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TEMPERATURE-INDUCED VARIABILITY IN BRIDGE DYNAMIC RESPONSE: A PREREQUISITE FOR RELIABLE DAMAGE DETECTION

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Abstract

As bridges age, ensuring their safety and longevity becomes an increasingly critical challenge for infrastructure management, creating a growing need for monitoring approaches capable of detecting early signs of structural deterioration. In this context, Structural Health Monitoring (SHM), particularly vibration-based monitoring using accelerometers, has become an important complement to traditional inspections, as changes in modal parameters can indicate structural degradation. However, a key challenge in practical applications is the strong influence of environmental effects, especially temperature, which can induce frequency shifts of similar magnitude as damage and thus complicate interpretation. Therefore, understanding temperature-induced variability is a necessary step toward reliable damage detection. This study is conducted within the Interreg Central Europe project BIM4CE at the IDA-KI openLAB bridge, an experimental full-scale structure enabling controlled investigations. The bridge is instrumented with twelve accelerometers and an embedded temperature sensor, complemented by several existing temperature sensors, providing a comprehensive dataset for long-term analysis. Based on continuous monitoring data, modal parameters are identified using Operational Modal Analysis (OMA) and analysed in relation to measured temperature. Particular attention is given to temperature–frequency relationships, including potential time-lag effects and the suitability of different modelling approaches. The results establish a foundation for distinguishing between environmental variability and damage-related changes in subsequent studies, supporting more reliable long-term bridge monitoring.

Keywords: bridge monitoring, structural health monitoring, accelerometers, temperature effects, operational modal analysis

1 Introduction

Bridges are essential elements of transport infrastructure, enabling safe and efficient movement of people and goods. However, the European bridge stock is ageing, while traffic loads and environmental impacts are increasing. Many of these structures were designed according to outdated codes that no longer reflect current traffic demands. This indicates that more intense deterioration is expected, reinforcing the growing need for reliable condition assessment methods. Structural Health Monitoring (SHM) is increasingly being adopted as a complementary approach to traditional inspection methods. Among SHM approaches, vibration-based monitoring using accelerometers is widely applied because it is relatively simple and captures global structural behaviour. Changes in modal parameters, such as natural frequencies and mode shapes, reflect variations in stiffness and mass and may indicate damage. Tracking these changes over time is a recognised approach for bridge assessment [1]. Operational Modal Analysis (OMA) enables the identification of modal parameters from

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ambient excitation without controlled loading. However, environmental effects, particularly temperature, can induce frequency shifts comparable to those caused by damage, complicating interpretation [2]. Therefore, understanding and quantifying temperature-induced variability is essential for reliable damage detection.
This study is conducted within the Interreg Central Europe project BIM4CE [3], which aimed to develop integrated frameworks for bridge monitoring by combining sensing technologies and digital-twin tools. The analysis is based on long-term measurements from the full-scale IDA-KI openLAB bridge in Germany [4, 5], which enables controlled investigation of structural behaviour. The bridge is instrumented with accelerometers and temperature sensors, providing a comprehensive dataset for analysing temperature–frequency relationships identified using OMA. Particular attention is given to potential time-lag effects, with the aim of improving the interpretation of monitoring results under environmental variability.

2 Test bridge and measurement campaign

This chapter presents a description of the test bridge and measurement campaign used to benchmark temperature-induced variability in bridge dynamic characteristics based on long-term measurements at the IDA-KI openLAB bridge.

2.1 openLAB bridge

The openLAB bridge in Bautzen, Germany, was constructed as a full-scale research and validation structure within the IDA-KI project [4, 5]. It serves as an experimental platform for the systematic investigation of monitoring systems, damage assessment methods, and structural behaviour in prestressed concrete bridges. An overview of the openLAB bridge and its characteristic cross-sections is presented in figure 1. The bridge is 45 m long and 4.5 m wide, consisting of three 15 m spans. Spans 1 and 2 are formed by three parallel precast prestressed concrete girders with a cast-in-place concrete deck, while Span 3 represents a rapid-construction concept. Each span targets specific research aspects, including typical deficiencies of older bridges, modern construction solutions, and innovative details. A key advantage of the openLAB bridge is that it allows controlled and accelerated simulation of damage scenarios, including loading up to the ultimate limit state, tendon cutting, and static and dynamic testing, making it a unique research platform for the validation of structural health monitoring approaches. Additional details of the bridge, its instrumentation, and the reference-condition dataset are reported in Jansen et al. [6]. The following section focuses on the measurement campaign and data used in this study.

