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Bridge condition monitoring using low-cost accelerometers

Filippo Lorenzoni, Riccardo Rossi, Michele Frati, Andrea Gentili, Simone Orcioni, and Massimo Conti

DII, Università Politecnica delle Marche, Ancona, Italy,

Abstract. The aim of Structural Health Monitoring is to guarantee the safety and integrity of infrastructure by providing real-time data on their structural health, enabling prompt maintenance and repair actions. This paper presents the development of a cost-effective Bridge Structural Health Monitoring system, featuring a low-power MEMS accelerometer sensor unit, without additional instrumentation, to detect bridge oscillations induced by heavy vehicles. In particular, it shows reliability in detecting heavy vehicle crossing events, delivering initial crucial insights into the deformation behavior of the bridge examined in the presented case study.

Keywords: Bridge Structural Health Monitoring, accelerometer sensors

1 Introduction

Regular monitoring of road and bridge conditions is essential to ensure the safety and integrity of the infrastructure, preventing damage and deterioration. Bridge Structural Health Monitoring (BSHM) involves continuous monitoring and assessment of the structural condition of bridges to detect damage or deterioration. The goal of BSHM is to ensure the safety and integrity of bridges by providing real-time data on their structural health, enabling timely maintenance and repair actions. BSHM is obtained using various techniques and sensors such as strain, displacement, vibration, and acceleration measurements. Recent advances include rotation-based BSHM methods that offer practical solutions to effectively monitor bridge responses [1] when it undergoes external loading as a result of vehicle crossing. However, BSHM systems often require additional instrumentation, leading to increased costs and complexity. They rely on continuous power and communication resources, which can be challenging in remote or resource-constrained locations. Additionally, some BSHM systems may generate excessive data, including irrelevant information, resulting in inefficiencies in data processing and transmission. Microelectromechanical systems (MEMS) accelerometers are increasingly used for Structural Health Monitoring (SHM) applications [2, 3], also for bridge monitoring due to their cost-effectiveness and precision to capture bridge deformations. The use of MEMS accelerometers for transient bridge rotation measurement due to vehicle crossing can contribute to

SHM, for example, throughout the identification of the occurrences, as well as classification and size of vehicle loadings, without incurring additional expensive instrumentation costs. Monitoring vehicle loads, especially trucks, provides crucial insight into how bridges respond to deformation. In contrast, car deformation signals offer limited information [4, 5]. The incidence of heavy vehicle crossings is particularly valuable for detecting damage: the rotation response can indicate changes in the structural stiffness of the bridge over time, potentially due to damage or deterioration [6].

In this paper, we describe the development of a cost-effective monitoring BSHM system that aims to detect bridge oscillations induced by vehicles. The system utilizes a medium-performance, low-power MEMS accelerometer and transmits data wirelessly to a remote server with precise timestamps for subsequent offline analysis. It also connects with a smartphone Bluetooth (BT) application for easy configuration. Moreover, we present a preliminary low-cost analysis of vehicle event detection across the time, magnitude, and frequency domains.

2 Methods

The structure of the entire system architecture is outlined in Figure 1. The sensor node's hardware components consist of three main parts: (1) the acquisition board, which includes an ESP32 System on Chip (SoC) development board (from AZ-Delivery) with a low-power, high-performance MCU chip and wireless data transmission capability; (2) the sensing unit, which contains the ADXL355, a 3-axis digital accelerometer (from Analog Devices), which offers a great cost/performance ratio in SHM applications with very low noise [7], and it was successfully used in other SHM studies [8–11]; (3) the micro-SD module, that is used for local data storage.

Accelerometer and SD module are connected to the main board via SPI interfaces. The sensor node is powered by a 5V DC supply (from a mains power supply or power bank).

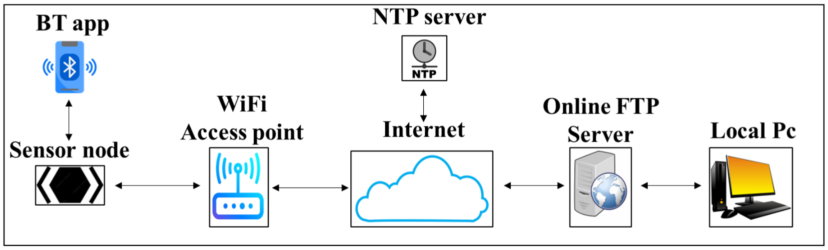

Fig. 1: Developed system for BSHM.

