analysis of this issue. For example, using long-term monitoring data, Ding and Li [52] addressed the temperature variation problem of the measured modal frequency of the steel box girder of a suspension bridge. They studied the daily and seasonal correlations of the frequency and temperature in detail. They concluded that temperature was the key source of modal variability, and there was an overall decrease in modal frequency with temperature for all identified modes. In addition, the vibration mode's daily average modal frequency had an obvious seasonal correlation with the daily average temperature.

Mao et al. [53] measured the dynamic characteristics (including acceleration, strain responses, and modal frequencies) of the Sutong Cable-Stayed Bridge for one year. They also analyzed the variability of structural modal frequency caused by ambient temperature. The results showed that temperature was the crucial environmental factor for vertical and torsional modal frequencies. Mosavi et al. [54] investigated the influence of temperature variations on the modal properties of a two-span steel-concrete composite bridge in North Carolina. Field tests included measuring the bridge's vibration response, temperature, and deflection throughout a summer day. They found that temperature variation could induce modal variability in a daily cycle. Teng et al. [55] carried out the long-term monitoring of an arch bridge. They used correlation analysis, numerical simulation, and the neural network technique to report the influence of temperature on structural frequency. They observed that due to the influence of temperature, the frequency of the beam mode was affected by boundary conditions and the elastic modulus, and the change in the elastic modulus only affected the frequency of the arch models.

Xia et al. [56] monitored a long-span suspension bridge for one year and studied the influence of thermal variations on structural performance under operating conditions. The authors statistically analyzed the long-term temperature and structural response data, including displacement, strain, and suspender frequency. The statistical analysis results showed that the longitudinal temperature distribution along the main beam was nonuniform. They [57] also proposed a structural damage identification method using the temperature-induced response. They derived the structural transfer function by taking the input and output data of temperature load changes and temperature-induced strain. Yun et al. [58] studied the Guangzhou New TV Tower (GNTVT) and they reported the varying patterns of the operational modal parameters under the effects of different environmental factors. The authors found that temperature only affected the modulus of elasticity and the geometric stiffness of the structure.

2.2.3. Temperature Test Method

The instrumentation and steps applied for measuring the effect of temperature on bridge structures are as follows. Firstly, thermal resistance is installed on the surface and inside the bridge structure, and a multi-point wireless temperature automatic test system is used to measure the temperature of the bridge pier and beam. Then, before and after the vibration tests, the thermal radiation value of the structure surface is measured by means of a thermal radiometer, and an infrared imager captures temperature field images of the structure during the test. Finally, the temperature-time history of the bridge structure, three typical temperature distribution modes of a beam (vertical positive temperature difference, vertical negative temperature difference, and transverse temperature distribution), and two directional temperature distribution modes of the pier are obtained.

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