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A Review of wavelet-based analysis for driving monitoring to detect local damage on bridges

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Abstract

The drive-by monitoring of bridges using indirect measurements from passing vehicles for bridge monitoring overcomes the expensive, time-consuming and very dangerous drawbacks of the previous method of installing many sensors on structures for health monitoring. Therefore, it has received a lot of attention from research scholars. Wavelet analysis has been increasingly used in drive-by bridge inspection techniques due to its robustness and sensitivity to discontinuities in the signal and has achieved some results. In this paper, we introduce the three parts of bridge structural health monitoring, drive-by technique and wavelet transform, and systematically summarize and summarize the literature related to driving monitoring based on wavelet analysis for detecting local damage of bridges to fill the existing research gaps.

Keywords: wavelet-based analysis; monitoring; bridge structural

Introduction

According to the latest data, more than 11% of bridges in the USA are structurally deficient. Most European bridges have been in place for 60 to 80 years[1]. Seventy-two percent of Australia's bridge transportation network was built before 1976[2]. In Japan, the bridge in- frastructure was developed between 1955 and 1975. As bridges are generally designed to last 100 years, it is expected that many bridges will suffer severe deterioration defects within the next decade[3]. In addition to ageing problems, there are defects in bridges' design and construction process. It includes overloading during service, environmental corrosion, material deterioration problems, and the effects of unexpected events such as typhoons and earthquakes that can lead to suboptimal performance or even complete collapse of the bridge structure[4]. Therefore, effective health monitoring of bridge structures to prevent bridge failures and collapses is quite urgent and essential.

This technique first proposed by Yang et al.[5, 6] is mainly based on extracting the bridge structure's dynamic characteristics from the passing vehicle's dynamic response, and then using the fast Fourier transform (FFT) to derive the bridge frequency from the dynamic response of the passing vehicle. Yang, Chang[7] and Lin, Yang[8] verified the practicality of this technique through instrumented vehicle crossing experiments. Yang et al.[9] combined both Hilbert transform and band filter techniques to construct bridge modal vibration patterns from passing vehicles successfully, finding that indirect measurements from the inspection vehicle provided better screening of bridge degrees of freedom than direct measurements from sensors mounted on the bridge structure[10].

Recent studies have shown that the acceleration spectrum is dominated by the vehicle response when the roughness of the road surface is considered, a situation where it is difficult to obtain accurate bridge frequencies. Therefore, Lin and Yang[8] and Fujino et al. proposed that lower vehicle speeds can lead to higher bridge frequency accuracy due to the higher spectral resolution and the lower influence of the road surface profile on the vehicle response.

The wavelet transform is a robust signal processing tool that has the ability to localise bridge damage due to its sensitivity to discontinuities in the signal. Khorram et al.[11] successfully estimated the damage location in a numerically simulated beam subjected to kinematic forces using a damage detection method based on the wavelet transform. Poudel et al.[12], Shahsavari et al.[13] used wavelet transforms with modal vibration difference functions for the theoretical localisation of structural damage in bridges.

In recent years, many researchers have attempted to apply wavelet analysis to drive-by inspection techniques to locate local damage in bridges, and some results have been achieved. However, there is a lack of systematic reviews in this area, so this paper will review the literature to fill the research gap.

Structural health monitoring(SHM)

Concepts of SHM

Structural health monitoring (SHM) in bridges involves the use of sensors, sensors data processing techniques, and other technologies to continuously monitor the structural performance and integrity of a bridge[14]. The goal of SHM is to detect, diagnose, and predict the evolution of damage and deterioration in a bridge in order to prevent failures and ensure the safety and reliability of the structure. SHM can be used to monitor various aspects of a bridge's performance, including its structural response to loads, material properties, and environmental conditions. By continuously collecting and analyzing data from sensors, SHM can provide early warning of potential problems and allow for timely repairs or maintenance to be carried out, ultimately extending the service life of the bridge and ensuring its continued safe operation[15].