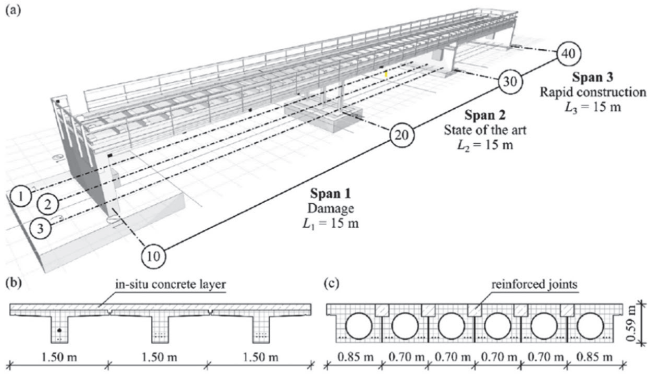

Figure 1 Illustration of the openLAB bridge: (a) overview (b) cross-section of span 1 (c) cross-section of span 3 [6]

2.2 Measurement campaign

Within the BIM4CE project, the openLAB bridge was instrumented during an experimental campaign conducted between May 5th and May 7th, 2025, to investigate structural response under controlled loading and damage scenarios. The monitoring system included accelerometers, a Bridge Weigh-In-Motion (B-WIM) system, temperature sensors, and a leakage sensor. This paper focuses exclusively on acceleration data. The system was installed approximately 3 weeks prior to the main campaign to enable long-term monitoring under operational and environmental conditions. This period provides valuable insight into temperature-induced variability in dynamic response, particularly in natural frequencies. Accordingly, the analysis presented in this paper focuses on the pre-experimental monitoring period from April 19th to May 5th, 2025. Based on continuous acceleration and temperature measurements, the influence of temperature on modal parameters is investigated.

3 Bridge instrumentation

The first two spans were instrumented with 12 triaxial Dewesoft IOLITEi-3xMEMS-ACC accelerometers [7], six per span, as shown in figure 2. The sensors were distributed approximately uniformly along each span, near midspan and quarter points, with minor in-situ adjustments due to other instrumentation and mounting constraints. All accelerometers were rigidly fixed to the underside of the bridge girders using small anchors to ensure stable mechanical coupling. The acceleration signals were sampled at 500 Hz. The measurement setup comprised 36 channels. Only channels measuring accelerations in vertical (Z) direction, i.e. 12 channels were considered in this paper. In addition to acceleration measurements, temperature was monitored using an embedded sensor at the bottom flange of the girder at axis X-6 (T_{BWIM}) and existing bridge sensors T_{KF1}, T_{KF2}, T_{KF3} and T_{Air}. The T_{KF} sensors are embedded in concrete at different heights near the construction joint, while T_{Air} measures the air temperature near the bridge.

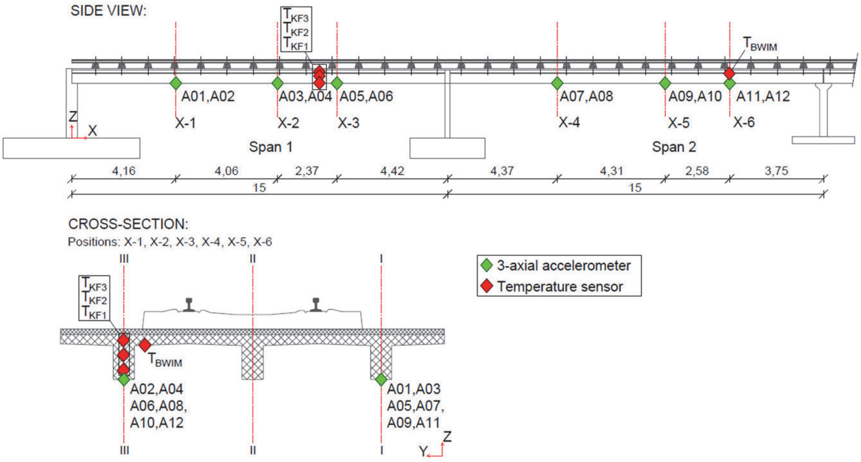

Figure 2 Sensor disposition: accelerometers and temperature sensors

4 Data processing and analysis of temperature-induced variability

4.1 Identification of natural frequencies and mode shapes

First, the measured acceleration data were processed using the Operational Modal Analysis (OMA) Frequency Domain Decomposition (FDD) technique in the Dewesoft Artemis OMA software [8]. For this purpose, acceleration data from the May 6th reference measurement were used, including nearly 50 minutes of controlled shaker excitation and ambient vibrations, designed to excite the bridge within a frequency range suitable for OMA analysis. Overall, 427 time windows, each with 1024 samples, were overlapped with 66%, resulting in the frequency resolution of the singular value decomposition spectra of 0.049 Hz. The identified mode shapes and frequencies are shown in figure 3.

