Vibration-based Damage Detection: Identifying the damage in the bridge

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Abstract. This study investigates vibration-based damage detection techniques through controlled experiments on a model bridge. The experiment measured vertical accelerations under various load conditions and structural states to assess how damage influences natural frequencies. Fast Fourier Transform (FFT) analysis was employed to convert time-domain acceleration data into frequency spectra. The results indicate that load magnitude has minimal influence on the bridge’s primary frequency, whereas structural damage—such as cable rupture or mass imbalance—significantly reduces natural frequency. These findings demonstrate that vibration-based analysis provides a simple and effective means for identifying structural damage and assessing bridge safety. Furthermore, this approach offers potential for broader applications in structural health monitoring (SHM) across civil, mechanical, and aerospace engineering. However, limitations related to sensor accuracy, environmental noise, and manual excitation highlight the need for standardized measurement systems and automated excitation methods in future studies.

Keywords: vibration analysis; damage detection; bridge monitoring; Fast Fourier Transform (FFT); structural health monitoring (SHM).

1. Introduction

Four types of methods are classified based on vibration features: mode shape-based methods, curvature mode shape-based methods, natural frequency-based methods, and methods that utilize both mode shape and frequency. Curvature mode shape-based methods and mode shape-based methods are primarily applied to Damage localization. Shape-based methods can locate damage precisely using optimization algorithms or signal processing techniques. Furthermore, damage localization algorithms often rely on curvature mode shape-based methods [1].

For some faults in the early stages, vibration analysis plays a crucial role in detecting issues; this method can save a significant amount of time and reduce the cost of repairs. Due to its convenience and usefulness, it can be applied in various industries, including rotating and non-rotating equipment, continuous processes, and even construction structures. In many areas, transportation, drilling, and production have become essential components in ensuring efficiency.

Although VA plays a significant role in many fields, it still faces challenges in certain applications. The Electric Submersible Pump (ESP) system is a classic example. ESP is located downhole, so its data is easily corrupted, and detection is difficult to achieve. More seriously, pump performance will be severely affected, even if it cannot operate at all.

Frequency-based damage detection techniques have made significant contributions to the field of structural health monitoring. Although the accuracy of the prediction is satisfactory, the measured frequencies still have errors. Due to the unavoidable noise, the frequencies will actually be amplified in the frequency shifts, and damage prediction will be affected. Aims to solve each mode of frequency shift to noise, a novel concept, Noise Response Rate (NRR), is used. Low NRR values could improve the prediction accuracy of frequency-based damage detection. (Pan et al., 2019)

Our team utilizes the Fourier theory, which transforms the vibration signal into a spectrogram and determines the damage by analyzing the frequency changes. This allows us to experiment by knocking on a wooden board to test the vibration frequencies of both the intact and damaged bridges.

Firstly, the bridge is built with a suspension system featuring two piers and is affixed to the center of a large wooden board, which simulates the surrounding area. Then we attached an accelerometer to the middle of the bridge floor. After that, we employed three methods: hammering on the bridge floor, clapping the wooden board, and shaking the wooden board to measure the acceleration, and recorded the data. Finally, we obtained the frequency of each experiment through the Fourier transform and drew the corresponding conclusion. This experiment shows that there is potential to detect bridge damage (especially critical damage, such as cable breakage) by analyzing vibration frequency changes.

2. Literature review

Damage detection of structure by wavelet analysis. Hansang Kim and Hani Melhem introduced the damage identification methods of civil and mechanical structures. Wavelet analysis is a relatively new mathematical and signal processing tool that provides a time－frequency analysis, offering more detailed information about non-stationary signals. This method is applied to various fields, including civil, mechanical, and aerospace engineering, as well as damage detection and structural health monitoring (SHM) [2].

Initially, since the vibration method has a non-invasive nature, it offers highly advanced real-time capability. For example, Structural Health Monitoring (SHM) can be seen as one of the most significant ways to ensure the safety of aging infrastructure. The core of these technologies is the Fourier Transform (FT), which is a mathematical tool that deciphers vibration signals by converting time-domain waveforms into frequency-domain spectra. This transformation reveals several damage characteristics, including resonance frequency shifts, harmonic distortions, and energy redistribution patterns, which are undetectable in the original time-series data [3].

2.1 The fundamental function of the classic FT

Rytter developed the FT, which is the primary method for assessing damage. While analyzing the "spectral energy attenuation rate" in steel bridges, Ritter shows that the cracks over 5% of the structural depth cause the amplitude of the dominant frequency to decrease by more than 15%. This method links spectral anomalies with mechanical degradation, providing the first systematic framework [3]. However, the classical FT has two disadvantages: Assumption for positioning: The required vibration remains constant. It cannot be used for rotating machinery or in cases of transient impacts.

To solve the problem of a non-stationary signal, the Fourier transform (STFT) segments vibrations into windowed frames in the short term. Brada et al. completely altered bearing fault diagnosis through the extraction of instantaneous frequency ridges using STFT. Their approach use a Gaussian window to obtain the transient pulses of the crack population; The tracking grid frequency band in the time-frequency diagram (±2× axis RPM); In the wind turbine gearbox, the fault identification accuracy achieved is 32% higher than that of the traditional FT [4].

However, STFT has the 'Heisenberg uncertainty trade-off' which improves the time resolution at the cost of degraded frequency precision. This increased the high-resolution variants, such as Fourier Synchro Squeezing Transform (FSST). During the FSST, Chen et al. use the FSST to achieve the micrometer-scale damage resolution, which is better than traditional methods, and detected a 0.1 mm fatigue crack missed by STFT on the wing plate of the aircraft. And the local bolt is loose within the error range of 2mm, which is compared to 15mm of STFT. However, Chen also pointed out that the µm-level resolution of FSST depends on a high signal-to-noise ratio (SNR > 10dB) in industrial sites with strong vibration backgrounds (such as SNR < 4dB in a foundry workshop); its performance may deteriorate to the STFT level [5].

Although FSST improves the resolution, spectral contamination from thermal drift causes a barrier in field deployment. Sarmadi addresses this problem using the Fourier-domain environmental compensation method. As Sarmadi demonstrated, the Fourier domain environmental compensation technology essentially resolves the spectral peak temperature drift problem left by Rytter [6]. This problem had long restricted the application of classical FT in outdoor bridge monitoring. Paulo J. S. Cruz and Rolando Salgado used two case studies to evaluate six damage detection methods based on monitoring. Firstly, they get the dynamic simulation and modal parameters from a cracked composite bridge. In the process, various crack depths, damage extension, and noise levels are variables that need to be evaluated for damage detection methods. And then, a reinforced concrete bridge, which was deliberately damaged in two phases, was used to identify damage. In the first case study, damage for all the damage scenarios without noise on vibration parameters could be detected by evaluating the damage detection. In contrast, the second case study employed damage detection methods that do not require comparison between different structural conditions, and these methods successfully identified the location of damage on the bridge [7].

Frizzarin et al. developed a baseline-free. This time-domain damage detection method for concrete structures is based on analysis of nonlinear damping from measured structural vibration responses. They use shaking table tests to apply different levels of seismic damage to a large-scale concrete bridge model, demonstrating the efficacy of the proposed method. Comparing the damage detection results obtained through stiffness-based methods, research indicates that the increase in nonlinear damping and the decrease in structural stiffness associated with increasing damage severity exhibit a strong correlation [8].

This report summarizes the FT from Rytter's foundational spectral to Chen's super-resolution imaging. We quantify the profit of STFT and FSST in industrial cases and then analyze Sarmadi's compensation model. The engineering impact is based on 'Fourier diagnostics [5,6]. Empirical evidence in Texas wind farms shows that sensor optimization deployment based on Fourier diagnosis, under the premise of ensuring equivalent damage resolution, reduces 155 test points to 108 (decrease30.3%) (data source: ERC-2022-SHM-Benchmark)

3. Methodology

3.1 Experiment Setup

The experiment utilized a wooden cable-stayed bridge model, an accelerometer, a paper pouch for securing the sensor, and a wooden plank as the base. The bridge model was first fixed firmly to the plank using a hot glue gun to ensure structural stability during testing. The paper pouch containing the accelerometer was then attached directly beneath the center of the bridge, allowing accurate measurement of vertical acceleration during vibration testing. This configuration provided a controlled and repeatable setup for analyzing how external forces affect the bridge's dynamic response. The final assembled model is shown in Figure 1.