There are various types of sensors and monitoring techniques that can be used in SHM for bridges. These can include sensors that measure strain, displacement, temperature, acceleration, and other physical quantities[16-18]. In addition, non-destructive testing techniques such as ultrasonic testing, infrared thermography, and corrosion monitoring can be used to detect and assess damage and deterioration in the structure.

SHM systems can be designed to be either online or offline. Online SHM systems continuously collect and process data in real-time, allowing for the immediate detection of any abnormalities or changes in the structure. Offline SHM systems, on the other hand, store data for later analysis, allowing for more detailed and comprehensive assessments of the structure's performance over time[18].

Overall, the use of SHM in bridges can provide valuable insights into the condition and performance of the structure, allowing for timely repairs and maintenance to be carried out and helping to ensure the safety and reliability of the bridge[19].

SHM in bridges

Effective bridge health monitoring systems have been commonly installed and operated around the world for many large-span bridges, where data are collected through sensors installed on the bridge, and the corresponding data processing methods are applied to the data to assess whether the bridge is in proper service condition[20]. However, some short to medium span bridges between 15m and 50m are numerous and represent a large proportion of the bridge network. Still, these bridges are often not well maintained because local authorities do not have sufficient funds for maintenance[21, 22]. The safety and stability of the bridge structure during service are closely related to the safety of people's lives and the rapid development of the social economy. Therefore, a bridge structural health monitoring (SHM) tool with fast and cost-effective operation is urgently needed.

SHM techniques can be divided into direct and indirect methods. The direct process generally involves installing many sensors on the bridge to monitor the dynamic response to identifying the bridge's dynamic characteristics [23]. This method can effectively obtain relevant information on the current bridge health condition[24], but it is not widely used. This is because it is impractical to deploy a dense network of sensors on a bridge to obtain large amounts of data with limited budgetary investment[25] and because the short lifetime of such electronic systems compared to the lifetime of the bridge structure implies high costs for the maintenance of the data acquisition system. Another disadvantage is that, when equipped with a fixed monitoring system, the sensing devices generate lots of data in real time, which is a complex problem to solve[26].

Drive-by techniques

Drive-by techniques conception

Indirect bridge monitoring, also known as drive-by bridge inspection, is a method for evaluating the condition of bridges that has gained widespread popularity among researchers[5]. This method, first proposed by Yang et al. in 2004, involves the use of one or a few vibration sensors on a test vehicle to assess the characteristics of a bridge based on the vehicle's response while passing over it. It is considered a more practical and cost-effective alternative to the direct method, which is often costly and short-lived. One of the main advantages of drive-by bridge inspection is its mobility, which allows for the assessment of multiple bridges in a single trip. It is also a convenient and efficient method for monitoring the condition of bridges over time.

Drive-by bridge inspection is a commonly studied method for evaluating the condition of bridges. It involves the use of one or a few vibration sensors on a test vehicle to identify the characteristics of a bridge based on the vehicle's response while passing over it[5, 26]. Instead of requiring the installation of numerous complex sensors on the bridge itself, this method utilizes the interaction between the moving vehicle and the vibrating bridge, known as the coupling effect. Researchers in this field have been particularly interested in modal identification techniques to determine frequencies, vibration patterns, and damping ratios, as well as damage detection methods for identifying local damage through various means[26]. Overall, drive-by bridge inspection has the potential to provide a convenient and cost-effective alternative to traditional bridge monitoring methods.

To further enhance the accuracy and effectiveness of drive-by bridge inspection, researchers have also explored the use of machine learning techniques and advanced signal processing methods. For example, some studies have used artificial neural networks to analyze the collected data and identify patterns that may indicate damage or other issues with the bridge. Other researchers have employed techniques such as wavelet analysis and frequency domain analysis to improve the accuracy of modal identification and damage detection. Additionally, there have been efforts to combine drive-by bridge inspection with other monitoring techniques, such as structural health monitoring, to provide a more comprehensive assessment of bridge condition[27]. Overall, the use of advanced techniques and technologies has the potential to greatly improve the accuracy and effectiveness of drive-by bridge inspection in identifying and addressing issues with bridge infrastructure.

