Continuous SHM of Railway Bridges Based on Vibration Analysis of Qualitative, Selected, Asynchronous Data

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Abstract. Since mid-2022, a consortium of 3 partners, SISGEO, LEMTA and SNCF Réseau, is carrying out the AUDACE project, as part of the "Smart Bridges" project in France. Our objective is to provide bridge managers with real-time information regarding the occurrence of a collision of a railway bridge deck. This type of incident, likely to cause damages that can impact the stability of the structure, represents more than 50% of incidents recorded on the SNCF Réseau (SNCFR) bridges. SNCFR selected several bridges regularly experiencing this type of incident for SISGEO to install a set of relevant sensors. Among them, the AD-SIGNUM solution provides a continuous and global SHM of the bridge. AD-SIGNUM is based on several key technologies. First, geophones are used to measure vibrations of structures giving access to low amplitude signals in either quiet or noisy environment. Then, a particular effort is paid on the processing of asynchronous signals in order to make deployment and maintenance of autonomous sensors easy, flexible, and efficient. Finally, rather than gathering an endless amount of data, we focus on a qualitative perspective. This in-depth approach aims to measure the own vibration of the structure, and its evolution over time, apart from punctual non-typical disruptions. The LEMTA will compare different "Machine Learning" algorithms with supervised, unsupervised and reinforcement learning approaches to select the best performing approach to identify the critical parameters to detect anomalies and signs of impact damage to finally draw conclusions for the bridges manager to take the right decisions.

Keywords: SHM · Edge-computing · Dynamic monitoring · Bridges · Machine learning · Shock · Small structures

1 Introduction

1.1 The AUDACE Project

The project takes place in the framework of the "Smart bridges" call for project launched by the CEREMA in 2021 (french public agency for developing public expertise in the fields of urban planning, regional cohesion and ecological and energy transition). The call for project is one of the french government responses to the technical report of the french *Sénat* about the state of bridges in France [1].

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The AUDACE project focuses on hits of trucks against railway bridges: detection of the shock, characterization of the origin, and consequences on the bridge. Figure 1 illustrates one of the various situations we focus on. We aim at building a decision helper for the authority in charge of safety and security of the bridge. The project is led by SISGEO, the partners are SNCFR (french company in charge of railway infrastructure) and LEMTA (public laboratory in charge of developing AI-based data processing on the vibration/shock records).

Fig. 1. The internet is full of examples of a truck hitting rail-bridges.

The final output of the project includes a long term indicator of the health state of the bridge, and a short term (real time) shock detection. Some additional parameters will be estimated in real time, including the displacement of the deck and origin of the shock: on/off-rail and direction of impact.

1.2 The AD-SIGNUM Solution

AD-SIGNUM is the brand of an integrated solution initially developed by SAM and now proposed by SAM and SISGEO.

The solution is based on edge computing. A sensor was specifically designed in this aim, it embeds 3 orthogonal geophones (X, Y, Z), a 3D accelerometer, a micro-controller (μC) for real time computing, and a modem for SMS or DATA transmission of sensor state of health (SOH) and structural messages.

The long term structural state is based on the signal obtained from the geophones. Geophones are the best compromise between cost, sensitivity, and power consumption. Figure 2 compares the intrinsic noise level of a geophone with MEMS accelerometers [3, 4] together with the earth noise reference commonly used in geophysics [2]. In the bandwidth of interest (1–10 Hz), the intrinsic noise level of geophones is one order of magnitude lower than the one of the best MEMS based products available on the market. On the economical point of view, the price of the solution based on geophone, including the analog-digital conversion (~40€ for 3 components) is still lower than the price for ultra low noise MEMS (several hundreds euro). Finally the power consumption of these MEMS is 2–4 times the power consumption of the complete PROBE-2 sensor (45mW).

To conclude, only commercial conventional MEMS could satisfy the requirements in term of price and power consumption, but in no case could these sensors be used in the aim of recording low amplitude signals.

