Proceedings of the 8th International Conference on Civil Structural and Transportation Engineering (ICCSTE'23)
Canada – June 04-06, 2023
Paper No. 164
DOI: 10.11159/iccste23.164

Development of Accurate Bridge Structure Strain Response Function Due to Temperature Changes Effect

Mohammed El-Diasty[1], Maryam Al Mazrouai[1], Mosbeh Kaloop[2]
[1]Civil and Architectural Engineering Department, College of Engineering, Sultan Qaboos University,
Muscat 123, Oman
m.eldiasty@squ.edu.om; s123626@student.squ.edu.om
[2]Public Works Engineering Department, Faculty of Engineering, Mansoura University,
Mansoura 35516, Egypt
mosbeh@mans.edu.eg

Abstract **-** Monitoring bridges performance is a vital task to ensure their safety and to plan their maintenance operations. The bridges are affected mainly by the traffic loads and the environmental changes. The bridge behaviour can accurately be monitored with the known traffic loads changes; however, the environmental changes effect is crucial and challenging to monitor. The most significant environmental changes effect is mainly produced by the temperature changes. Therefore, this research investigates the temperature changes effect on the concrete bridge behaviour. The objective of this paper is to develop an accurate bridge stain model to precisely represent the temperature changes effect. The current state-of-the-art method for bridge strain modelling is developed in time domain. This paper proposed a frequency response method for bridge stain modelling where the model is developed in the frequency domain. The frequency-domain response method is significantly preferable than time-domain method because the low frequency band of interest can be easily selected in the modelling and the high frequency band (noise band) can be neglected. To examine the performance of the proposed frequency-domain bridge strain response model, the datasets were collected from strain and temperature sensors installed on the Fu-Sui Bridge, China. The frequency-domain bridge strain response model is developed using the Least Squares Frequency Transform (LSFT). The input to the frequency-domain bridge strain response model is the temperature changes and the output is the static strain data. The results shows that the significant strain response dynamic due to the temperature changes is in low frequency band (0.00 – 0.15 Hz) with the peak value at 0.05 Hz for Fu-Sui Bridge case study. Moreover, the bridge strain impulse response can be accurately developed form the bridge strain frequency response using the Inverse Least Squares Frequency Transform (ILSFT). The significance of the developed impulse response is that it can be convolved with the temperature changes in time domain to estimate the strain response of the concrete structure due to the temperature changes in real-time mode. Consequently, the strain differences between the estimated strains and the measured strains are used to monitor any anomaly that can be interpreted as a sign of fatigue in the concrete structure under investigation.

Keywords**:** Frequency Response, LSFT, Monitoring, Bridge, Strain, Temperature

1. Introduction

The bridges performance monitoring is considered as a crucial task to ensure their safety and to plan their maintenance operations. The bridges are affected mainly by the traffic loads and the environmental changes. The bridge behavior can accurately be monitored with the known traffic loads changes; however, the environmental changes effect is crucial and challenging to monitor. The most significant environmental changes effect is mainly produced by the temperature changes. The strain produced by the temperature changes is heavily investigated by many researchers using different approaches in time domain (see [1-5]). However, the temperature-based strain frequency response in frequency domain has not been investigated.

This paper investigates the bridge strain frequency response in frequency domain due to the temperature changes effect. The frequency-domain response method is significantly preferable than time-domain method because the low frequency band of interest can be easily selected in the modelling and the high frequency band (noise band) can be neglected. The Least Squares Frequency Transform (LSFT) to convert the time temperature changes and stain from time domain to frequency domain. Then, the frequency response of the bridge strain due to the temperature changes is estimated. Afterwards, the bridge strain impulse response can be estimated from the bridge strain frequency response using the Inverse Least Squares

Frequency Transform (ILSFT). The importance of impulse response is that it can be convolved with the temperature changes in time domain to estimate strain due to the temperature changes in real-time mode.