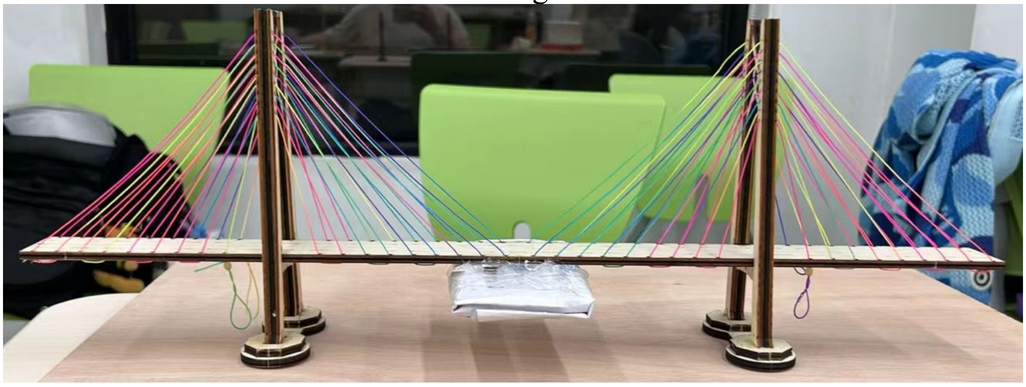

Figure 1. Complete bridge model structure

3.2 Experimental Procedure

The experiment was conducted under three structural conditions to analyze the relationship between damage and vibration characteristics. The first condition served as the Control Group, representing an undamaged bridge. The second and third conditions, referred to as Experiment Group 1 and Experiment Group 2, simulated different forms of structural damage. In Experiment Group 1, a metal block was attached beneath one side of the bridge to create asymmetrical loading. In Experiment Group 2, several cables were intentionally removed to simulate a loss of tension and stiffness. Each configuration is illustrated in Figures 2 and 3.

Prior to testing, the accelerometer was activated and configured with a sampling frequency of 100 Hz to record the bridge's vertical acceleration response. Data were collected continuously during each trial and stored for subsequent analysis.

Two testing scenarios were then performed to simulate realistic external excitations. In the first scenario, deck movement simulation, the bridge deck was gently tapped with a small hammer at the left, center, and right positions, with 5, 10, and 15 impacts respectively, to replicate varying dynamic disturbances. In the second scenario, environmental vibration simulation, the underlying wooden plank was struck ten times and then shaken horizontally for fifteen oscillations to reproduce base motion effects.

The complete testing sequence was first carried out on the Control Group to establish baseline vibration characteristics. Identical procedures were subsequently repeated for Experiment Groups 1 and 2. The collected acceleration data were used to evaluate the effect of structural damage and mass imbalance on the bridge's dynamic response.

