Development of Vibration Base Health Monitoring in Bridge

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Abstract. Vibration-based health monitoring uses non-destructive sensing technology to monitor and analyze changes in structural characteristics in time, frequency, or modal domains. The optimization of this system has always been the focus of the research community. Structural monitoring systems can start monitoring from building construction to destruction. It includes many kinds of methods and issues in different structure. This paper reviews the method of bridge structure damage identification based on vibration measurement that has been verified by the test. The use of the vibration excitation method is discussed, as well as the main issues currently. Structural monitoring systems determine that which and where damage is present in the structure, even the prediction of the remaining service life of the structure. In the field of civil engineering, structural monitoring systems have the potential to reduce economic losses and maintain modern infrastructure, even it may obvious geological changes to present disasters in the future.

1. Introduction
Bridge structure damage monitoring can generally be divided into overall detection and partial detection. Local inspection mainly includes visual inspection, dyeing method, rebound method, ultrasonic pulse method, radiation method, magnetic field perturbation method and other physical methods of non-destructive flaw detection. This type of method is relatively mature and can detect and quantitatively analyze structural defects more accurately. However, such methods need to know the approximate location of damage in advance, and the inspection team needs to have a good understanding of the structure of the entire structure and the location where damage is likely to occur. In addition, many parts of the structure are difficult to detect with the above methods. The overall monitoring method is currently measuring structural vibration signals, establishing structural vibration modal analysis and parameter identification. It does not require large-scale loading equipment, does not affect the normal operation of the bridge, can be continuously or intermittently detected, and can even be automatically monitored all-weather. It has become a hot topic in this research field in the past two decades. The basic principle of this kind of bridge structure damage monitoring method based on vibration measurement is that the dynamic characteristics of structural vibration (natural frequency, modal shape, modal damping ratio, etc.) are a function of the physical characteristics of the structure (mass, stiffness, damping, etc.). Therefore, the occurrence of cracks in the structural part or the looseness of the connecting parts will cause the structural stiffness to decrease, which will cause detectable changes in the frequency response function and modal characteristic parameters. The changes of them and their derived quantities can be used as characteristic indicators of structural
damage, and the vibration-based damage diagnosis process is finally simplified to some form of pattern recognition problem.

Due to the various challenges brought by different structures and systems, various technologies and new methods are applied to the condition monitoring system. Rytter [1] classified the various methods based on the level of identification attempted:

- Level 1: Determination that damage is present in the structure
- Level 2: Determination of the geometric location of the damage
- Level 3: Quantification of the severity of the damage
- Level 4: Prediction of the remaining service life of the structure

At present, the bridge structure damage monitoring method based on vibration measurement mainly provides damage identification at level 1 and level 2 without using the structural analysis calculation model. Under the condition of using the structural analysis model, level 3 can be given for some structure types. Level 4 prediction usually also involves fracture mechanics, fatigue life analysis, etc., so it is not in the scope of the review. In addition, methods based on structural nonlinear vibration response analysis or non-parametric models (such as neural network-based methods) will not be discussed in this article.

2. Vibration excitation method for damage identification of bridge structure

When testing the dynamic characteristics of the bridge's vibration, it is first necessary to have the external environment or artificial application to stimulate the vibration response of the bridge structure on site. The artificial vibration method is the same as that used in the bridge dynamic load test. Manual excitation includes two methods: sudden loading and sudden unloading. The sudden loading method is to rapidly apply a force on the structure under test. For example, in the field test, the sudden drop of the rear wheel of the test vehicle from the triangular pad has an impact on the bridge and arouses the vertical vibration of the bridge. When testing a certain component (such as a cable), the method of percussion with a wooden hammer is often used. The sudden unloading method is to load on the structure to cause the structure to produce a displacement, then suddenly removing the load and using the elasticity of the structure to make it vibrate freely. This kind of method is convenient to change the point of action and can generate broadband vibration.

Using a special excitation device, such as a vibration exciter, to apply an excitation force to the bridge structure can cause the structure to vibrate. For the prototype bridge structure, vehicles passing the bridge at different speeds can cause the bridge to produce varying degrees of vibration. For example, a ten-ton test vehicle is used to conduct vibration tests at speeds of 20, 40, 60, and 80km/h.

Engineers can evaluate the future state of the bridge by analyzing the vibration response under the environment (wind load, ground motion, vehicle excitation, etc.) under the actual use environment. For large bridges, it is one of the most feasible ways to excite vibration. It has the characteristics of good economic management, high safety, and does not affect the operation of the bridge. The test data of structure dynamic response measured under natural environmental vibration conditions are nonlinear, small amplitude, strong randomness and huge data capacity. However, the inability to grasp the range of the excitation frequency band brings great difficulty to the identification of structural systems, and it is also an interesting topic in the current research field.

3. Vibration measurement method for damage identification of bridge structure

The use of modal curvature in damage identification is based on the assumption that the change of modal curvature is highly confined to the damaged area. Compared with the change of modal displacement, the change of modal curvature is more obvious although Alampalli et al. [2] showed that this is not necessarily the case, especially for structures with large redundancy.

Rathcliffe and Bagaria [3] used the gap smoothing method to successfully locate the delamination in an experimental composite beam. They first used the Laplace difference equation to convert the displacement mode shape to the curvature shape. Then at each point, a polynomial with gaps is used to
locally smooth the curvature shape. The damage index is the difference between the curvature and the polynomial at each point. The largest index is the hierarchical position.