The main tasks of the firmware running on the ESP32 and programmed using the Arduino IDE include:

1) an easy remote configuration of nodes using a BT smartphone application with detailed log status information;

2) time synchronization to obtain accurate timestamps for each data sample using Network Time Protocol (NTP), with periodic ESP32 clock drift correction;

3) measurement and data storage for a reliable acquisition of acceleration data with related timestamps, then saving the data to the micro-SD;

4) the sending of data to FTP server;

5) an optimized transmission of the data format to the remote server via File Transfer Protocol (FTP).

The MEMS unit collects acceleration data and transfers them to an online FTP server called Tophost through Wi-Fi. The data are also saved on a microSD card. The NTP protocol is used for precise timestamps and clock correction during data acquisition. Configuration settings and commands are delivered through a BT application on a smartphone. After data transmission, the datasets can be accessed and downloaded to a local PC for offline processing.

3 Experimental setup

An initial experiment was conducted to assess the sensor system's effectiveness in detecting load events induced by individual vehicles crossing on a bridge.

The sensor node consists of hardware elements soldered onto a perforated board and housed in a 3D-printed frame. The unit is encased within a PVC container that has a base weight of about 1 kg for stability. With the lid secured, the container becomes waterproof, which improves the sensor node's interface with the road surface. This setup is designed to maximize the signal-to-noise ratio (SNR) (see Figure 2).

In November 2023 a preliminary data collection campaign was conducted on the Ponte delle Ricostruzione in Ancona (Figure 3). The bridge is a multiple-span, precast reinforced concrete beam and slab structure that supports a dual-lane carriageway. During this campaign, accelerations resulting from deformations of the bridge were measured under regular vehicular traffic. The goal was to assess the efficacy of the developed sensor system in recording the association between raw accelerometer data at the road level and load events induced by individual vehicles, within the experimental constraints given. For data acquisition, the ADXL355 accelerometer was employed, utilizing a sampling frequency of 62.5 Hz during a test conducted late in the morning. The experimental setup involved placing the prototype halfway across the span, placed on the floor next to the parapet adjacent to one of the traffic lanes. The coordinate systems x, y, and z correspond to the transverse, longitudinal, and vertical axis, respectively. The test, which lasted approximately 5 minutes, included various vehicles such as trucks, cars, and buses, which were also recorded on video using a smartphone for later validation of the results.

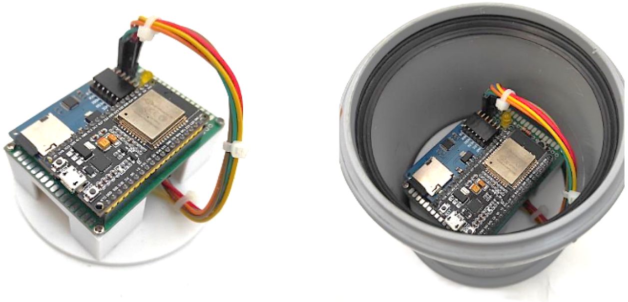

Fig. 2: Developed sensor node: hardware prototype (left) and case (right).

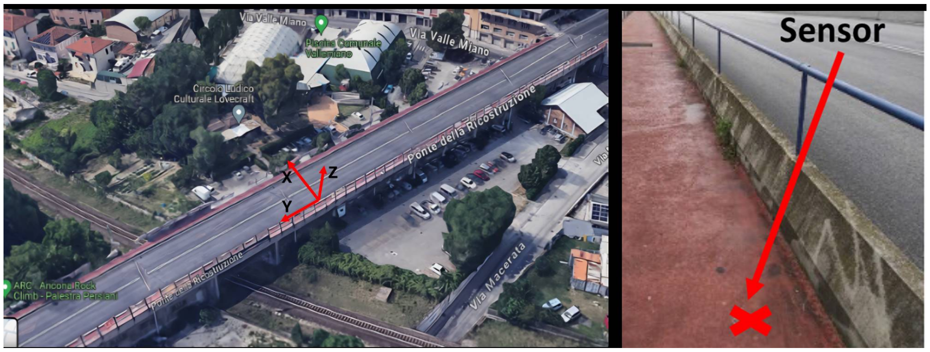

Fig. 3: Photographs of the Ponte della Ricostruzione, Ancona (*left*), and location of the sensor node on the sidewalk (*right*).

4 Results

An initial time-frequency domain analysis on the raw accelerometer data offline in a MATLAB environment was performed. Figure 4 shows the results of the raw accelerometer signals acquired during the entire acquisition period of the test.