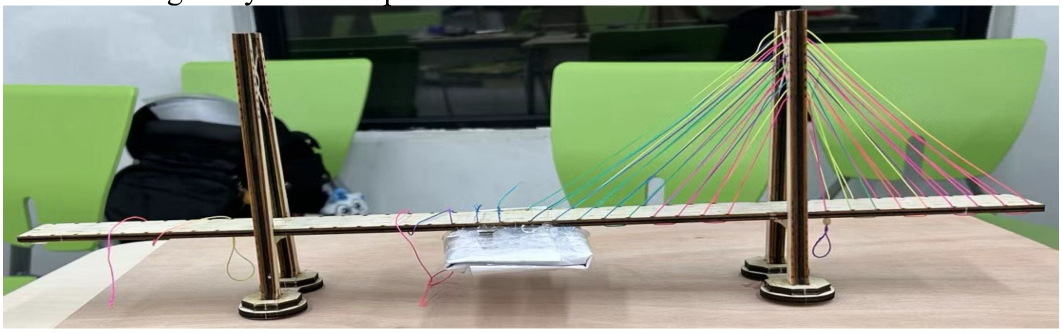

Figure 2. Bridge model under damage

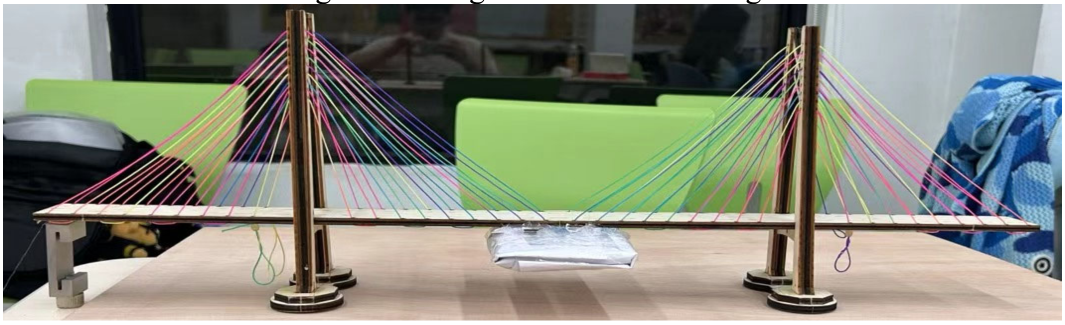

Figure 3. Bridge model with vibration

3.3 Data Processing

The collected acceleration data were first processed using the Fast Fourier Transform (FFT) method to convert time-domain signals into frequency-domain spectra. This transformation allowed the identification of the bridge's characteristic vibration frequencies by analyzing the amplitude distribution across different frequencies. The frequency corresponding to the maximum relative amplitude was recorded as the fundamental or dominant frequency for each test scenario. This approach enabled direct comparison of frequency shifts between undamaged and damaged bridge conditions, providing insight into how structural defects influence dynamic performance.

4. Results

After processing the record vertical acceleration of the bridge using the FFT to convert the time domain to the frequency domain, the main frequency of testing a and b in the control group is plotted in the following graph (Fig. 4). According to the data, the range of the main frequency is from 18Hz to 20Hz.

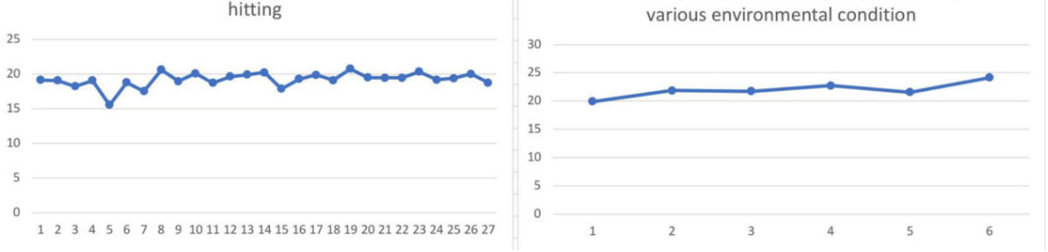

Figure 4. Main vibration frequency of the control group

For the main frequency calculated from the testing experiment group 1, the frequencies have a great decline; the frequency range of Test A is reduced to 13Hz to 16Hz, compared with the range of the control group, and each frequency is plotted in Fig. 5. However, the range of the main frequency in test b is too large to be used in the analysis, which would be negligent in this paper.

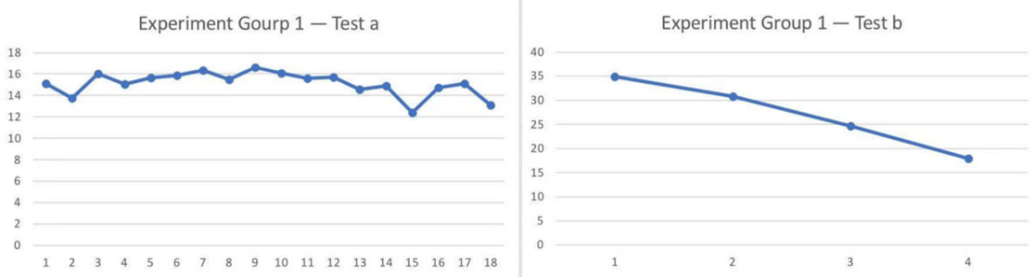

Figure 5. Main vibration frequency of the experiment group in two tests

According to the data of experiment group 2, the main frequencies are plotted in Fig. 6. The range of the main frequency (16Hz~18Hz) is slightly less than the range of the control group, but for the frequency of test b, the range is 14.4Hz to 28.2Hz, which is too wide to be used in this paper.

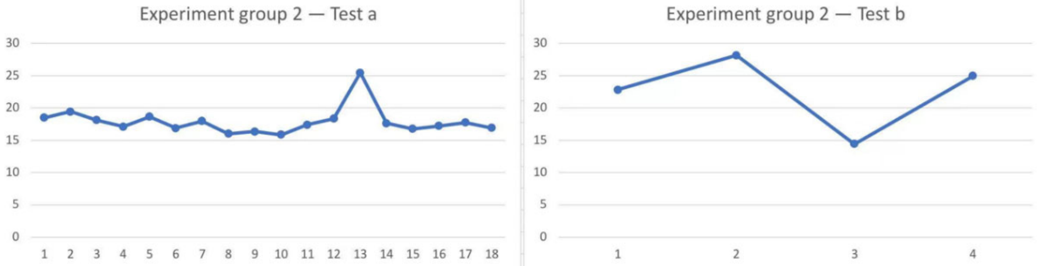

Figure65. Main vibration frequency of the experiment group 2 in two tests

Based on the above experimental results, the damaged bridge has smaller frequencies than the undamaged bridge.

5. Discussion

Considering the limitations of this experiment, there may be some limitations. Firstly, in this experiment, the accelerometer built into the phone was used. The phone was placed in the paper pouch, but there was some space between the pouch and the phone, which would increase the range of the vertical vibration of the phone. As a result, the phone could not vibrate like the bridge vibrates, and this would lead to imprecise data. Additionally, the force and frequency of each group of hits are different. This would generate many random errors during the experiment, which would enlarge the range of frequency. Furthermore, the shaking of a wooden plank could also generate inaccuracies because the force applied to it varied every time.

On the other hand, to make future experiments more accurate and the data more reliable, several areas can be upgraded and improved. One efficient idea is not to let people hold the accelerometer, but to fix it firmly in the middle of the bridge. The reason for doing this is that people hold the instrument in their hands. No matter how stable they are, it is inevitable that there will be some unconscious shaking or hand tremors. This slight action will alter the vibration signal of the bridge itself, which is precisely what we want to measure. By firmly fixing the accelerometer in the key position in the middle of the bridge, it can 'empathize' and truly capture the purest and most realistic vibration state of the bridge, and the measured data will naturally be more accurate and credible.

Another way to significantly improve the quality of the experiment is to refrain from knocking on the bridge with a hammer. Manual operation, even if performed by the same person, is difficult to achieve the same force, angle, and frequency of knocking each time (such as knocking three times in a row; how long is the interval between each knock)? This man-made 'variable' will cause unnecessary fluctuations and errors in the experimental data, and it is difficult to conduct a strict comparative analysis. The solution to this is to use a robotic arm as the 'knocker'. Program the robotic arm to accurately and consistently knock on the designated position of the bridge with the same force every time, while strictly controlling the time interval (frequency) between each knock. That is, robots replace human hands to completely standardize the action of 'knocking'. In this way, the key factor of 'knocking' has become a 'constant' throughout the experimental process.

6. Conclusion

This study mainly focuses on vibration analysis and damage detection of a bridge. Firstly, it is essential to prove that the different magnitudes of load do not affect the main frequency of the bridge. By comparing the collected frequencies of each group, it was determined that this was not the case. From the data analysis, the ranges of a and b for the control group are 18-20Hz and 21-23Hz, respectively. This similar range of frequency suggests that, for different magnitudes of load, the frequency of the bridge does not vary significantly. This trend is also evident in all the experimental groups, further supporting the correctness of this suggestion.

Additionally, this study aims to demonstrate that different types of bridges have their own unique central frequency. From the data analysis, the hammer hitting range is 18-20Hz. In contrast, the frequency range of the control group (16~18Hz and 13 Hz~16.5Hz) differs from that of the experimental group (18~20Hz), suggesting that the frequency range of the undamaged bridge is unique. Therefore, engineers could use a different frequency range to detect the damage to the bridge.

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