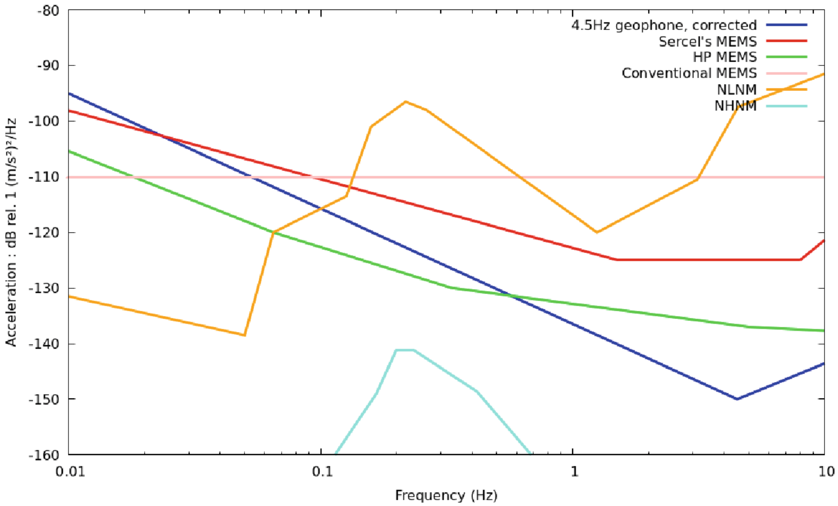

Fig. 2. Sensor noise comparison for the geophones with AD converter used in PROBE-2 (blue) converted to acceleration, Sercel MEMS (red), HP MEMS (green), and commercial low cost/low power MEMS (pink). USGS earth noise reference (New Low Noise Model and New High Noise Model) are also shown as reference in light blue and orange (resp.). (Color figure online)

Sensors are installed on the deck 2–3 m off the abutment, directly on the concrete part in order to get the best coupling with the structure. As a summary of the process involved, each sensor computes Fourier transforms in real time on 3 geophones for each sample at 125 samples per second. It builds power spectrum densities (PSD) over user-settable time windows (typically 30–60 s), and selects the PSD that most probably represents the actual signature of the structure over an other user settable time window (typically 15 min for high frequency monitoring to 24h for long term monitoring). In order to reach the low power specification, there is no internal mass storage for data, only a message buffer flushed on GSM connection cycles. For the same reason, the sensors do not include any time synchronization system other than GSM network time (1 s resolution, not compatible with synchronized digital signal processing). [5] propose to process asynchronous data acquired on mobile sensors along accurately reconstructed paths to reconstruct the shape of selected modes. Our approach is complementary since our sensors are fixed and we do not use any apriori information about the behavior of the structure and so, about the frequency range of interest.

In order to reduce the communication bandwidth requirement we only transmit the major peaks of PSDs: 15 central frequency-height of peak pairs for each PSD. This leads to a compression ration of 1:300 000 compared to the transmission of continuous signal. Structural messages consist of these major peaks of PSD and threshold based velocity or acceleration messages (shock detection). The "shock" messages include the time of event, the maximum amplitude of the event and the duration of threshold excess. On user setup, the shock messages may be supplemented by the PSD of the event for further check of internal processing. Each sensor also sends its own SOH messages including environment and signal parameters so that at any time we are able to know if the sensors are in their nominal state or not.

The solution applies to long term monitoring of concrete (eventually reinforced), masonry and mixed steel-masonry or steel-concrete bridges but not to steel-only structures due to the very fast and strong response of the structure to the temperature changes [6].

All the messages are transmitted into the cloud and processed using standard operational modal analysis algorithms leading to an estimation of eigenfrequencies of the structure. The full procedure is detailed in [6] and [7]. For each time-period, equal to the time-period defined for PSD selection and transmission, we obtain a set of EF from OMA algorithms. As the data injected into OMA algorithms do not represent the complete continuous signal but only a small part, selected on the lowest energy approach, we consider the eigenfrequencies output of OMA as the *most probable set of eigenfrequencies* of the structure, within the user-defined bandwidth, for the considered time-period. A change in the distribution of these probable eigenfrequencies will be considered as reflecting a change of the response of the structure to the input signal that is the ambient noise: earth seismic noise, wind, swell, or load of river etc.

One should understand that this process does not give access to the absolute state of the structure but is *only* sensitive to a change of state. Thus, in the scale of SHM level proposed by [8] we only aim at level 1: the detection of damages.

2 Experiment

2.1 Selection of the Targets

SNCFR manages more than 32000 bridges in France. A majority of them are so-called *pont-rail* (PRA): rail-bridge. PRAs are usually small structures: single span (typically 7-16m long), mixed steel/reinforced-concrete as illustrated in Fig. 3. Each year, more than 50% of the recorded incidents are due to hit by trucks. SNCFR selected four PRAs based on their high probability to be hit by a truck.

2.2 Instrumental Setup

SISGEO displacement sensors measure the relative displacement of the span with respect to the abutment. These sensors will give integrated static measurement of the displacement of the deck that can lead to misalignment of rails.

Fig. 3. Destructive test on the Vignacourt PRA.

Each PRA is also equipped with triggered velocity/acceleration sensors installed as a reference sensor for the need of the study. A preliminary destructive test [9] on a steel-only PRA has evidenced the advantage of continuous time records of shocks as a base/reference data set. During the test, the hit was simulated by a mass launched from a crane (Fig. 4), with increasing kinetic energy and soft and hard masses (big-bag filled with sand, wrecking ball, steel box filled with concrete). The preliminary continuous records have also evidenced the strong short term response of the steel-bridge to temperature changes.

Fig. 4. Left: Trignac PRA with the maximum height sign. Right: PROBE-2 sensor during the installation on the PRA in April 2022.

