Determination Method for Conversion Sampling Frequency of Structural Deflection Monitoring of Small-and Medium-Span Bridges

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Abstract. This paper proposes a method for determining the frequency of interest of static and dynamic deflection responses based on the analysis of components of the deflection deformation of small-and medium-span bridges in service. By analyzing the impact of sampling frequency on the time-domain signal amplitude, this paper determines the maximum sampling frequency limit of undistorted signals, thereby providing reference for the determination of the sampling frequency for the real-time monitoring of the deflection of small-and medium-span bridges.

1. Introduction

Existing bridge health monitoring systems assume that the equifrequent data acquired by the sensor nodes can be used to accurately obtain the true structural deformation status of the bridge. High-frequency sampling can help us to collect the actual deformation of the bridge structure, but it will cause a significant increase in cost and data volume. Low-frequency equifrequent sampling, however, cannot guarantee the retention of key points, resulting in significant errors in the monitoring results and actual data. The structural deformation of the bridge is continuously changing, and equifrequent sampling is just a discrete process of continuous changing deformation. Therefore, there exist problems such as missing key points and curve distortion.

Based on the analysis of the deflection deformation components of the bridge structure in service, this paper divides the frequency period of interest in deflection monitoring, proposes the method for determining the frequency of interest in each period, and analyzes the impact of the sampling frequency on the amplitude. On this basis, this paper puts forward the determination method for the maximum sampling frequency limit of undistorted signals, thereby providing reference for the setting of the conversion sampling frequency for structural deflection monitoring in the bridge health monitoring system.
2. Determination of the limit frequency of interest of dynamic response based on deflection component analysis

The structural deflection of the bridge is an overall response parameter. The performance of the bridge under various loads and environments and the variation of the bridge material can be reflected by deflection. The deflection of the bridge after operation can be categorized into the following types: 1) permanent structural deflection deformation due to internal causes such as concrete shrinkage, creep, and material degradation; 2) deflection deformation caused by component cracking, component spacing connection damage (hinge damage, damage of simple supported-continuous cast-in-situ section; 3) deflection deformation caused by temperature and other effects; 4) deflection deformation caused by vehicle load (including crowd load, etc.). Among the above four aspects of deflection components, the first and second require lower sampling frequency in principle (collecting data in hours or even days can deliver good data results). For temperature-induced deflection deformation, in the general case of non-extreme temperature abrupt changes, the samples are usually taken in the unit between 10 minutes and 1 hour; at the same time, the components of deflection caused by temperature can also be measured. As the vehicle crosses the bridge, its deflection deformation components include the static effect components under the vehicle's own weight load and the dynamic response components under the vehicle vibration. For small-and medium-span bridges, it is necessary to collect data in milliseconds so as to obtain the actual deformation.

The deflection monitoring of the highway bridge structure in service can be divided into two modes according to the characteristics of the monitoring indicators and the types of sensors currently used in this field: ① use dynamic and static displacement sensors (such as magnetostrictive displacement sensor, differential variable-pressure displacement sensor, laser displacement sensor, etc.) to monitor static, quasi-static and dynamic deflection; ② use vibration measurement sensors to test the dynamic deflection of the key parts only.

Generally speaking, the above ① mode can be used for the deflection monitoring of mid- and small-span bridge structures in service; for the long-span bridge structure, the ① mode is often difficult to achieve due to field and economic limitations; therefore, it is feasible to use ② mode supplemented by static test equipment. This research monitors the deflection deformation of small-and medium-span bridge structures. Therefore, the analysis focuses on the frequency limits of static deflection components and dynamic deflection components under the deadweight of vehicles crossing the bridge.

2.1 Division of frequency of interest period for deflection monitoring of small-and medium-span bridges

As shown in Figure 1, the time-history curve of mid-span deflection deformation of a reinforced concrete beam bridge structure under normal operation caused by vehicle load can be divided into three time periods:

① The magnitude of the deflection caused by the vehicle is relatively small (which needs to be determined according to the actual structural parameters). At this point, the structure is in a safe state, during which the data collected is generally not used for warning, but often as a record of deflection. Therefore, the upper limit of the static frequency range can be used as the frequency of interest.

② When there is no operational load on the bridge, then there is no frequency range of interest. Data collection at this stage can be performed with reference to the sampling frequency of the temperature test. When conditions permit, the frequency of interest can be used as the basis of sampling frequency.

③ When there exist possibilities that the part with larger deflection deformation exceeds the warning state, as shown in the time period from 17:48:30 to 17:48:42 in Figure 1, the deflection deformation response frequency of interest shall be determined based on the analysis results of the dynamic deflection spectrum.
2.2 Methods for determining the frequency of interest in each period

Based on the three monitoring frequency periods, it is necessary to decompose the components of the static and dynamic deflections monitored in Figure 1, which can usually be performed using a zero phase difference filtering method.

The low-pass part is the static deflection component under the vehicle's own weight, and the high-pass part is the dynamic deflection component. Then the cut-off frequency of the filter is determined according to the first-order natural vibration frequency of the structure (-3dB is taken for the static deflection separation caused by the vehicle's own weight). Figure 2 shows the results of static and dynamic deflection analysis.

2.3 Methods for determining the frequency of interest of static and dynamic deflection components

The frequency of attention for static and dynamic deflection components can be determined through decomposition of the real-time signal and Fourier transform.

However, it is worth noting that the span of a given bridge structure is fixed and is one of the main factors determining the static component. The other determinant is the speed of the vehicles passing the bridge and the number of vehicles on the bridge. Therefore, it is feasible to select representative traffic conditions during the trial operation of the monitoring system and conduct statistical analysis so as to determine the frequency of interest.

The frequency component of the dynamic deflection is not determined using the upper limit of the natural structural frequency. The frequency component of the dynamic deflection response is often related to the ratio of the excitation frequency to the natural frequency of the vehicles passing the bridge, which is difficult to be made clear using theoretical calculation. However, for most bridge structures under normal circumstances (the vertical natural vibration frequency is not close to the natural frequency of the bridge, and the bridge deck is not seriously uneven), the dynamic deflection response can be basically controlled within the vibration frequency of the first few orders. The specific order can be determined based on the statistical analysis of the typical traffic conditions selected during the trial operation of the monitoring system. Figure 3 is the amplitude spectrum of static and dynamic deflection deformation before separation. Figure 4 is the amplitude spectrum of dynamic deflection deformation.
It can be seen from Figure 3 that for the static deflection caused by the vehicle's own weight, the frequency of interest due to the impact of the vehicle speed and bridge span can be controlled at 0.2686 Hz. From Figure 4, it can be seen that for the dynamic deflection, the frequency component of interest should be at least 3.394 Hz.

3. Principles and methods for determining the deflection frequency of bridge structures

3.1 Principles for determining the maximum sampling conversion frequency

The sampling rate (fs) must be greater than twice the highest frequency (fn) component of the tested signal. This frequency is often called the Nyquist frequency.

\[ f_s > 2 \times f_n \] (1)

If the signal is band-limited and the sampling frequency is greater than twice the signal bandwidth, then the original continuous signal can be completely reconstructed based on the samples. In general, the sampling frequency is guaranteed to be 2.56 to 4 times of the highest signal frequency. The sampling theorem explains the relationship between the sampling frequency and the signal spectrum, which is the basis for the discretization of continuous signals.

The sampling theorem provides the most basic conditions for analog-to-digital conversion. However, under these conditions, the analog signal, even a simple sinusoidal signal waveform, cannot be reconstructed after digitization. Assume there is a certain sinusoidal signal with a frequency of 2.0 Hz and take samples using 3, 5, and 8 times of the signal frequency (6.0 Hz, 10.0 Hz, and 16.0 Hz). The sampling results in Figures 5 to 7 shows that the sampling frequency that only satisfies the sampling theorem is not enough for restoring the waveforms. It is clear that the sampling theorem is the most basic condition to avoid aliasing distortion of the signal in the frequency domain, but not the condition to avoid the distortion of time domain signal.

**Figure 3 Amplitude spectrum of static and dynamic deflection deformation before separation**

**Figure 4 Amplitude spectrum of dynamic deflection deformation**

| a) Sampling frequency: 6.0 Hz | b) Sampling frequency: 10.0 Hz |
|------------------------------|-------------------------------|
| ![a) Sampling frequency: 6.0 Hz](image) | ![b) Sampling frequency: 10.0 Hz](image) |
3.2 Effect of sampling frequency on time-domain signal amplitude

The data in Table 1 is taken from the article "Effect of Sampling Frequency on Amplitude of Vibration Signal" by Professor Zong from Institute of Structural Engineering and Earthquake Protection, Tongji University.

| Frequency band (Hz) | Peak error (%) | Peak error (%) | Maximum error |
|---------------------|----------------|----------------|---------------|
|                     | mean value     | standard deviation |          |
| 20                  | 8.3            | 7.0             | 37.5          |
| 25                  | 7.0            | 6.1             | 28.8          |
| 30                  | 5.3            | 4.8             | 21.4          |
| 40                  | 2.3            | 2.2             | 11.6          |
| 80                  | 0.99           | 0.87            | 3.8           |
| 100                 | 0.62           | 0.59            | 2.7           |

The data in Table 1 shows that when the sampling frequency is 10 times the frequency of interest, the average error of the mean value and standard deviation is less than 1%.

3.3 Determination of the highest sampling frequency for ensuring undistorted signal

It is recommended that the sampling rate shall be at least 5 times the analysis frequency, at which point the average percentage reduction of the maximum peak value of the sampled signal compared to the real peak value can be controlled within 3%. As for the sampling with strict peak requirements, it is still necessary to further increase the sampling rate. When the sampling rate is 8 to 10 times of the analysis frequency, the peak value of the signal is basically close to the real signal peak.

4. Conclusion

Based on the current situation of equifrequent sampling for real-time monitoring of deflection of small- and medium-span bridges in service and the component characteristics of their deflection deformation, this paper puts forward a method for determining the frequency of static and dynamic deflection components. By analyzing the influence of the sampling frequency on the amplitude of time-domain signal, this paper clarifies the range of the maximum sampling frequency limit that ensures undistorted signals, thereby providing reference for the determination of the real-time sampling frequency of the deflection of small-and medium-span bridges.

References

[1] Yulong Ma. (2014) Analysis of vehicle-bridge coupling vibration on highway curved continuous bean bridge[D]. Hunan University.
[2] Gang Wang. (2017) Research on Bridge Frequency Test Method Based on Vehicle-bridge
Coupling Theory[D]. Zhengzhou University.

[3] Yong Tu, Xiaoming Chen, Hui Zhao. (Jun 2019) Continuous T-beam bridge based on the LS-DZNA highway Research on Vehicle-Bridge Coupling Vibration Response Painted. Highway. pp 107-112.

[4] Mige Liu (May 2019) Research on Sampling Theorem. Journal of Xi’an University (Natural Science Edition) pp64-68.

[5] Hao Tang, Jianyun Zhang, Xiaodong Zhang. (May 2019) Application of Multi-Source Data Analysis on Bridge Operation Monitoring. Technology of Highway and Transport. pp88-93.