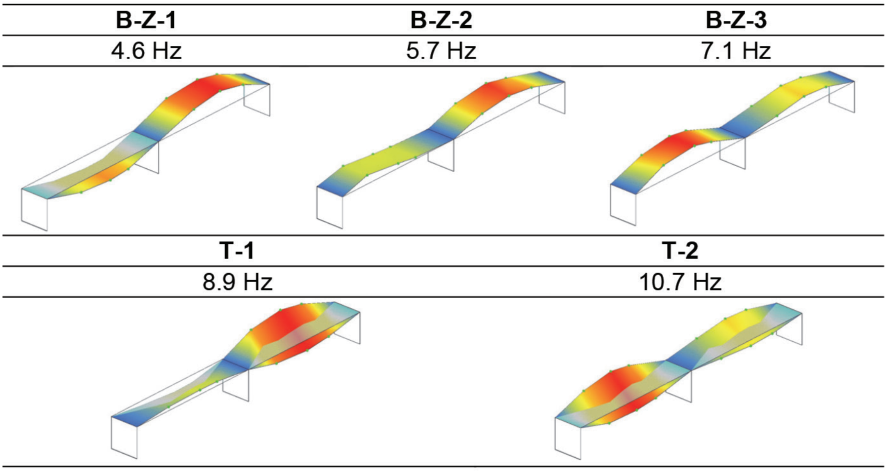

Figure 3 Identified mode shapes and natural frequencies: three vertical bending modes (B-Z-1 to B-Z-3) and two torsional modes (T-1 and T-2)

4.2 Analysis of the acceleration response

Since the objective of this study was to assess the influence of temperature on bridge modal parameters, the acceleration response was analysed throughout the pre-experimental period from April 19th to May 5th, 2025. For this purpose, the Average Normalised Power Spectral Density (ANPSD) method proposed by Felber [9] was used, where natural frequencies are identified as peaks of the averaged normalised power spectral densities [10]. Owing to its simplicity, the method is suitable for an initial assessment of structural behaviour. The results were benchmarked against the FDD method. The comparison showed strong overall agreement between the two methods; however, a detailed investigation of subtle differences and method-specific features is beyond the scope of this paper. For the ANPSD analysis, separate 30-minute-long acceleration data sets were used. For each set, the ANPSD was calculated with 4096 samples per time window. Considering the 66% overlap and reduced sampling frequency of 50 Hz, the resulting frequency resolution was 0.012 Hz. Figure 4 shows the waterfall plot of the ANPSD over time. Dark blue regions indicate periods of low vibration activity, typically during the night and weekends, whereas yellow regions correspond to periods of increased excitation. Most of the excitation is attributed to the working hours of the nearby industrial facilities.

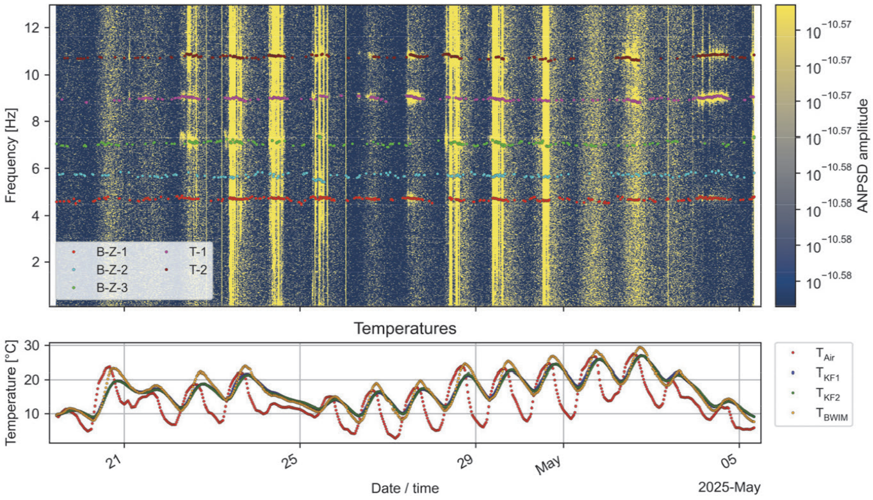

Figure 4 ANPSD waterfall plot with identified natural frequencies and temperature series