History of drive-by monitoring system

Kawatani and Kim[28] introduced a new approach to bridge health monitoring in 2010, specifically for short-span bridges. Their approach involves using a vehicle to drive over the bridge to assess its condition. The paper described two methods in detail: using inspection vehicles to identify bridge damage and using modal parameters to effectively identify anomalies in the bridge. This approach, known as a drive-by bridge health monitoring system, offers a convenient and efficient way to assess the condition of short-span bridges.

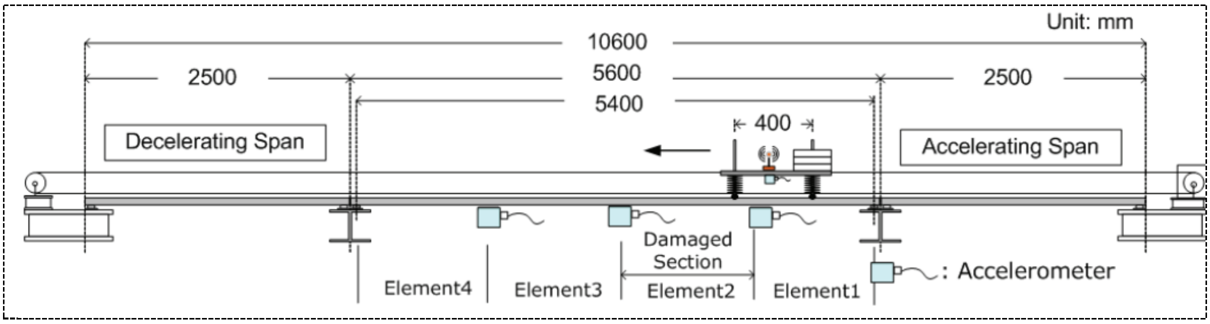

Figure 1. *Experimental configurations for a drive-by bridge health monitoring system[28].*

In 2011 Kim et al. proposed three driving bridge inspection methods for short-span bridges depending on the data collected and analysed: (a) using vehicle vibration data; (b) using bridge vibration data, and (c) combining both vehicle vibration data and bridge vibration data. The reasonable application of the above three methods can effectively solve the problem of lack of effective stimulation during the health inspection of small-span bridges.

In 2014, Kim and his colleagues used an instrumentation vehicle to collect data on a bridge's inherent frequency and structural damping in order to determine its health[21]. By identifying relevant dynamic parameters, they were able to assess the bridge's condition. The feasibility of this method was verified through laboratory experiments. This approach allows for the convenient and efficient collection of data to assess the health of a bridge using an instrumentation vehicle.

In 2014, McGetrick and Kim[29] developed a method for monitoring bridge safety using wavelet analysis. To test its effectiveness, they conducted laboratory experiments using accelerometry-mounted cars under various conditions, including different bridge models, speeds, road conditions, and other variables. The results of these experiments were used to evaluate the ability of damage detection vehicles to detect changes in bridges using acceleration equipment. This approach offers a promising method for monitoring the safety of bridges using wavelet analysis and acceleration equipment.