2. Frequency Response Analysis

The Least Squares Frequency Transform (LSFT) term is originally derived from the Least Squares Spectrum Analysis (LSSA). The LSSA was first developed by [6] as an alternative to the classical Fourier methods that overcomes all inherent limitations of Fourier techniques. It provides many advantages [7-8] such as, unequally spaced data series can easily be transformed to the frequency domain. Unequally spaced series are very common in structural health monitoring system. LSSA uses the least squares approximation, which is closely related to the least squares parametric adjustment [7-8]. An observed time series is represented by $d = d(t) = \{d_i\},\ i = 1,\ 2, \cdots,\ n$. The main objective is to extract periodic signals from d, especially when d contains both, random and systematic noise. Thus, we can set up a model g that can be expressed as follows:

$$g = \Phi x \tag{1}$$

where Φ is a matrix of known base functions and $\boldsymbol{x}$ is the vector of unknown parameters. To estimate the model parameters x, the standard least-squares is applied [7-8], in which the difference between g and d becomes minimum. In spectral analysis we search for periodic signals that are expressed in terms of sine and cosine base functions. So, if we specify the form of the base functions to be trigonometric based on a set of spectral angular frequencies $\omega_i,\ i = 1,\ 2, \cdots,\ m$, we have:

$$\hat{g}(\omega_i) = \hat{x}_{1i}\cos\omega_i t + \hat{x}_{2i}\sin\omega_i t \tag{2}$$

where ω_i is the angular frequency and t is the time.

Let $\hat{\boldsymbol{x}} = [\hat{x}_{1\boldsymbol{i}}, \hat{x}_{2\boldsymbol{i}}]^T$ and $\Phi = [\cos\omega_i t, \quad \sin\omega_i t]$, then $\hat{\boldsymbol{x}}$ can be determined from using standard least-squares technique. The amplitude $|D(\omega_i)|$ and phase $\angle D(\omega_i)$ at each frequency can be estimated as follows:

$$|D(\omega_i)| = \sqrt{\hat{x}_{1i}{}^2 + \hat{x}_{2i}{}^2} \tag{3}$$

$$\angle D(\omega_i) = \tan^{-1}(\hat{x}_{2i}/\hat{x}_{1i}) \tag{4}$$

Also, the associated covariance matrix of $\hat{x}$ is also used to provide the corresponding covariance matrix for $|D(\omega_i)|$and $\angle D(\omega_i)$ using the covariance law. If we stopped the derivation at Equations (3) and (4), then we can call this Least Squares Frequency Transform (LSFT). However, if we complete the derivation to find the spectrum, then we call it Least Squares Spectrum Analysis (LSSA) according to [6] and [7]. In his paper we use Least Squares to find the amplitude and phase of the temperature/strain single input/output system, therefore, LSFT term is used and not LSSA.

Consider a linear dynamic system with input and output as shown in Fig. 1 (upper box). The LSFT is used to transform the input vector d and output vector r from the discrete time domain to the frequency domain to provide input vector *D* and output vector *R* as shown in Fig. 1 (lower box).

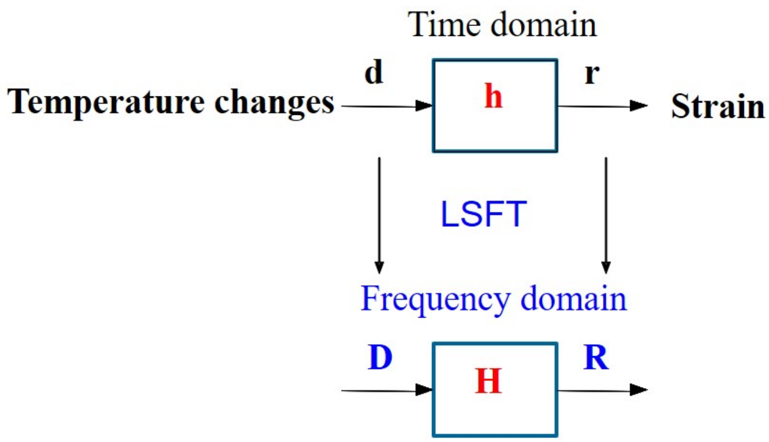

Fig. 1: Time-domain and LSFT-based frequency-domain representation of a single input/single output system

The system frequency response $H(\omega_i)$ can be estimated in form of transfer function $|H(\omega_i)|$and phase $\angle H(\omega_i)$ as follows [9]:

$$|H(\omega_i)| = \frac{|R(\omega_i)|}{|D(\omega_i)|} \tag{5}$$

$$\angle H(\omega_i) = \angle R(\omega_i) - \angle D(\omega_i) \tag{6}$$

where $D(\omega_i)$ the $R(\omega_i)$ are the system inputs and outputs in the frequency domain.