Wahab and De Roeck [4] successfully applied the curvature-based method to the Z24 bridge in Switzerland (picture 1). They introduced a curvature damage factor CDF, which is the curvature difference before and after the average damage in multiple modes. They concluded that it is feasible to use modal curvature to locate damage in civil engineering structures. Wahab [5] used the simulated beam curvature shape in the sensitivity-based model update algorithm to identify damage. Although the curvature is more sensitive to damage than the modal displacement shape, the convergence cannot be improved by adding modal curvature.

Figure 1. Z24 Bridge benchmark – Structural Mechanics bwk.kuleuven.be

It is assumed that structural damage only reduces the structural rigidity and does not affect the structural quality. Through the numerical simulation of the simply supported beam, it is believed that the modal curvature of the structure before and after the damage will undergo abrupt changes at the damage location, and the magnitude of the abrupt change is proportional to the damage degree. This is because the curvature of the beam is inversely proportional to its bending stiffness. When the structure is damaged, the rigidity of the structure at the damage site will decrease, and the curvature here will increase, causing the curvature of the mode shape curve to increase. From the measured displacement modes before and after the damage, the curvature of the modes can be calculated numerically. Therefore, the change of the curvature mode can reflect the change of the local damage of the structure. For local structures, it can be used to determine the occurrence and location of structural damage, which is an ideal damage identification.

The displacement mode reflects the natural vibration form of the complex structure and represents its inherent energy balance form. Strain is the first derivative of displacement, and corresponding to each displacement mode, there must be a corresponding inherent strain distribution state. This inherent strain distribution state corresponding to the displacement mode is called the strain mode. Similar to the displacement mode, the strain mode reflects the inherent characteristics of the structure. When a structure is damaged, its equilibrium state will change. This change can be obtained by measuring the strain mode of the structure before and after the damage. The internal force redistribution reflects the size of the damage. Since the internal force redistribution is the largest near the damage, the damage location can be determined according to the drastic changes in the strain mode. The strain mode is very sensitive to the local changes of the structure, such as cracks, and is more conducive to the detection of structural damage. The strain-based damage location method is better than the displacement-based damage location method.

The number of modal curvatures available in the damage identification routine is limited by the number of available displacement mode shapes. To increase the amount of data that can be input into the damage recognition program, Sampaio et al. [6] applied the curvature method to all frequencies within the measurement range by using FRF data. The method was tested by using data from
deliberately damaged bridges and found that this method is most suitable for the data before the first resonance or anti-resonance, and found that its performance is higher than the curvature method. Therefore, the method needs to be further developed to better quantify and characterize damage. For multi-degree-of-freedom systems, the flexibility matrix and the stiffness matrix are reciprocal. Therefore, the flexibility matrix is related to the static load and displacement response of the structure. From the moment of stiffness, each column of the flexibility matrix represents the displacement change of each degree of freedom of the structure under the action of unit load. The damage identification method based on the change of the flexibility matrix is to compare the difference of the flexibility matrix before and after the structural damage to carry out the damage identification. The damage location can be located by the change of the flexibility matrix and the corresponding stiffness matrix. Patjawit and Nukulchai gave an overall flexibility index to infer the deterioration of the health of highway bridges. The physical relationship between stiffness and mass change and natural frequency change, as well as easy measurement of natural frequency, is the key to identify damage using modal methods [7]. There is a question about the effectiveness of using changes in natural frequencies and it is to indicate structural damage. The first four frequencies of the steel trough did not show a deviation of more than 5%, because a single notch was severe enough to cause the trough to fail under its design load. Given that it is recognized that frequency changes caused by accidental/environmental vibrations and environmental influences can be as high as 5-10%, they believe that lower frequency deviations are not necessarily a useful indicator of damage. The tests carried out on the I-40 bridge [8] and the T-beam slab deck [9,10] all support this conclusion. When the cross-sectional stiffness of the center of the main girder on the I-40 bridge is reduced by 96.4%, and the flexural stiffness of the entire bridge section is reduced by 21%, the modal frequency is not significantly reduced. Nevertheless, researchers still support the use of modal frequency shift for damage identification. De Roeck et al. [11] Monitored the Z24 bridge in Switzerland over a period of one year. After monitoring the impact of air temperature, humidity, rain, wind speed and wind direction on the environment and readings from 16 accelerometers per hour, new conclusions can be drawn according to the damage test procedure. Once the environmental impact is filtered out, if the corresponding frequency shift is greater than 1%, a decrease in stiffness will be detected.

4. Conclusion

A review of the latest technologies in vibration-based condition monitoring reveals numerous methods. These methods use data in the time domain, frequency domain, and flexibility. Generally, there is no consensus in the research community on the best method for damage detection, location or quantification using measured vibration data. However, it is worth noting that the sensitivity and measurability of modal parameter changes caused by local damage are issues between the research community. In addition, in view of the absence of an algorithm for predicting the remaining service life of the structure, the condition monitoring research community still faces the challenge of dealing with the 4-level identification. The identified algorithms also vary in the number of sensors required and the level of damage attempting to identify. Those methods that use data from a large number of sensors, such as those based on residual force vectors, are usually successful. Those methods that rely on a single or a few sensors, such as those based on natural features, are not completely successful. The emergence of statistical pattern recognition techniques seems feasible with few sensors, although the purpose of these pattern recognition techniques is still limited to first-level recognition. In the author's view, the issue of sensor affordability is one of the most important decision-making constraints faced by structural health systems. Optimizing the number and location of sensors to improve work efficiency and finding more effective statistical methods to identify new methods of structural damage is also one of the challenges currently facing the research community.
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