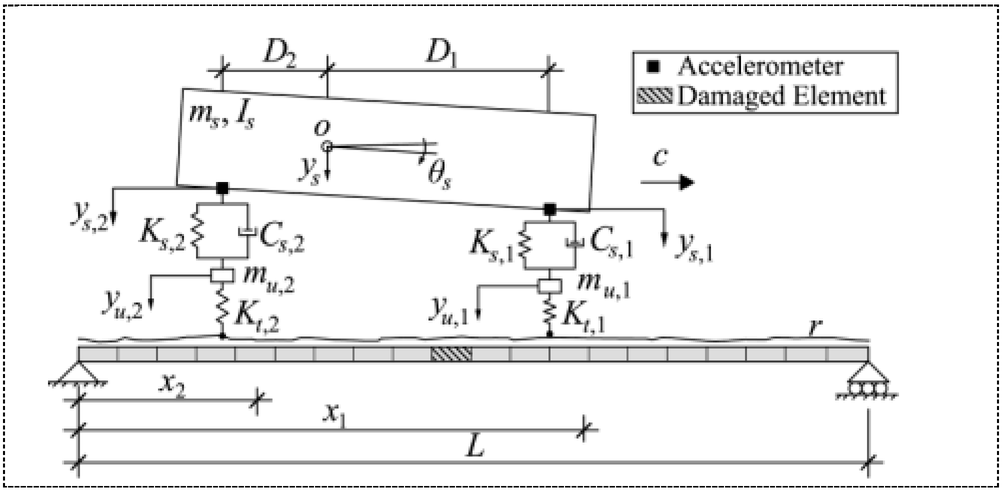

Figure 2. *Illustration of the experimental setup for a drive-by bridge health monitoring system using wavelet analysis[29]*

In 2020, Aloisio and his team introduced a new approach to assessing the condition of bridges using a vehicle testing system equipped with a laser sensor pendulum[30]. This system is capable of providing more accurate data compared to traditional instrumented vehicle methods and can be used to analyze the bending stiffness of supported beams. The use of laser sensor technology in this system allows for a more precise and accurate assessment of a bridge's condition, making it a valuable tool for bridge health monitoring. This approach has the potential to significantly improve the accuracy and efficiency of bridge condition assessments, helping to ensure the safety and stability of bridges.

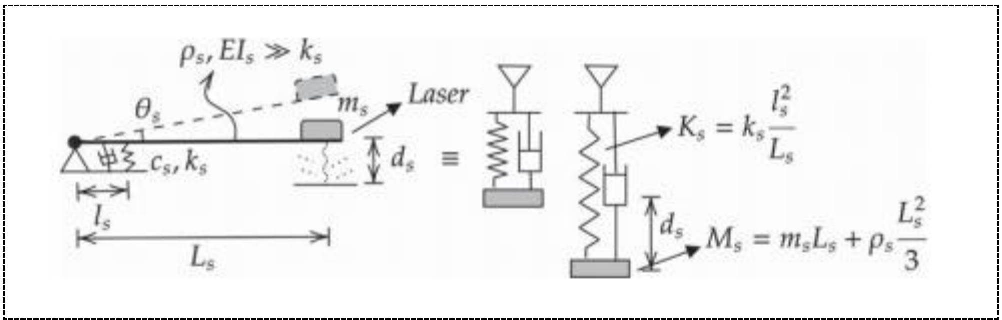

Figure 3. *Laser sensor pendulum[30]*

The drive-by bridge monitoring system has been the subject of extensive research in recent years due to its potential to provide a cost-effective and efficient method for evaluating the condition of bridges[31]. This system involves the use of a vehicle to collect data about a bridge's condition as it drives over it, which can then be analyzed to determine the bridge's serviceability.

There are several approaches to this system, including the identification of bridge damage by inspection vehicles and the use of modal parameters to identify anomalies in the bridge[1]. These methods have been tested in the laboratory and have shown promising results for assessing bridge condition.

Overall, the development of the drive-by bridge monitoring system represents a significant advancement in the field of structural health monitoring, offering a quick and cost-effective way to evaluate the condition of bridges and ensure their safety and stability[11].

Wavelet transform

As a time-frequency domain method, the wavelet transform is mainly used for modal parameter identification in the absence of a known excitation signal, which means that only the excitation of the structure by the ambient random vibration is analysed. This section describes the development of wavelet transform theory and how researchers have applied it to bridge damage identification.

Wavelet transform theory

The evolution of wavelet transform theory can be divided into three phases: (a) the period of independent application, (b) the period of rapid development and popularisation, and (c) the period of full-scale application.

The period of independent applications. The orthogonal wavelet basis proposed by Haar in 1910 can be regarded as the originator of wavelet analysis theory. Still, the first introduction of the concept of wavelet analysis can be traced back to French geophysicist Morlet in the analysis of seismic signals in 1984. Morlet and Grossmann introduced time-scale wavelets to analyse and process geological data. They also named this wavelet as Grossmann-Morlet wavelet. In their research, Morlet discovered that the contradiction between the time and frequency resolution of the short-time Fourier transform meant that the window width should automatically adjust to the variation of the non-stationary signal to form wavelets.