As of January 2023, a PROBE − 2 sensor that combines continuous/long term, and real-time/short term monitoring is installed on one of the 3 bridges (see Fig. 4). More PROBE-2 will be installed on the other bridges to fulfill the instrumentation. Finally, a automatic camera trap will help us to identify the origin of each shock detection. The instruments are connected to GSM network and transmit their data periodically or in real time. Also note that each instrument has its own solar power supply.

3 Results

Preliminary analysis by LEMTA shows a variety of shock detection wider than expected. As an example, unsupervised machine learning (clustering) was applied to the Villeneuve-le-Roi bridge to detect and classify the different types of shocks from August to November. We decided to work with 3 clusters since we assume that there are 3 different types of signals for events: normal passage of a train, passage of a train with anomaly and passage of a vehicle under the bridge. The algorithm tested is k-means [10, 11]. Figure 5 represents the type of each event as a function of the peak velocity along direction X (road) and Z (vertical). The unsupervised technique produced interesting results for the detection of shocks, but it was not able to distinguish between normal and abnormal train passages (Cluster 1 and 2) with sufficient precision.

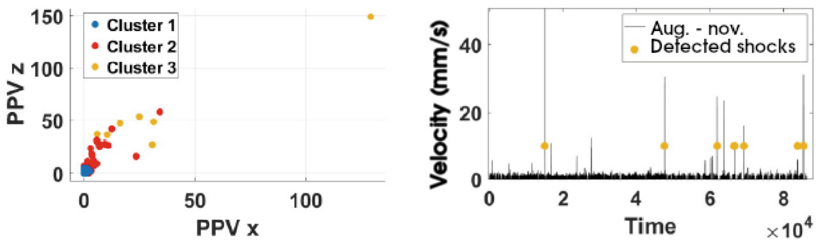

Fig. 5. Classification of events based on the unsupervised machine learning approach from August to November. Left: distribution of events as a function of X (road direction) and Z (vertical); yellow: hits; red: train with anomaly; blue: normal train. Right: time history of the hits.

A fine analysis indicates that the source for abnormal signal is on-rail: flat-wheel is probably the reason for these signals. Although these phenomena are out of the scope of the project, the algorithm should be able distinguish between off- and on- rail sources (Fig. 6 and 7).

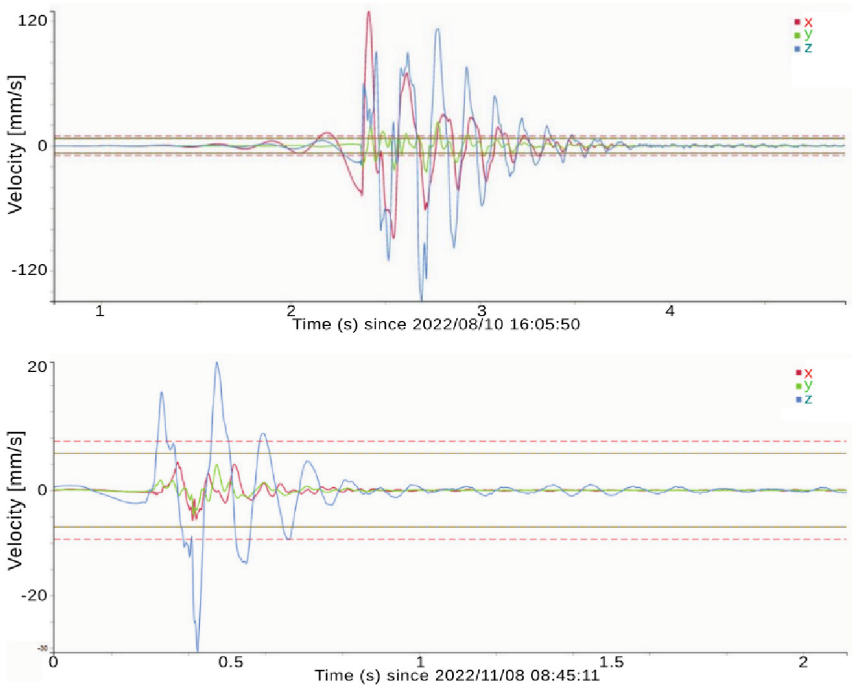

Fig. 6. Two examples of velocity records on Villeneuve le Roi PRA, for a hit by a truck (top) and probably a flat-wheel train (bottom). X (red) is parallel the road direction, Y (green) is parallel to the rail direction and blue is vertical. (Color figure online)

In January 2023, the Trignac bridge is the only PRA fully equipped. The measurements started in April 2022. “Unfortunately”, no hit occurred since the beginning of the monitoring. The fourth PRA, located in Mulhouse and suffering recurrent hits, will be monitored from April 2023.

Figure 8 shows the evolution of selected parameters of the PROBE-2 sensor installed on Trignac PRA. *Shocks* are measured as Peak Ground Acceleration in the horizontal direction, Peak acceleration and Peak velocity are measured along each direction (blue is the rail direction, green is the road direction and red is vertical). