SHM: Railroad bridge monitoring using Dragonfly® piezoelectric strain gauge

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Abstract
Structural Health Monitoring (SHM) applied to civil structures such as bridges, high-rise towers, and electricity pylons can help plan their maintenance, detect damages or unexpected events, and extend their remaining operating lifetime. Typical sensors for this field have limitations in terms of sensitivity, drift, and reliability. Dragonfly® new piezoelectric strain gauges, with a resolution three order of magnitude over classic sensors, solve these issues and enable new applications. This paper presents the implementation of Dragonfly® sensors on a railroad bridge. With a single sensor, it has been possible to identify the bridge girder first two resonance using ambient noise, train passage loading for fatigue-life analysis, train passage reproducibility, and pedestrian passage on the walkway. A complete comparison with a classic metallic foil strain gauge and a vibration specialized MEMS accelerometer is detailed.

Key Words
Piezoelectric, Structural Health Monitoring, Bridge monitoring, Strain gauge, Fatigue-life, Event Detection

Figure 1: The railroad bridge monitored. The external metal girder on which the sensors are installed is visible.

1 Introduction

In France, 25% of the existing bridges are reaching their expected service life. Moreover, 79% of the total park present structural defects that need to be assessed [1]. Monitoring the critical structures becomes essential to prevent a catastrophe. The present study concerns the usage of Dragonfly® (DGF) piezoelectric strain gauges for Structural Health Monitoring (SHM) of a railroad bridge.

Metallic foil strain gauge (SG) and vibrating wire are the historic sensors used to measure strain on civil structures. However, civil structures are designed to undergo little deformation in service (0.1-50 µdef). Both SG and vibrating wire are limited by their resolution around 1 µdef in best case scenarios. Moreover, they are known for their DC drift over time, which complexifies long term monitoring. There is therefore a need for more sensitive and less prone to drift sensors in the time domain.

As strain has been historically difficult to monitor, industry has been relying on acceleration measures. Piezoelectric accelerometers, precise but expensive, have been the reference sensor to make modal analysis of structures. More recently, there has been an update in the field with the creation of MEMS accelerometers specialized for vibration measurement. These are interesting cost-wise but have generally lacked the sensitivity required for SHM [2,3].

The present study presents the usage of flexible piezoelectric strain sensors for SHM of a railroad bridge. This applicative context is used to demonstrate the interest of high sensitivity strain sensing in SHM.

1.1 Dragonfly sensors

Dragonfly® sensors sensitive element is an extremely thin piezoelectric ceramic, packaged in a flexible PCB, and pre-wired with a SMA connector. The sensor is glued with cyanoacrylate glue to the object to be studied. The specificity of this sensor is that it enables measurements down to 5nm/m.

Like all sensors based on piezoelectricity, Dragonfly® are dynamic sensors by nature. With adequate charge amplifier electronics, they can measure slow events (up to quasi-static). However, Dragonfly® sensors dynamic nature is very interesting for civil structure monitoring as it is insensitive to slow thermal expansion.

1.2 The railroad bridge studied

The bridge monitored is in Grenoble, France, in proximity to the train station. It has 3 railways and an auxiliary wooden walkway accessible to the public (Figure 2 &Figure 3). The bridge is a simple girder bridge with 12 steel beams. Trains are circulating in both directions (towards Grenoble and Lyon).

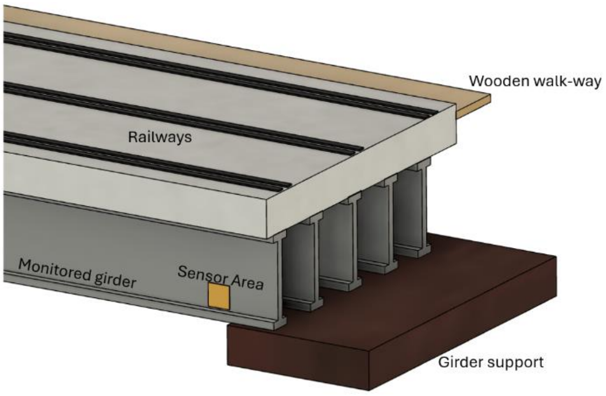

Figure 2: Schematic of the bridge girder and walkway.

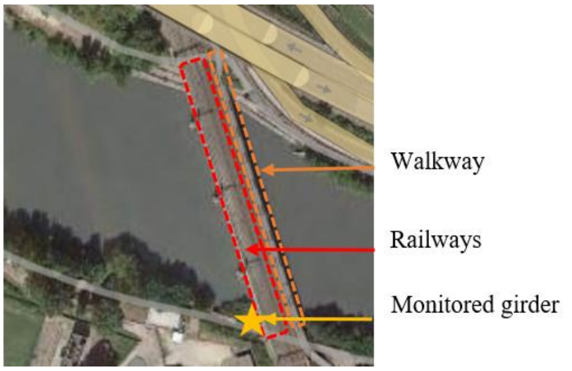

Figure 3: Schematic (left) and sky view (right) of the monitoring area.

2 Sensing strategy

Standard strain gauge (SG), Dragonfly® sensor (DGF) and MEMS accelerometer (MEMS) have been installed. They are all located on the external girder of the bridge, on the opposite side of its walkway as depicted on Figure 2. This configuration has been chosen because it is easy to access, and it provides maximum deformation of the girder. For better acceleration measures, the MEMS should be installed at the center between two support elements. This location is, however, not accessible. All sensors have therefore been installed close to the girder support element. It should be noted that there is a power line passing within 1 m of the sensor location. There is therefore a high level of 50 Hz radiation. This is particularly an issue for non-shielded sensors like SG and MEMS.

The surface was polished and cleaned to ensure proper bonding of sensors. All three sensors are measured by a Dewesoft IOLITE 6-STG system. A video camera was installed for the analysis of train passage.

2.1 Strain gauge setup

A standard HBM 120Ω strain gauge has been installed and protected with ABM75 by HBM. The strain gauge is measured in quarter bridge configuration.

2.2 Accelerometer setup

We used a state-of-the-art 3-axis MEMS accelerometer on an evaluation board (EVAL-ADXL356CZ) by Analog Devices.

2.3 Dragonfly® setup

A Dragonfly® passive sensor has been installed parallel and near the strain gauge. The same external ABM75 protection was applied. Signal was measured with a charge amplifier. In this configuration, the lower cut-off frequency is limited by the amplifier at 0.01 Hz.

Figure 4: Dragonfly sensor before protective layer installation

3 Results & analysis

3.1 Bridge resonance at rest

For this section, the bridge is at rest with no passage. The signal Power Spectral Density (PSD) is presented in Figure 5 & Figure 6 for DGF, SG and MEMS. The only peaks on the SG are related to ambient electrical grid radiation (50 Hz and harmonics). These are also dominant on the MEMS. On DGF and MEMS, two sharp peaks (28 and 60 Hz, identified in red) can be attributed to structural components. Additional low frequency content between 6 and 20 Hz is observed on the DGF. We would need the complete model of the bridge to understand its overall mechanical behavior.

Tracking eigenfrequencies of structures is often used for structure damage monitoring [2-4]. Though it is typically done through accelerometers, the data can now be obtained through the high sensitivity of the piezoelectric strain gauge like DGF.

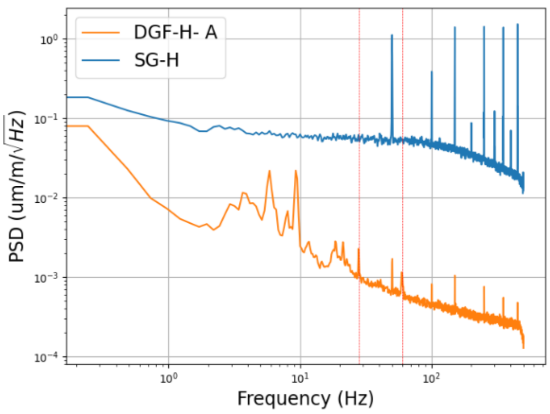

Figure 5: PSD of the bridge at rest for Dragonfly® (DGF) and strain gauges (SG)

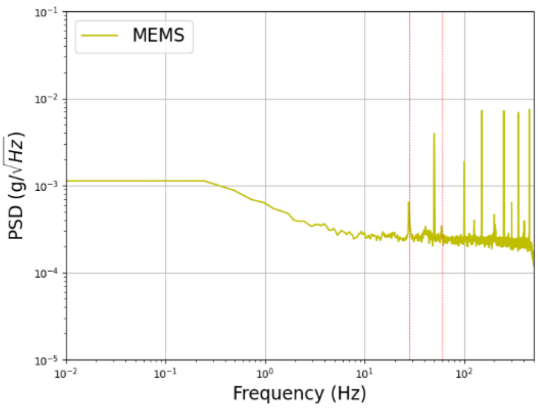

Figure 6: PSD of the bridge at rest for the MEMS accelerometer

3.2 Train passage analysis

Figure 7 shows the temporal signal for all three sensors during significant mechanical solicitations from train passage. The SG signal received consequent ambient radiation noise produced by the nearby electrical lines.

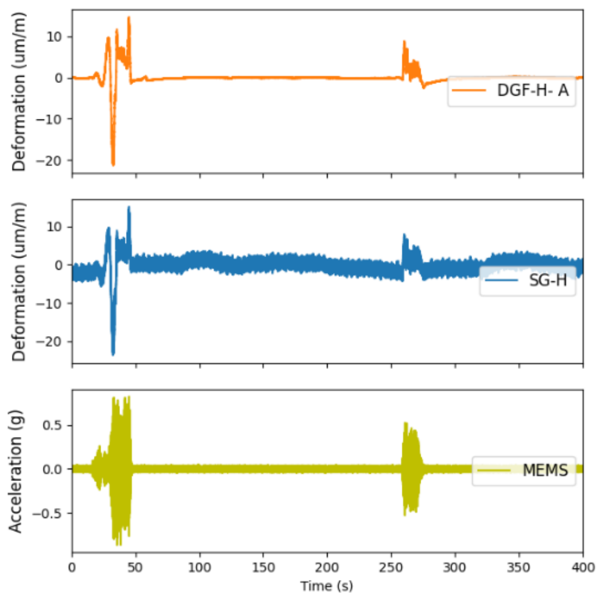

Figure 7: Raw signal with 2 train passages

For further analysis low-pass first-order IIR filter at 45 Hz has been applied to the SG for sensor comparison. Moreover, the DC drift from initial sensor calibration was removed for the SG.

Figure 8 &Figure 9 presents the spectrogram for the DGF and the MEMS for the same period. Though the high frequency intensity is better for the MEMS, we can see an extinction under 20 Hz. This is coherent with Figure 5 where DGF also caught more detailed information in this frequency range. DGF measures a deformation that is proportional to the bridge displacement. As the acceleration is proportional to the second derivative of the displacement relative to time, it is easier to measure deformation than acceleration at low frequencies.

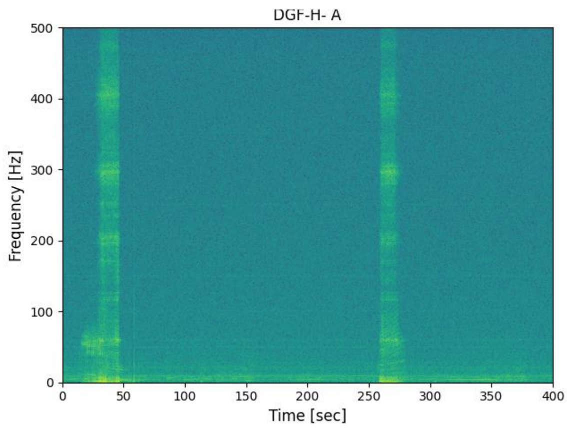

Figure 8: Spectrogram for the DGF measurement of Figure 7.

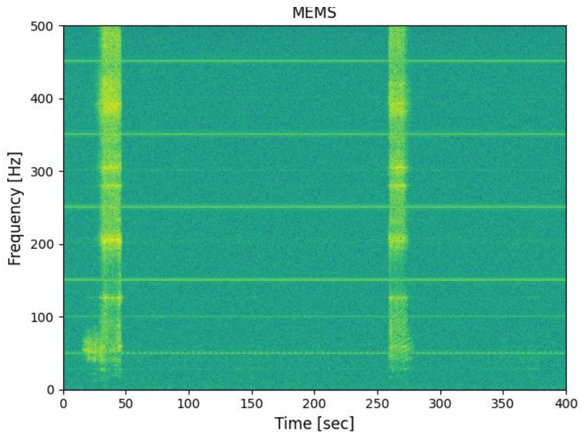

Figure 9: Spectrogram for the MEMS measurement of Figure 7.

After signal treatment, excellent agreement between the strain gauge and the Dragonfly is obtained as demonstrated in Figure 10. For the train in the figure below, the maximum load is 8.77 µdef and occurred at the locomotive wagon passage over the sensor location. The passage of 8 wagons can be identified.

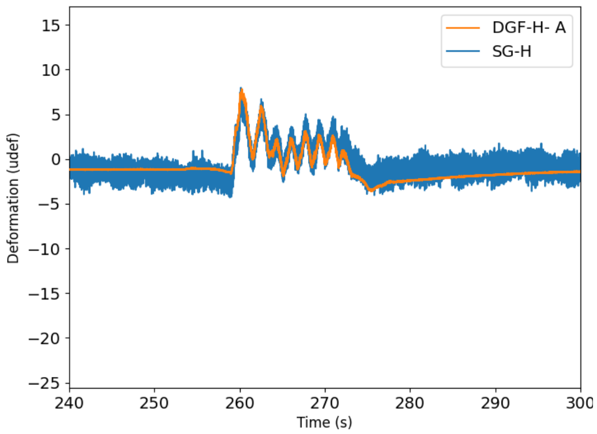

Figure 10: Passage of a passenger train (*Figure 7* at 250s)

Rainflow load counting is a widely used method to calculate the structure remaining service lifetime [5-6]. In these studies, strain amplitude measured with classic strain gauge is small (<10 µdef). The SG resolution in the best condition is around 1 µdef. SGs have to be installed on areas of the bridge undergoing a maximum of deformation to have some chance of success. As the signal-to-noise ratio is greatly increased with Dragonfly®, sensor installation can be done in convenient and accessible bridge area where deformation is smaller.

On figure 7, two trains passed simultaneously on the bridge on different railways at 30s. It resulted in a very different signal pattern for event identification.

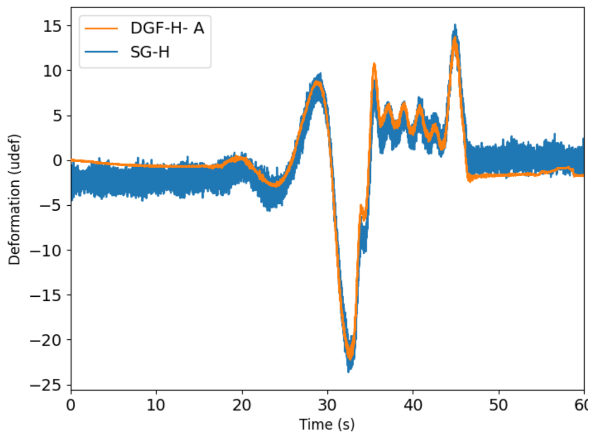

Figure 11: Dragonfly® (DGF) and SG signal while 2 trains pass on the bridge (Figure 7 at 30s)

3.3 Pedestrian passage identification

Large strains such as the ones created by trains are useful to measure the fatigue life of a structure. However, it is interesting to monitor events of smaller amplitude for surveillance applications. The dragonfly resolution being very low (0.01 µdef), the strain generated by a single individual passing on the bridge is easily measured. The figure below shows the peak-to-peak signal intensity increasing as walkers pass over the walkway. It is notable that even though sensors are installed on the girder on the opposite side of the walkway, strain amplitude is sufficient for event identification.

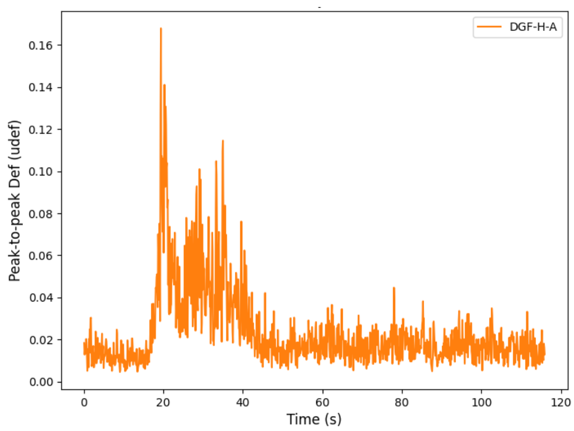

Figure 12: Signal peak-to-peak for pedestrian passage on the walkway.

3.4 Train passage reproducibility

The graph below presents the passage of two different trains, with the same number of wagons, same direction and departure railway. An exact superposition of the signals can be seen for DGF. For this measure, an IEPE version of the Dragonfly® was used. This sensor is compatible with IEPE acquisition systems and does not require a charge amplifier. The IEPE acquisition adaptor lower cut-off frequency is 0.16Hz, thus modifying the signal shape.

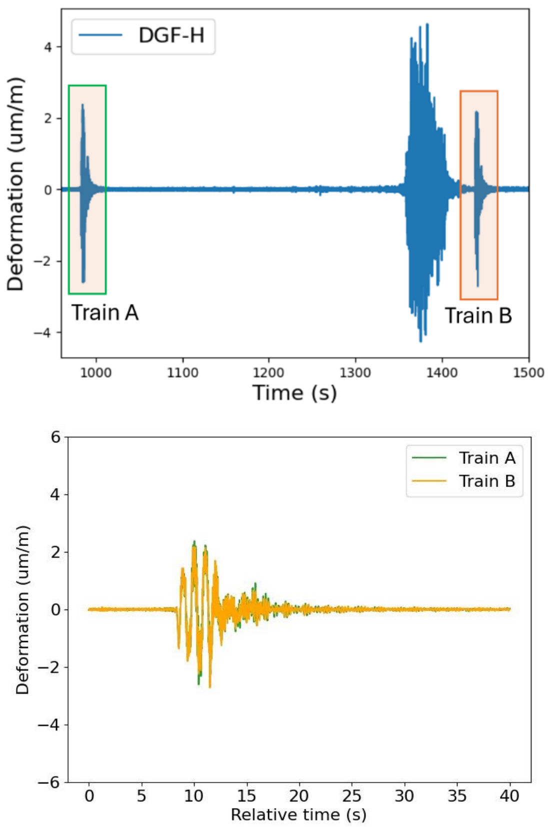

Figure 13: Dragonfly® (DGF) for 2 different passenger trains coming from the train station. Train B time has been shifted for superposition.

4 Conclusion

Dragonfly piezoelectric strain gauge has been tested in the context of civil structure health monitoring. Structure resonance frequencies have been measured using the ambient noise, which enables a follow-up of the monitored structure integrity. Events causing the structure to fatigue such as train passage have been quantified. The values are in excellent adequation with conventional metallic foil strain gauge. The higher SNR of dragonfly enables them monitoring of very precise events, from train repeatability to pedestrian passage detection. The Dragonfly® could bridge the measurement worlds of strain and vibration in SHM in a single sensor.

References

[1] https://www.senat.fr/rap/r18-609/r18-6095.html Cerema, IQOA Ponts - campagne d'évaluation nationale 2017

[2] Cigada, Alfredo, Massimiliano Lurati, « Evaluation of the metrological performances of MEMS accelerometers to the aim of their application in Structural Health Monitoring », January 2008.

[3] Ribeiro, Renan, t Rodrigo Lameiras. « Evaluation of low-cost MEMS accelerometers for SHM: frequency and damping identification of civil structures ». *Latin American Journal of Solids and Structures* 16, June 2019.

[4] Jang, Shinae, Hongki Jo, « Structural Health Monitoring of a Cable-Stayed Bridge Using Smart Sensor Technology: Deployment and Evaluation ». *Smart Structures and Systems* 6, July 2010.

[6] Warsi, Zain Hussain, Shahzadi Mahaa Irshad, « Sensors for Structural Health Monitoring: A Review ». In *2019 Second International Conference on Latest trends in Electrical Engineering and Computing Technologies (INTELLECT)*, 1-6, 2019.

[7] Ni, Yi-Qing, Yun-Xia Xia. « Strain-Based Condition Assessment of a Suspension Bridge Instrumented with Structural Health Monitoring System ». *International Journal of Structural Stability and Dynamics*, March 2016.

[8] Schuler, Harald, et Florian Meier. « Monitoring the Prestressed Rods in the Basel Border Bridge Maintenance Project: Data Analysis during the Passage of Trucks ». *Sensors* 21, n° 16, January 2021.