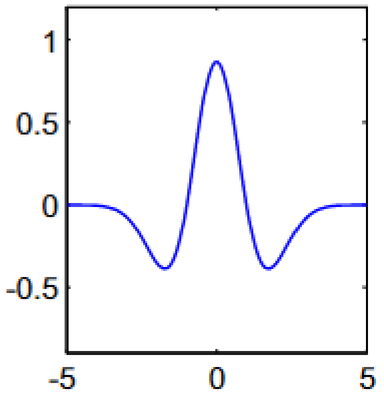

Figure 4. *Mexican Hat wavelet[32]*

In his "over-zero" theory, the famous "Mexican Hat" wavelet was also proposed by the renowned computer vision expert Marr as a filter that could vary according to "scale". Marr’s pioneering work on the "Mexican hat" wavelet inspired Mallat’s work on "multi-scale analysis" or "multi-resolution analysis", and this part of his research became the basis for the orthogonal wavelet[33]. This research became a central part of the theory of orthogonal wavelet construction. During this first development phase, researchers and engineers in various fields independently and intellectually developed ’wavelets’ to meet their needs in their respective fields. From a microscopic point of view, although it appears that they only use wavelets in particular configurations for specific problems in certain areas of scientific research[34], from a macroscopic point of view, many scientific studies and applications in various fields of research are being advanced by these specialists and engineers, and this heralds the next period of rapid development of wavelet analysis theory research and applications.

Since its inception, the use of wavelets has expanded beyond the fields of computer vision and image processing where it was initially developed[35]. Today, wavelets are used in a wide range of scientific and engineering applications, including signal and data processing, medical imaging, geophysics, and financial analysis.

One of the key advantages of wavelets is their ability to represent both local and global features of a signal or data set. This is achieved through the use of wavelet bases, which are sets of wavelets that can be used to represent any signal or data set with a given level of accuracy[31]. The wavelet basis can be chosen to match the characteristics of the signal or data, allowing for efficient and effective analysis.

In addition, wavelets are well-suited for analyzing data with non-stationary and transient features, as they can adapt to the changing characteristics of the data over time[36]. This makes them particularly useful for analyzing signals and data in fields such as engineering and finance, where data can exhibit complex and dynamic behavior[27].

Overall, wavelets have become an important tool in a variety of scientific and engineering applications, and their use is expected to continue to grow in the coming years.

The period of rapid development and popularity. In 1986 the French mathematician Meyer succeeded in developing a smoothing function with specific decay properties[37]. A binary scale stretching and multiple translations of the binary integral were performed to obtain the orthogonal basis of the 4-parametric function space, a well-known system of functions.

Meyer and the computer scientist Mallat developed the concept of multi-resolution analysis. They successfully integrated various methods for constructing wavelets based on the work of Stromberg, Meyer, Lemarie and Battle.

At the same time, Mallat also developed a discrete wavelet numerical algorithm based on multi-resolution analysis, which he used for the decomposition and reconstruction of digital images, the famous Mallat decomposition and synthesis algorithm. In almost the same period, the Belgian mathematician Daubechies constructed orthogonal wavelet bases and finitely supported symmetric double orthogonal wavelets based on polynomial methods. Cui and Wang developed single orthogonal wavelet functions based on spline functions. They also carried out discussions about strategies for constructing scale functions and wavelet functions with optimal localisation properties.

In the second stage of development, marked by Meyer’s successful development of orthogonal bases for 4-parametric function spaces, wavelet analysis theory formally entered a phase of rapid growth and large-scale popularisation, which also heralded the next step of complete application of wavelet analysis theory in various fields of scientific research and engineering.

The period of full-scale applications. After the second phase of wavelet analysis, Mallat decomposition and reconstruction algorithms for digital signals and digital images have been refined, validated and confirmed by researchers in the field[6]. From 1992 to the present, applications concerning wavelet analysis have also spread rapidly in almost all areas of scientific research and applied research in engineering and technology. This means that wavelet analysis has entered its third full-scale application phase.