Also, the associated covariance matrix of $D(\omega_i)$ and $R(\omega_i)$ are used to provide the corresponding covariance matrix for $|H(\omega_i)|$ and $\angle H(\omega_i)$. It should be noted that the system transfer function and phase in Eqs. (5) and (6), respectively are estimated at all frequencies in the bandwidth of interest.

In the frequency domain, the system transfer function ($|H(\omega_i)|$) of the strain/temperature system usually contains unexpected and sudden spikes, which have no physical meaning. Therefore, the Parzen spectral window smoothing is employed here to estimate a smooth system transfer function. It should be noted that the impulse response can be estimated from the transfer function using the Inverse Least Squares Frequency Transform Method (ILSFT) method [8].

3. Data Description and Methodology

To examine and assess the performance of the proposed methodology, temperature and strain data were collected from sensors installed on Fu-Sui Bridge, China. Fig. 2 shows the configuration of the structural health monitoring system of the Fu-Sui Bridge. The bridge consists of eight continuous spans of six inner spans at 150 m each and two outer spans of 80 m each. The bridge's main girder is a single-cell box with a cross-sectional height range from 9 m at the pier section to 3.5 m at the mid-span. It has a top slab that is 11.25 m wide, a bottom slab that is 5.85 meters wide, and a web slabs that are 2.7 meters long on each side. The structural health monitoring system of Fu-Sui Bridge consists of 24 FBG strain (S) sensors are installed in six positions, six internal temperature sensors installed in these six sections and six internal and external temperature sensors installed in one more section.

The temperature and strain data of June 2012 was collected at 25 Hz sampling rate for 1666 min. long (about 27.777 hr). The temperature and strain data of three different internal temperature sensors and strain sensors installed in the first three middle span sections along with external temperature sensor were implemented in this paper (so called; $T1_{internal}$ and S1, $T2_{internal}$ and S2, $T3_{internal}$ and S3, $T4_{external}$). The raw temperature and strain data are noisy data; therefore, the raw temperature and strain data were smoothed before the implementation of the proposed response analysis method. Figs. 3 and 4 show sample temperature (external and internal) and strain raw and smoothed data.