Figure 5 (top pannel) shows the normalized signals after subtracting their mean value. A preliminary visual inspection indicates that the x-axis and y-axis components are quite similar in both amplitude and phase, unlike the z-axis component. Hence, to improve the SNR only the magnitude for the x-axis and y-axis components was also computed. From the magnitude signal, shown in Figure 5 (bottom pannel), the largest peaks in amplitude can be readily attributed, through video frame inspection comparison, to the single-pass of heavy vehicles in both lanes (annotated as 2,3,5 and 6). On the other hand, the signal does not allow for the differentiation of smaller amplitude transients caused by light single-pass vehicles (annotated as 1), and vehicles crossing the two lanes simultaneously (annotated as 4).

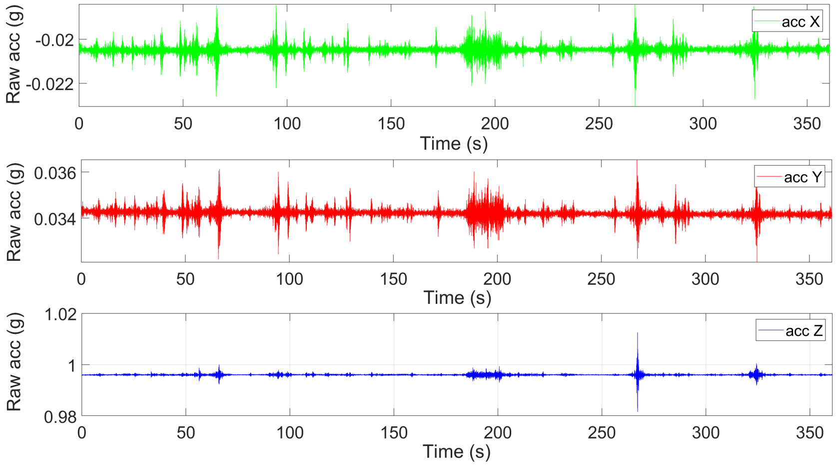

Fig. 4: Raw accelerometer data.

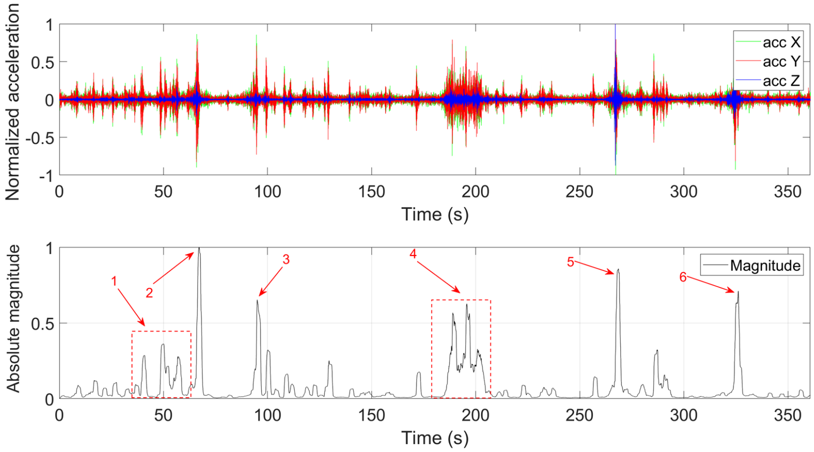

Fig. 5: Normalized acceleration data: 3-axis components (*top pannel*), x-axis and y-axis magnitude (*bottom pannel*).

Moreover, Figure 6 illustrates two 0.5 s windows, one showing no passing vehicle and the other a single-pass heavy vehicle, respectively. Each sliding window in this study was set based on the estimated average time required for a vehicle to pass the sensor node, considering an average vehicle speed of 60 km/h and an average vehicle length of 8 m. In the top pannel (no vehicle), the individual spectral power frequency components show similar but uncorrelated, amplitude peaks. In the bottom pannel (heavy vehicle) the PSD amplitude is two order of magniture higer with respect to the "no vehicle" pannel. The x-axis and y-axis components display high correlation with identifiable frequencies around 25 Hz and the z-axis frequencies ranging from 10 Hz to 20 Hz.

Lastly, Figure 7 presents the spectrogram (computed with a sliding window of 0.5 s, overlap of 10% and n = 1024 points for the FFT calculation) on the entire acquisition. A simple visual inspection indicates that the spectral power over time for both the x and y-axis signals is often concentrated around 25 Hz during vehicle passages close to the sensor node, a pattern that is not observed otherwise. Likewise, similar behavior occurs for the z-axis for frequencies concentrated between 10 and 20 Hz during vehicle passage.