The wavelet transform is a powerful mathematical tool that is widely used in various fields of scientific research, including signal analysis, image processing, speech recognition, seismic survey, electromagnetic field, machinery fault diagnosis and monitoring, numerical analysis, and bridge health monitoring[38]. It is a multi-scale analysis tool that can highlight specific aspects of the research problem being studied and is particularly useful for the analysis and processing of non-stationary signals.

One of the key features of the wavelet transform is its time-frequency analysis capability, which allows for the acquisition of local characteristics of signals in the time-frequency domain[39]. This makes it an attractive alternative to the traditional Fourier transform, which does not have the same level of time resolution for different frequency components. The ability of the wavelet transform to provide varying time resolutions for different frequency components is what sets it apart and makes it a valuable tool for many different applications.

As research continues to advance, the use of wavelet analysis is expected to expand even further, with new applications being developed and implemented in a variety of fields. Its versatility and effectiveness have made it a popular choice for many different types of research and analysis, and it is likely to continue to be a valuable tool in the years ahead.

Using wavelet transform theory for identifying bridge damage

The use of wavelet transform for structural damage detection is based on the idea that sudden changes in a signal can indicate the presence of damage in a monitored bridge[40]. When a bridge is subjected to an abrupt change, such as damage, the wavelet transform can effectively analyze and extract transient features, such as signal singularities, due to its strong time-frequency localization properties. This allows for the quick identification of the location of damage based on the spatial distribution of the signal.

One popular research area in this field involves combining wavelet transform and dynamic load analysis to identify structural damage[41]. This approach involves using the wavelet transform to analyze the dynamic response of a structure under multi-scale moving loads, extracting relevant feature information from the transform results, and comparing it to the original signals to identify singular features that may indicate the presence of damage. This approach offers a powerful tool for identifying damage in structures by combining the time-frequency localization capabilities of the wavelet transform with dynamic load analysis.

There are several advantages to using wavelet transform for structural damage detection. One of the main benefits is its ability to provide strong time-frequency localization, which allows for the quick identification of damage based on the spatial distribution of the signal. This is particularly useful for structures, such as bridges, where the location of damage can be critical for determining the appropriate repair or remediation measures.

Another advantage of wavelet transform is its ability to analyze non-stationary signals, which are commonly encountered in structural health monitoring. Bridges are subjected to a wide range of external forces, such as wind, traffic, and earthquakes, which can cause their movements and vibrations to vary significantly over time. Traditional methods of signal analysis, such as the Fourier transform, are not well-suited to handling non-stationary signals, as they assume that the signal is stationary. In contrast, wavelet transform is specifically designed to handle non-stationary signals and can provide valuable insights into the dynamic behavior of a structure.

Based on previous research, three main methods of applying wavelet transform in structural damage identification are described below: (a) variation of wavelet coefficients; (b) singularities in the time domain signal; (c) energy variation after wavelet decomposition.

Variation of wavelet coefficients. Structural damage detection using the wavelet transform is a method for identifying changes in a structure that may indicate the presence of damage[5]. This approach involves applying the wavelet transform to the dynamic response signal of a structure to obtain the time and frequency domain curves of the corresponding wavelet coefficients. These coefficients change when the structure is damaged, and by comparing the time-frequency curves of the wavelet coefficients before and after the damage, it is possible to identify any changes that may indicate the presence of damage[41]. This method is based on the principle that the wavelet transform is an effective tool for analyzing the dynamic response of a structure and identifying changes that may indicate the presence of damage. It can be a valuable tool for ensuring the safety and stability of structures such as bridges, and can help to protect the lives and well-being of those who rely on these structures[34].

One of the main benefits of using the wavelet transform for structural damage detection is its ability to accurately identify changes in the dynamic response of a structure at different scales[32]. The wavelet transform decomposes a signal into different frequency bands, allowing for the analysis of changes at different scales[38]. This can be particularly useful for identifying small, local changes in the structure that may not be detectable using other methods.