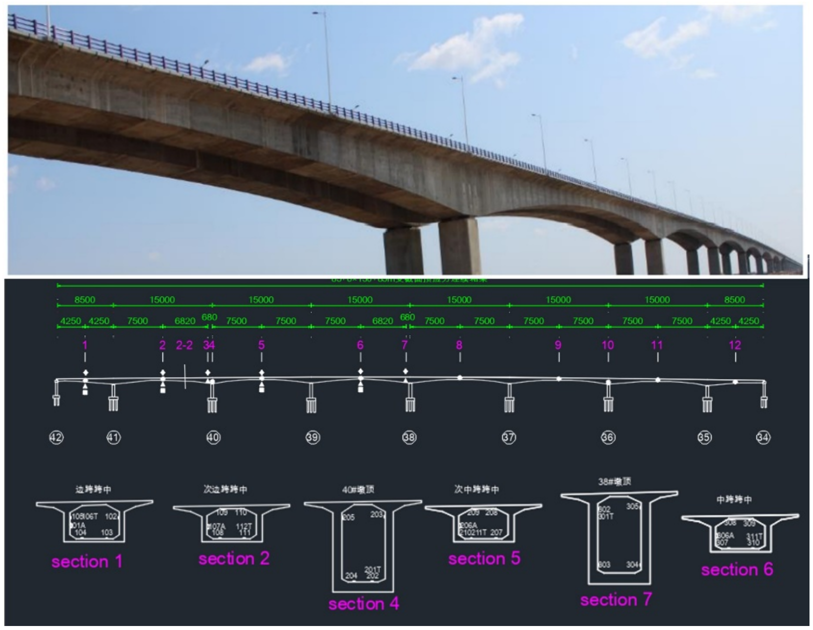

Fig. 2: Fu-Sui Bridge and structural health monitoring system configuration

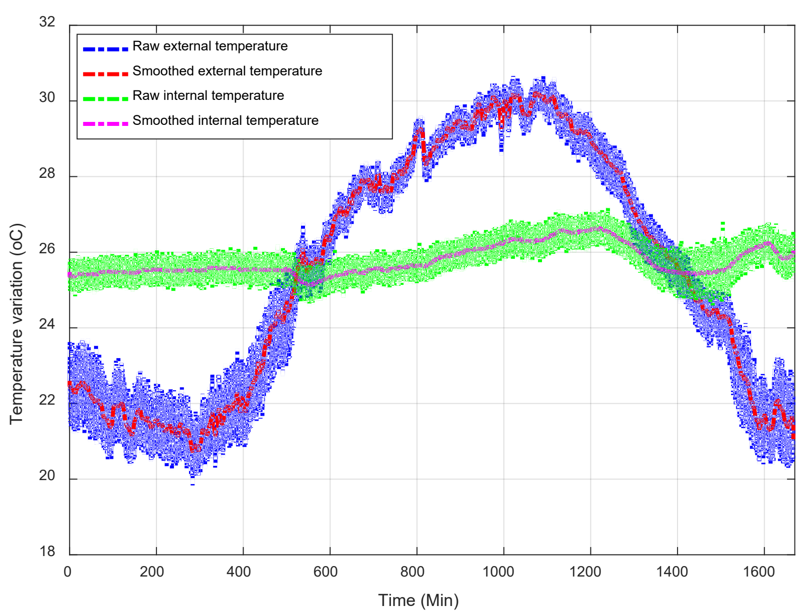

Fig. 3: Sample raw and smoothed temperature data ($T4_{external}$ and $T1_{internal}$ cases)

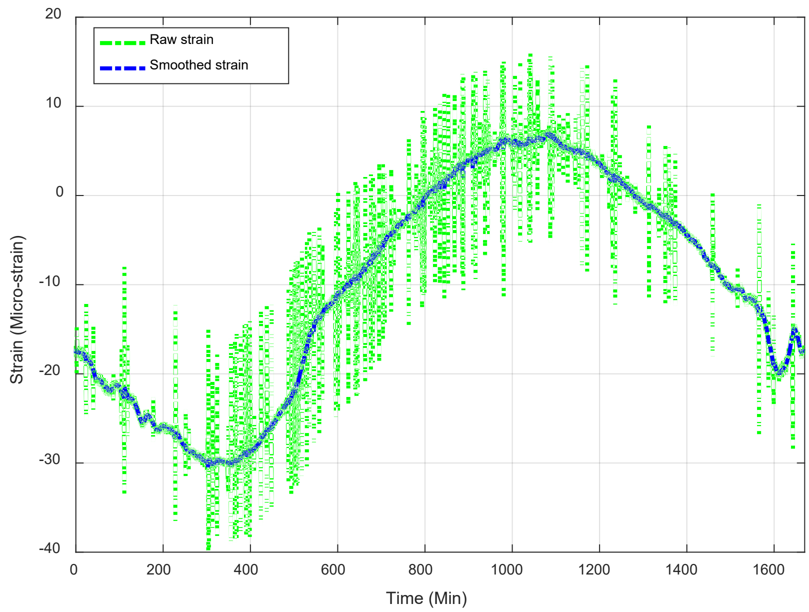

Fig. 4: Sample raw and smoothed strain data (S1 sensor).

To estimate the bridge strain frequency response due to the temperature change effect, the LSFT methodology is employed to transform the input signal (d) which is the temperature changes time series ($T_{external} - T_{internal}$) and the output signal (***r***) which is the strain (S) time series. Then the frequency response (***H***) is estimated using the transformed temperature changes data (***D***) and transformed strain data (***R***) in frequency domain as shown in Fig. 1. In the frequency domain, the system transfer function (***H***) is smoothed using the Parzen spectral window to remove any spikes in frequency domain and provide proper transfer function. The smoothed bridge strain frequency response is estimated from different sections temperature changes and strain. Then, the overall (mean) bridge strain frequency response (transfer function) is estimated. Finally, the bridge strain impulse response is estimated using ILSFT method.

