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DEVELOPMENT OF A STAND-ALONE VIBRATION MEASUREMENT SYSTEM FOR BRIDGE MONITORING

Dio Lins[1], Steffen Franke[2], Roger Weber[3], Bettina Franke[4], Joel Karolin[5]

ABSTRACT: The quality assurance of timber bridges is currently ensured mainly manually by regular visual inspections over the entire life cycle. To reduce this (cost) effort, the possibility of continuously recording the condition of bridges through monitoring is being investigated. This would also increase the confidence in the long-term load-bearing capacity of timber bridges among planners and public. In addition to the permanent recording of the wood moisture content, conclusions can also be drawn about the condition and even possible damage by recording the natural frequencies which depends on the stiffness. For this purpose, a stand-alone vibration measurement and evaluation system was developed, which is easy to handle and suitable for long-term monitoring due to its energy efficiency. Beside a first application on a low-traffic timber bridge for several months, the system was validated with investigations on various types of artificial damages on the natural frequency of timber components.

KEYWORDS: Vibration measurement system, timber bridges, natural frequency, damage identification, quality assurance

1 INTRODUCTION

Every structure vibrates due to natural excitation or use in its natural frequency (see Figure 1), which depends on the mass and stiffness. If damage in individual structural members or the complete structural system occurs, the stiffness may change and so does the natural frequency [1]. By continuously recording the natural frequency, possible damage can therefore be detected at an early stage. However, the previous studies on this topic mostly refer to steel or reinforced concrete structures [2]. In timber construction, knowledge is available for the pure vibration assessment of timber ceilings or bridges, e.g. [3], [4]. The application to timber bridge structures for condition assessment is not yet established. Bridges are normally used daily and the slow traffic as well as heavy traffic causes the supporting structure to vibrate. The continuous recording of the changes of the natural frequency of timber bridges therefore not only serves to detect damage, but also to systematically gain knowledge.

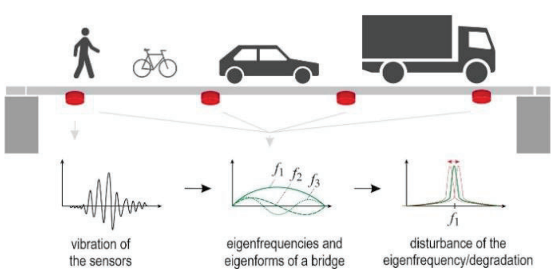

Figure 1: *Daily loading situations of a bridge*

Bridges are indispensable in the traffic area and are subject to regular quality inspections. In Germany for example, bridges must undergo a simple and a main inspection every three years alternately [5]. These are always carried out close to hand and therefore entail a great deal of effort, especially for timber bridges [6], [7], [8]. Efficient digital tools for monitoring purposes are missing in everyday life and are not specifically adapted to the material or purpose of timber bridges.

For the development of a monitoring system of the natural frequencies, the constantly occurring measurement data (accelerations, vibrations) must be digitally recorded, filtered, and analysed so that differences in the vibration behaviour, in the natural frequency, can be recognised. In this way, e.g., as a traffic lights principle, authorities can obtain results about the condition of the timber bridge and at the same time engineers or researchers can obtain general data sets to improve vibration measurement or design. Here, the development of a measurement system of vibration sensors including online analysis for monitoring the vibration behaviour of timber bridges during daily use should support.

[1] Dio Lins, Bern University of Applied Sciences, Switzerland, dio.lins@bfh.ch
[2] Steffen Franke, Bern University of Applied Sciences, Switzerland, steffen.franke@bfh.ch
[3] Roger Weber, Bern University of Applied Sciences, Switzerland, roger.weber@bfh.ch
[4] Bettina Franke, Bern University of Applied Sciences, Switzerland, bettina.franke@bfh.ch
[5] Joel Karolin, Bern University of Applied Sciences, Switzerland, joel.karolin@bfh.ch

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2 THE NEW VIBRATION MEASUREMENT SYSTEM

2.1 COMPOSITION OF THE MEASURING SYSTEM

For the development of a standalone, wireless, battery-operated, easy to use and to install vibration measurement system, the requirements for the specific application at timber bridges or timber floor systems were examined, such as the measurand (speed/acceleration), the required accuracy and whether 1- or 3-axis sensors can be used. Focus was also given to the lowest possible energy consumption for the acquisition and transmission of the measurement data (digitisation).

The developed system consists of several sensor nodes and a powered HUB, (see Figure 2). Each sensor node includes an accelerometer (+/- 6g) with a sampling rate of 2 kSamples/s and a bandwidth of 70 Hz, and subsequent downsampling to 100 Samples/s and allows the 3-axial acquisition of the accelerations. They are battery-operated (runtime 0.5 year) and communicate up to 100 m with the HUB via Bluetooth Low Energy 5.2. A nRF52840 from Nordic is used as CPU and BLE transceiver.

The HUB is based on a Linux board from Toradex (Apalis i.MX8), is powered by the network and is located within the 100 m range of the sensor nodes. Raw data is stored locally and sent via LTE to the database on the server (see Figure 3). The HUB controls and monitors the sensor nodes. Problems such as short disconnections to the sensor nodes are detected and handled so that long-term use is ensured.

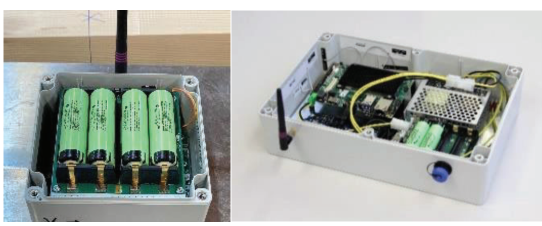

Figure 2: *Sensor node with 3-axis acceleration sensor below the battery pack (left) and HUB (right)*

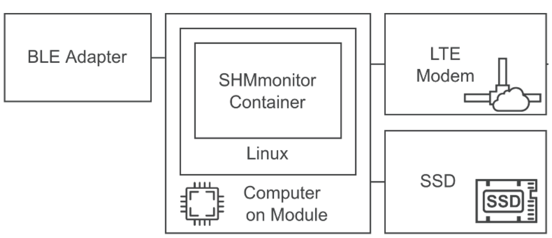

Figure 3: *Details of the HUB*

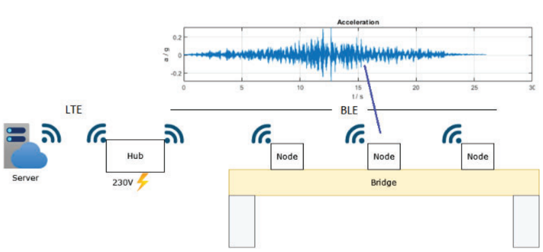

Figure 4: *Schematic diagram of the measuring system as cluster configuration*

2.2 SINGLE AND CLUSTER USE

In cluster use, several nodes can be integrated into one measuring system by the HUB to analyse several vibration frequencies at the same time or to determine the vibration form of the structure. All sensor nodes transmit the raw acceleration data to the HUB, which sends the data on to a server (see schematic diagram in Figure 4). Here, the data is evaluated and visualized offline by the SHMlive software developed in-house. Sensor data can be displayed in the time domain as well as in the frequency domain. Thus, it is possible to display the natural frequencies and to detect a shift/change of the frequencies.

As an alternative to the cluster use with the HUB, an adapter and notebook can be used to create a status recording or single use of one node. In this configuration, the sensor node directly transmits the raw acceleration data to a PC in real time where it can be further analysed. For this purpose, the SHMlive software is directly used to control the sensor nodes and visualise the acceleration data.

2.3 VALIDATION OF THE SYSTEM

The accuracy of the system was tested. To this end, status recordings were carried out on single span beams that were triggered by an impact (see Figure 5). The results of

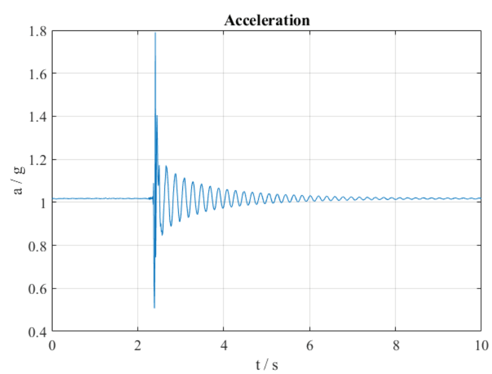

Figure 5: *Time domain: Acceleration over time*

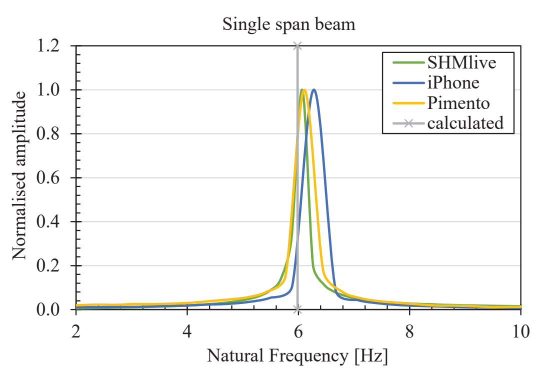

Figure 6: *Comparison of natural frequencies between different measurement systems*

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the new system were then compared with existing measurement systems. Those were "Pimento" with one sensor and the application "phyphox" developed by RWTH Aachen University on the mobile phone (IPhone SE). As you can see in Figure 6, there is only a difference of 0.6 % compared to the "Pimento" system in this test. The deviations from "phyphox" are greater with 3.5 %, but this is also not a scientific measuring system as an application for the mobile phone. In addition, the repeatability of the new system was tested in various trials and found to be 0.05 Hz. In all these trials, it was also possible to ensure that the handling of the newly developed system is practicable and easy.

3 INVESTIGATION OF ARTIFICIAL DAMAGES

3.1 METHODOLOGY AND TEST SETUP

Tests were carried out to quantify what influence various types of artificial damage have on the natural frequency of timber components and to what extent these can be detected with the new system. For one of the experiments, a beam with a cross-section of 60 mm x 80 mm was used. This single span beam was separated at half span and a lap joint was created. To reconnect the two parts, side members with the same height and half thickness were screwed on both sides on the beams with 6 screws per connection and shear plane (Figure 7). By means of a 4-point bending test (see Figure 8) the lap joint was stepwise plastically deformed to analyse the influence on the natural frequency. It was loaded and unloaded in 8 cycles, increasing the maximum force for each of them, cp. Figure 9. After the individual cycles, the beam was retested for its natural frequency with an additional weight of 5 kg and 20 kg placed in the middle of the beam to analyse the influence within two different frequency ranges.

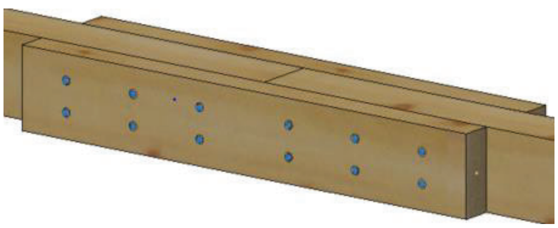

Figure 7: *Lap joint with screws (4.5 mm x 60 mm)*

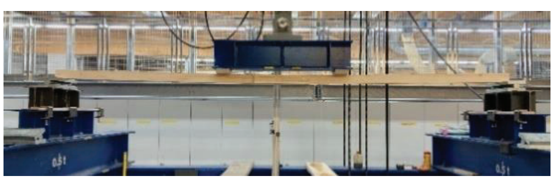

Figure 8: *Test setup*

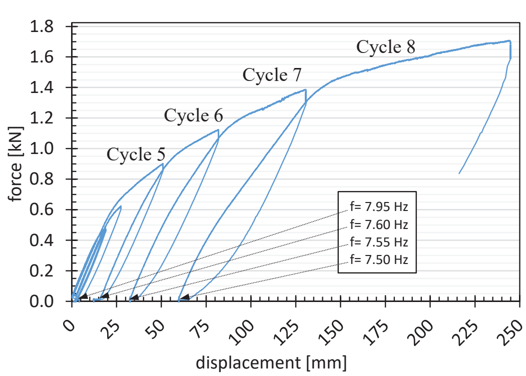

Figure 9: *Force-deformation diagram with associated natural frequencies*

3.2 RESULTS

Figure 10 shows the beam with lap joint at maximum deflection in the test setup (top) and a detail of the deformed joint (bottom). In the last loading cycle a maximum force of 1'684 N and a maximum deformation of 245 mm was achieved.

The force-deformation diagram in Figure 9 shows the load levels considered and the corresponding natural frequencies with an additional weight of 5 kg. The experimental investigation shows that frequencies can be measured with a resolution of 0.05 Hz using the developed system. This results from the FFT analysis and essentially depends on the analysed time duration, which was chosen to be about 15 s. As expected, the natural frequency of the beam tends to decrease with increasing artificial damage. However, the differences are very small, and the observation did not occur consistently across all measurements (see Table 1), so the results are still subject to some uncertainty.

Table 1 shows all the measured natural frequencies with the different additional weights. Even though it tends to decrease with increasing plastic deformation, for 5 kg an

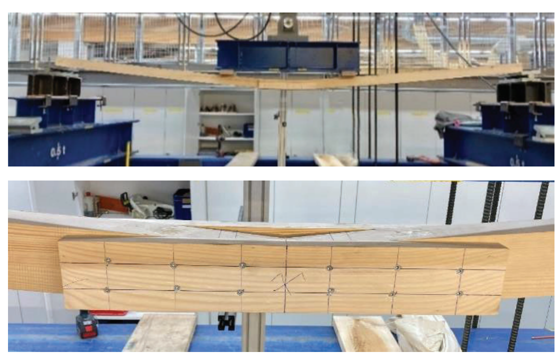

Figure 10: *Test setup (top) and deformed joint (bottom) at maximum displacement*

Table 1: *Natural frequencies [Hz]*

Load-cycle	1	2	3	4	5	6	7	8
5 kg	7.90	7.80	7.85	7.95	7.60	7.55	7.50	7.60
20 kg	5.20	5.20	5.20	5.15	5.10	5.10	5.15	5.10

increase of 0.05 Hz and 0.10 Hz is evident after cycles 3, 4 and 8. For an additional weight of 20 kg, an increase of 0.05 Hz can be observed after cycle 7. To validate these observations, further investigations need to be carried out with larger cross-sections and static systems.

4 MEASUREMENTS AT NEUMATT-BRIDGE AS APPLICATION

4.1 TEST SETUP

The developed vibration measurement system was installed on the Neumatt-Bridge near Burgdorf (Figure 11 and Figure 13). The Neumatt-Bridge is a covered truss system bridge made of soft- and hard wood products. With a span of 59 metres, it is the largest free-span timber truss bridge in Switzerland. It is used for slow traffic (mainly pedestrians and bicycles but also agricultural vehicles). With regard to be used at a Swiss Festival in 2013, four mass dampers adjusted to the natural frequency of the bridge were installed in order to limit the vibration accelerations. The new vibration measuring tool was installed at three positions, and each node measures the accelerations in x-, y-, and z-direction. The positions of the sensor nodes on the bridge were chosen to be at the points of maximum deflection of the first and second eigenform, i.e., two at the midpoint (at both trusses) and one at a quarter point of the bridge (see Figure 12). The sensor nodes were attached to the top chord of the trusses so that direct influences from the roadway planking did not falsify the results and the overall structural behaviour could be analysed.

__Figure 11:__ Neumattbridge Burgdorf, side view of the timber bridge (top) and location of the measuring sensors and data logging station (bottom)

During the monitoring period from March to June 2022, a data logging of the acceleration was started every 10 minutes for a period of 30 seconds with a sampling rate of 100 Hz. This corresponds to 144 measurements per day (Figure 14), whereby a PSD (Power Spectral Density) analysis was carried out for each measurement to determine the natural frequencies accordingly (Figure 15). The first natural frequency was averaged over one complete day. The data transmission and management are used as described before in chapter 2.1 and 2.2.

4.2 RESULTS

Figure 14 to Figure 16 show the results of the long-term vibration measurement in vertical direction of the timber bridge. Figure 14 shows in example the acceleration over time of one randomly selected single measurement. In Figure 15 the corresponding power spectral density analysis (PSD-analysis) is shown. The peak at a frequency of approx. 2.9 Hz represents the first natural frequency. Figure 16 summarizes the determined first natural frequencies averaged over one day for the complete measuring period. The results of all three sensors are shown for the first month. The results of sensor 3 are shown for all three months. In average, the fluctuations are between 2.5 Hz and 3.0 Hz. The sporadic higher readings are related to the daily analyses of the PSD rather than a change in the condition of the structure.

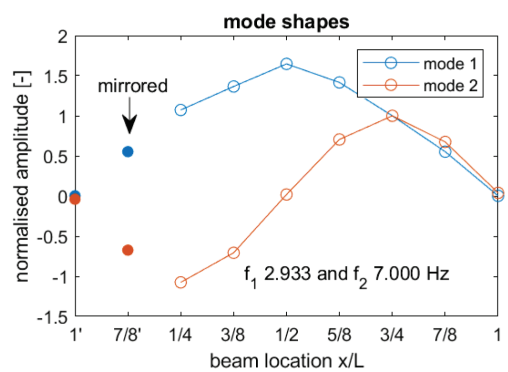

__Figure 12:__ First and second eigenform measured of the bridge

__Figure 13:__ One of the sensor nodes of the new vibration tool

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A visual inspection of the Neumatt-Bridge was carried out before and after the measurement period. No visible defects were found in the supporting structure or in the connection details what is confirmed by the measurement results. Especially the measuring sensor 3 in Figure 16 does not show any trend development from the average level.

The vibration measurement handling and results are satisfying. The measurement sensitivity was sufficient for this first application and in relation to the built-in vibration dampers. Changes in the natural frequency could only be recorded through the daily stimulation by the random slow traffic. The measurement results achieved confirm the generally good condition of the Neumatt-Bridge.

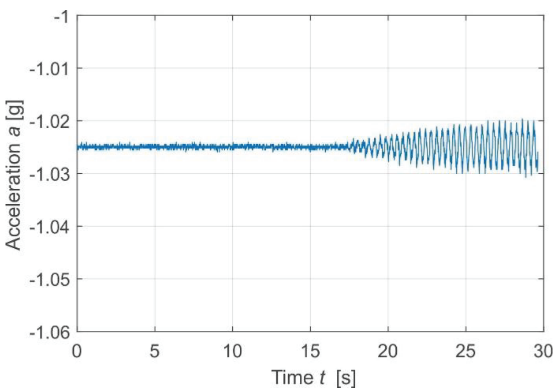

Figure 14: *Time domain: Acceleration over time*

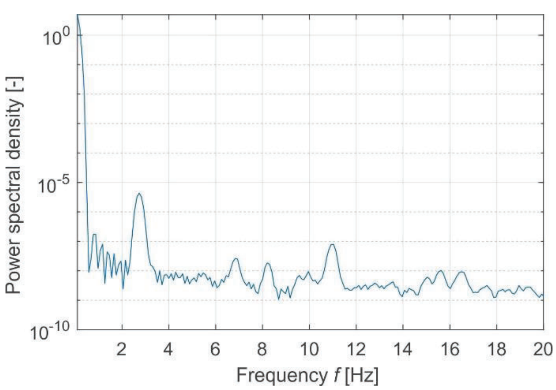

Figure 15: *Frequency domain*

5 CONCLUSIONS AND OUTLOOK

It was possible to develop a new type of vibration measurement system for simplified use, quick measurements, but also for monitoring. In a first step, the developed vibration measuring system was compared with other measuring systems. It shows a comparable accuracy to existing vibration measuring systems. However, the accuracy of the natural frequency measured is not only dependent on the hardware, but also on the evaluation period and the sampling rate of the recording.

The influence of different artificial damages on the natural frequency of timber components was investigated experimentally on a simple system (single span beam) at small scale. The artificial damages considered were investigated regarding their influence on the natural frequency. In general, artificial damage led to a decrease in the natural frequency. Damage to the structure usually leads to a loss of stiffness, which leads to a reduction in natural frequency. The first results reached are plausible but should be further verified on larger cross-sections, and long-term measurements. It was shown that the occurrence of artificial damage to beams can be detected by means of a natural frequency analysis. However, it was realised that a high measurement resolution is required to detect already smallest damages or anomalies.

The 3-month measurement at the Neumatt-Bridge in Burgdorf showed almost constant values of averaged natural frequencies. This confirms the overall good condition of the timber bridge by visually inspections. To be able to distinguish possible damages from seasonal fluctuations in the evaluation, measurements would have to be carried out for longer periods, at least one year. On consideration of the large fluctuations of the natural frequency on individual days it is noticeable that the frequencies are multiples of the most commonly measured frequency in the range of 2.5 Hz to 3.0 Hz and thus represent other natural frequencies of the bridge.

The vibration measurement system achieved is promising for the quality monitoring of timber structures and timber bridges. The wireless connection between the sensors and the HUB makes it possible to measure vibrations in buildings over several floors or rooms, for example. Due to the simple evaluation of the data, the required values

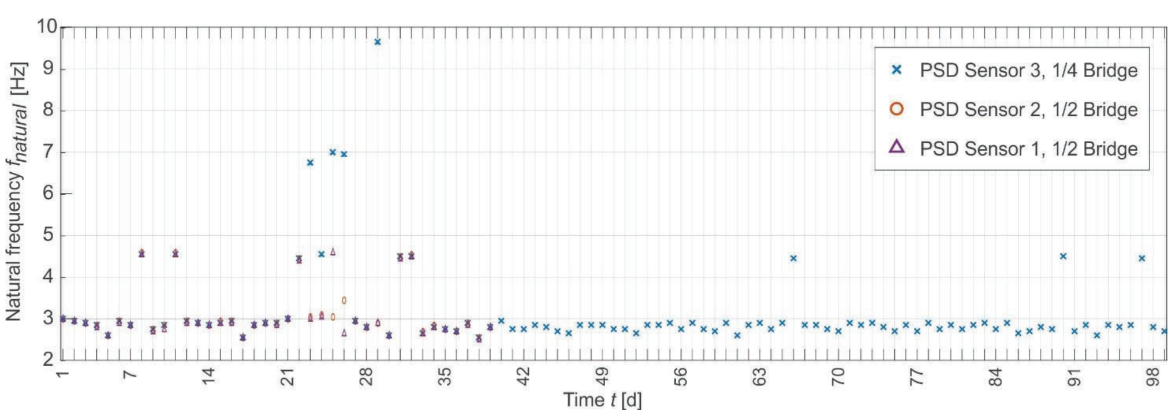

Figure 16: *First natural frequency vs time*

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can be determined immediately. In addition, a live output of the intended values is possible by means of the supplied software.

In next steps, further areas of application in the monitoring of supporting structures or other materials could be examined. For long-term vibration monitoring of structures, it is also important to learn about damage-independent fluctuations of the natural frequency due to e.g., data analysing, averaging and climatic changes (temperature, humidity respectively wood moisture content) or seasonal changes. With this results, possible damage could be qualitatively reliably detected. The extent to which changes in load-bearing structures can be diagnosed at an early stage cannot yet be assessed with the experiments currently being carried out. Damages can only be detected so far, but neither localised nor determined in its extent.

The newly developed vibration measurement system can be requested for monitoring timber structures. With these continuing monitoring campaign, open questions can be answered, and possible market entry can be achieved.

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