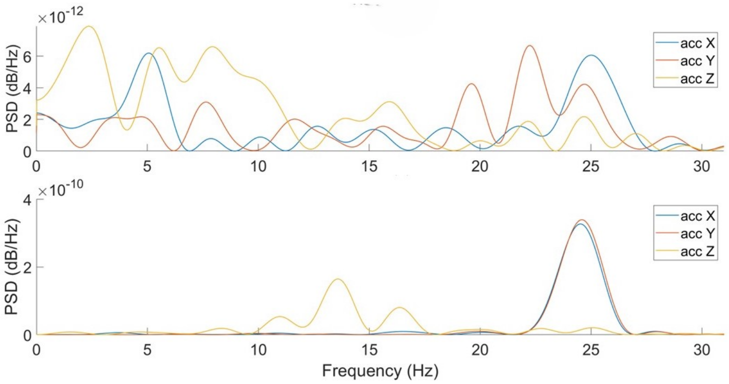

Fig. 6: Example of noise-window signal (*top pannel)* and event-window signal (*bottom pannel*), in frequency domain.

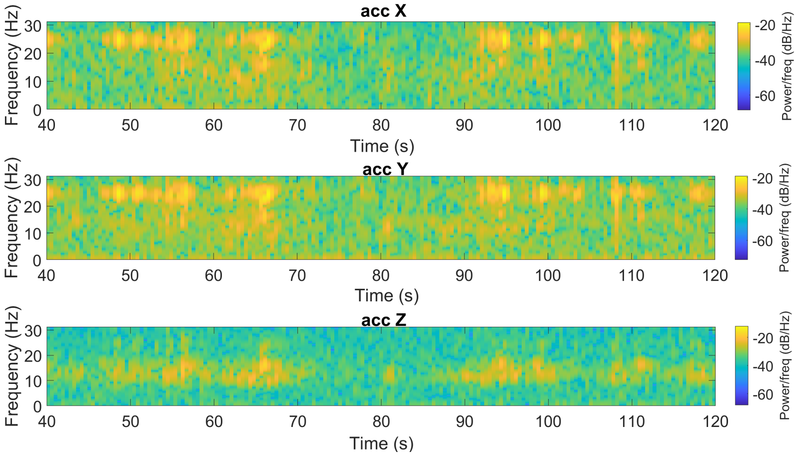

Fig. 7: Spectrogram of acceleration data.

5 Discussions

The proposed SHM acquisition system employs cost-effective hardware, featuring a MEMS accelerometer sensing unit with medium to high performance and low power usage. The setup is conveniently configured with a BT application, and the firmware transmits precise time-stamped data wirelessly to a remote server for further analysis and offline post-processing on the PC. The complete system was tested in an initial short-acquisition campaign on a bridge, observing its vibrations during vehicle crossing.

In this preliminary study, the monitoring system was able to detect bridge oscillations caused by vehicle loading events, resulting from the offline analysis in the time and frequency domains. In particular, the acceleration data contain numerous transient signals caused by vehicles crossing the bridge. However, when tracking vehicles on the bridge, significant observations were made: distinctive patterns were detected in the accelerometer signals during passages of heavy vehicles, in contrast to instances without any crossings, as verified by video comparisons. It is possible to identify the crossings of heavier vehicles, such as bus or track, from both time-frequency domain analysis. Yet, most signals related to lighter vehicle crossings were of low magnitude, making it difficult to differentiate them from background noise by applying a simple threshold to the amplitude signal.

6 Conclusions and Future Works

The cost-effective monitoring system presented effectively detects bridge oscillations due to heavy vehicles. Using a low-power MEMS accelerometer sensor unit that wirelessly transmits data for offline analysis, the system was tested during vehicle traffic on a bridge. It found distinct time-frequency patterns for heavier vehicles, despite the challenges of identifying lighter vehicles using only raw acceleration signals. Whereas lighter vehicles are harder to detect from the magnitude or frequency domain, they generally do not damage bridges, whereas instead heavier vehicles provide significant data for damage detection, crucial for assessing structural integrity, offering significant data for the advancement of damage detection algorithms. Moreover, the system distinguishes between traffic activities and ambient noise, eliminating the need for additional vehicle detection equipment, and making it a cost-effective solution to monitor bridge health in a power-limited and communication-restricted environment.

Future efforts will include extended data collection campaigns, varying the conditions of the bridge sensor setup, and the use of sophisticated analytical methods. These efforts aim to enhance the discrimination and collection of detailed information regarding the bridge's response to transient vehicle loading events, leading to improved identification of the target area and any long-term degradation of the bridge. Moreover, a larger dataset could help develop reliable markers and statistical models, for example, through machine learning methodologies, aimed at identifying and classifying vehicular crossings and extracting additional vehicle-related information.

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