4. Results and discussions

The temperature changes (external temperature minus internal temperature) and strain time series for three samples were employed to estimate the strain/temperature bridge frequency response system. Fig.5 shows temperature changes and strain data from three different sensors at three different sections. Fig. 6 shows the estimated and smoothed frequency responses from three different sensors at three different sections. Fig. 7 shows the overall (mean) smoothed temperature-based strain frequency response representing the transfer function for the bridge in frequency domain. The significant strain response dynamic due to the temperature changes is in low frequency band (0.00 – 0.15 Hz) with the peak value at 0.05 Hz. To check the impulse response in time domain, the ILSFT is employed, and Fig. 8 shows the bridge temperature-based strain impulse response for the bridge. The importance of impulse response is that it can be convolved with the temperature changes in time domain to estimate the strain response of the concrete structure due to the temperature changes in real-time mode. Consequently, the strain differences between the estimated strains and the measured strains are used to monitor any anomaly that can be interpreted as a sign of fatigue in the concrete structure under investigation.

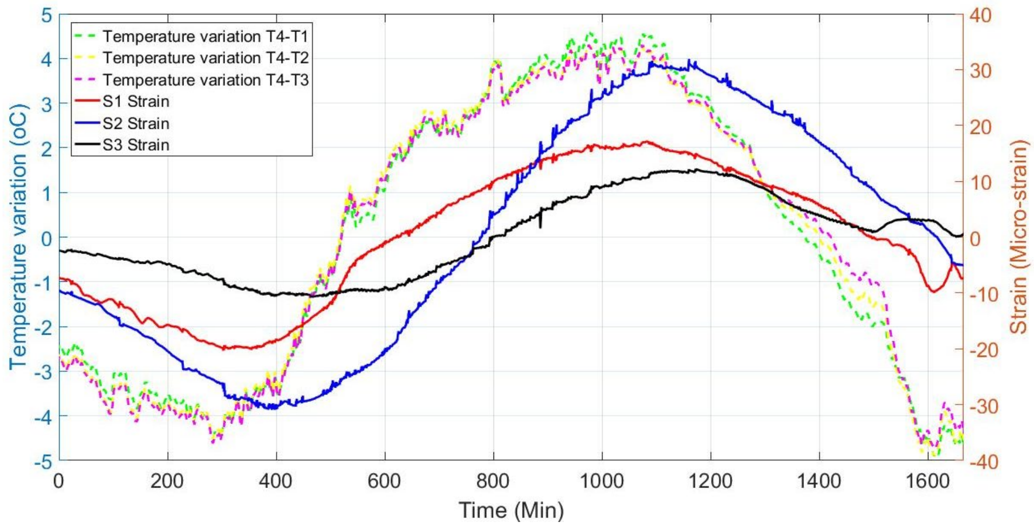

Fig. 5: Temperature changes and strain data from three different sensors at three different sections.

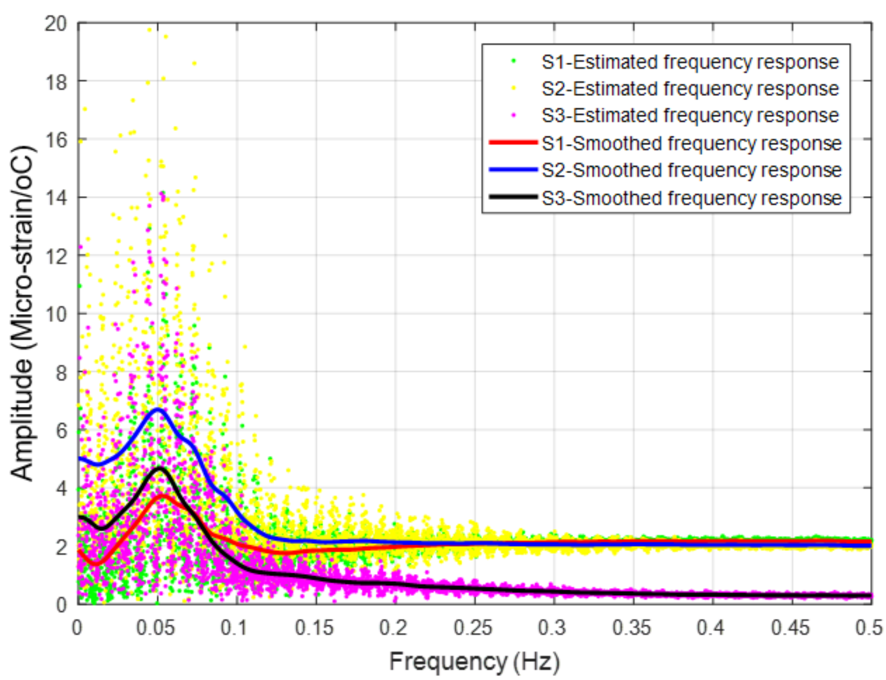

Fig. 6: The estimated and smoothed frequency responses from three different sensors at three different sections

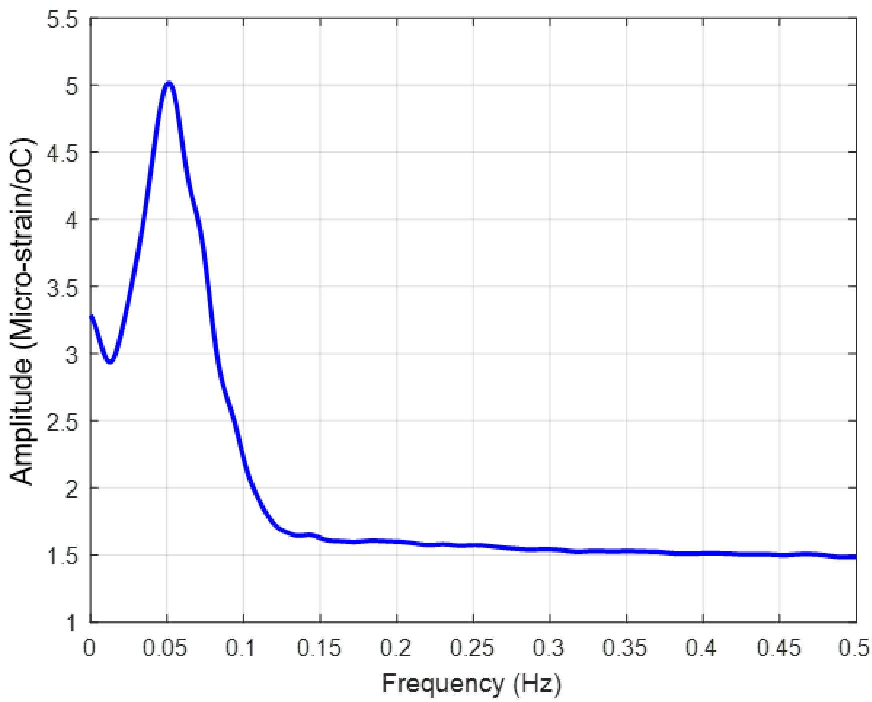

Fig. 7: Overall (mean) smoothed temperature-based strain frequency response representing the transfer function for the bridge in frequency domain.