Coloured markers overlaid on the waterfall plot indicate the tracked frequencies over time. Peaks were identified within predefined frequency windows around the expected eigenfrequencies using criteria based on prominence, amplitude, spacing, and distance from the reference frequency, with fallback candidates introduced where necessary. The final modal trajectories were determined by dynamic programming and refined in a second pass to improve robustness and continuity. The lower plot shows temperature variation from four temperature sensors. The identified natural frequencies were analysed against temperature using linear and quadratic regression with both unshifted and time-shifted temperature data. The lag analysis was used to assess the delayed frequency response across different temperature sensors, reflecting the bridge's thermal inertia. Table 1 shows the results, where positive lag indicates that frequency changes occur after the corresponding temperature change; for each sensor, only the lag yielding the highest R^2 is reported. Figure 5 compares regressions for unshifted T_{Air} (left) and T_{KF1} with a 1.0 h lag (right), which gave the highest R^2 of all sensors and analysed lags. Lag analysis was performed for the time range of [0, 24] hours. The results indicate a clear temperature dependence of the identified natural frequencies, although the strength of this dependence varies between modes. Similarly, the sign of the correlation varies among modes, as it is negative for all modes except B-Z-2. Similar as reported for example for the well known Z24 bridge [11]. In general, introducing a positive lag improved the regression quality, indicating a delayed modal response to thermal inertia. Quadratic regression generally provided a slightly better fit than linear regression, suggesting a mildly nonlinear temperature–frequency relationship. Based on these results, temperature-compensated frequency series can also be constructed to reduce reversible environmental effects and improve interpretation of long-term structural behaviour.

Table 1 Time lags for different temperature sensors, corresponding to the maximum R^2 values obtained from linear and quadratic models of temperature-induced changes in natural frequencies

	Time lag [h]	R^2 linear*	R^2 quadratic*
T_{Air}	5.5	0.230	0.237
	6.0	0.232	0.236
T_{KF1}	1.0	0.233	0.261
T_{KF2}	0.5	0.232	0.257
	1.0	0.233	0.255
T_{KF3}	2.5	0.242	0.256
	3.0	0.243	0.254
T_{BWIM}	1.0	0.242	0.258
	1.5	0.244	0.257

* calculated as mean value across all five identified modes

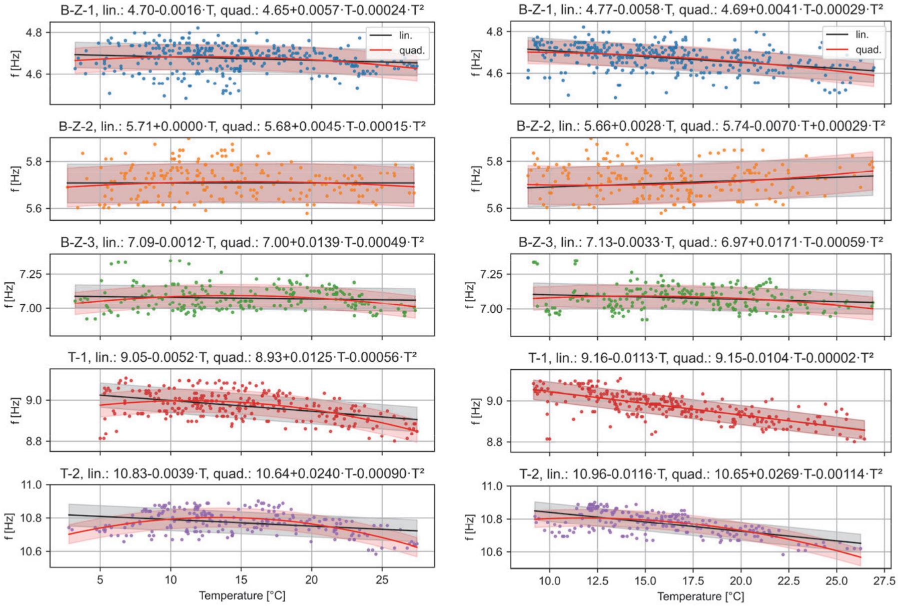

Figure 5 Comparison of linear and quadratic regression between temperature and identified natural frequencies considering unshifted T_{Air} (left) and T_{KF1} with a 1.0 h time lag (right); the shaded area indicates ±1 standard deviation

5 Conclusion

This study examines the influence of temperature variability on the dynamic response of the openLAB bridge using long-term monitoring data collected prior to the testing campaign. The results indicate temperature-induced frequency shifts of about ±0.1 Hz, or roughly 1–2% depending on the mode. Although modest, these changes are highly relevant for SHM, as shifts of similar magnitude may also result from early-stage damage and thus mask or mimic damage-related effects. The observed negative correlation is consistent with analogous studies (e.g. [12]).

By quantifying the temperature–frequency relationship, including time-lag effects, this study establishes a reference condition for the undamaged bridge, a prerequisite for reliable damage detection and for future analyses of frequency changes during controlled load testing and damage-induction scenarios.

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