Another advantage of this approach is its ability to accurately identify changes in the time domain as well as the frequency domain. By analyzing the time-frequency curves of the wavelet coefficients, it is possible to detect changes in the structure's response over time, which can provide valuable information about the progression of damage[14].

Overall, the use of the wavelet transform for structural damage detection offers a powerful and accurate method for identifying changes in the dynamic response of a structure that may indicate the presence of damage[3]. It can be a valuable tool for ensuring the safety and stability of structures, and can help to protect the lives and well-being of those who rely on these structures..

Singularity in time-domain signals. Structural damage can significantly alter the dynamic behavior of a structure, causing changes in its intrinsic frequency and local stiffness that can be detected through the appearance of singularities in its dynamic response signal[42]. These abrupt changes in the regional characteristics of the signal can be identified by applying the wavelet transform to the time domain signal before and after damage. The wavelet transform is particularly useful for this purpose because it allows for the analysis of higher harmonics, sub-harmonics, and chaos in the signal, which can provide valuable insights into the dynamic characteristics of the structure. By analyzing these characteristics, it is possible to identify the location of singularities and determine the presence of damage in the structure[30].

One of the key challenges in using the wavelet transform for structural damage detection is selecting the appropriate wavelet function and decomposition level. The wavelet function used and the level of decomposition can have a significant impact on the accuracy and effectiveness of the analysis. It is therefore important to carefully consider these factors in order to ensure the most accurate and reliable results.

In addition to selecting the appropriate wavelet function and decomposition level, it is also important to consider the noise present in the signal. Noise can significantly impact the accuracy of the wavelet transform analysis[16], and it is necessary to take steps to minimize its influence on the results. This can involve using signal processing techniques such as filtering to remove unwanted noise from the signal[33].

Overall, the wavelet transform is a powerful tool for detecting structural damage, as it allows for the analysis of the dynamic response of a structure and the identification of singularities that may indicate the presence of damage[32]. By using this approach, it is possible to ensure the safety and stability of structures and protect the lives and well-being of those who rely on them.

Change in energy after decomposition. The wavelet packet decomposition of a structural dynamic response signal is a useful tool for identifying damage in a structure. This process allows for the easy calculation of the system's dynamic response wavelet packet energy spectrum, which represents the energy distribution of the signal across different frequency bands. When damage occurs to the structure, it can alter the energy distribution of the dynamic response signal, leading to changes in the wavelet packet energy spectrum. By comparing the energy distribution of each frequency band before and after damage, it is possible to effectively identify cracks or other abnormalities in the system[26].

Wavelet packet decomposition is an effective method for detecting damage in structures, particularly bridges, due to its ability to evenly distribute noise signals across frequency bands[38]. By increasing the number of layers in the decomposition process, it is possible to more clearly identify changes in the energy spectrum, which can aid in the identification of damage. This can improve the accuracy of the damage detection process and ensure the safety and stability of the structure for those who rely on it. Another advantage of using wavelet packet decomposition for damage detection is its ability to analyze the dynamic response signal of a structure at different frequency bands. This allows for a more detailed analysis of the structure's response to external loads and can help identify subtle changes that may not be detectable using other methods[23]. In addition, wavelet packet decomposition can be used to identify the location and extent of damage, as well as the type of damage that has occurred. This information can be used to prioritize repairs and maintenance, ensuring that the structure is maintained in a safe and functional condition. Overall, the use of wavelet packet decomposition in damage detection can greatly improve the efficiency and effectiveness of structural analysis and maintenance[26].

Conclusion

This paper summarizes and concludes the literature on wavelet analysis-based drive-by monitoring to detect localized damage in bridges. The bridge structural health monitoring, drive-by technique and wavelet transform are mainly introduced. The following conclusions can be obtained.

- Drive-by bridge monitoring is cheaper and applicable to a large number of bridges compared to traditional bridge health monitoring techniques
- The history of wavelet transform theory can be roughly divided into three periods: the independent application period, the rapid development and popularization period, and the full-scale application period.
- The methods of applying wavelet transform in structural damage identification mainly include the change of wavelet coefficients, the connection of singularity in the time domain signal and the energy change after wavelet decomposition.

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