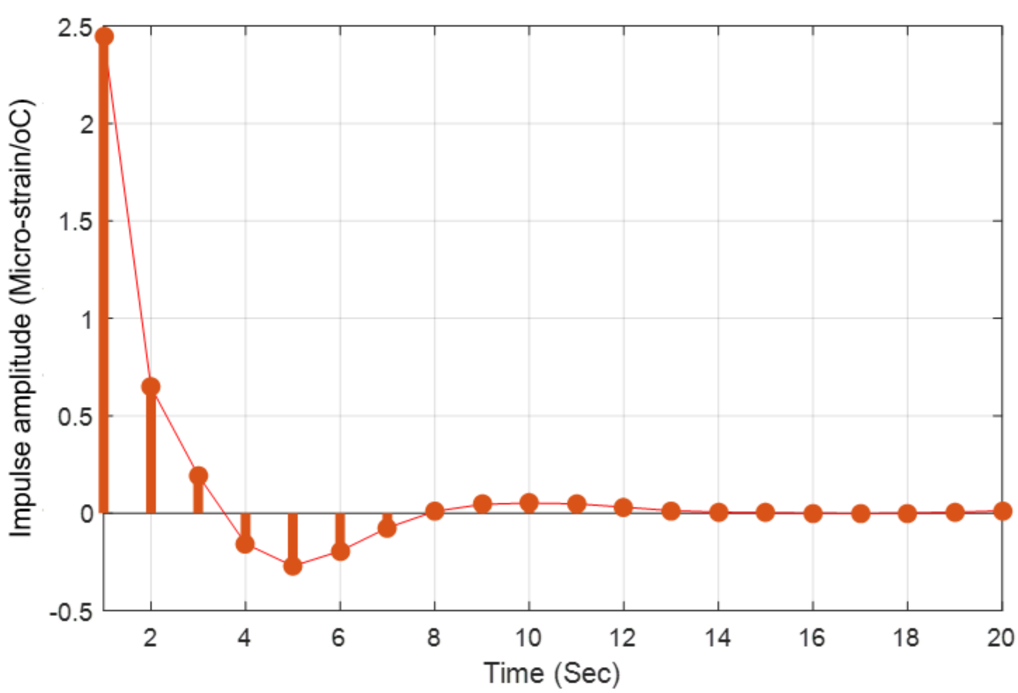

Fig. 8: The temperature-based strain impulse response representing the transfer function for the bridge in time domain.

5. Conclusion

The LSFT method was employed to estimate the bridge strain frequency response. It was found the significant strain response dynamic due to the temperature changes is in low frequency band (0.00 – 0.15 Hz) with the peak value at 0.05 Hz for Fu-Sui Bridge case study. Moreover, the bridge strain impulse response can be accurately developed form the bridge strain frequency response using the Inverse Least Squares Frequency Transform (ILSFT). In practice, the developed impulse response of the bridge structure is employed to estimate the bridge strain response. In real-time concrete structure health monitoring mode, the strain differences between the estimated strains and the measured strains are used to monitor any anomaly that can be interpreted as a sign of fatigue in the concrete structure under investigation.

Acknowledgements

The authors would like to thank the deanship of research at Sultan Qaboos University for the support.

References

[1] M. Li, WX. Ren, TL. Huang and NB. Wang "Experimental investigations on the cross-correlation function amplitude vector of the dynamic strain under varying environmental temperature for structural damage detection.", Journal of Low Frequency Noise, Vibration and Active Control. 39(3) (2020) 631–649.

[2] C. Chen Y. Wang, MR. Kaloop, T. Wang and J. Ma, "Continuous Box-girder Bridge Condition Assessment based on Structural Health Monitoring System: A Case Study.", International Conference on Intelligent Transportation, Big Data & Smart. (ICITBS), (2020),734-740

[3] MR. Kaloop, JW. Hu and E. Elbeltagi, "Time-Series and Frequency-Spectrum Correlation Analysis of Bridge Performance Based on a Real-Time Strain Monitoring System.", ISPRS International Journal of Geo-Information. 5(2016): 61.

[4] R. Kromanis and P. Kripakaran "SHM of Bridges: Characterising Thermal Response and Detecting Anomaly Events Using a Temperature-Based Measurement Interpretation Approach." Journal of Civil Structural Health Monitoring 6, no. 2 (2016): 237–54.

[5] Q. Han, Q. Ma, J. Xu, and M. Liu. "Structural Health Monitoring Research under Varying Temperature Condition: A Review." Journal of Civil Structural Health Monitoring 11, no. 1 (2020): 149–73.

[6] P. Vanícek, "Approximate Spectral Analysis by Least-squares Fit.", Astrophysics and Space Science 4 (1969):387-391.

[7] S. Pagiatakis, "Stochastic significance of peaks in the least-squares spectrum." Journal of Geodesy. 73 (1999): 67-78.

[8] M. El-Diasty and S. Pagiatakis. "A Frequency-Dependent Efficient INS/GPS Impulse Response Model for Bridging GPS Outages.", Journal of Navigation. 63 (4), (2010): 627-643.

[9] R. Pintelon and J. Schoukens, *System Identification: A Frequency Domain Approach.*, John Wiley & Sons, 2004.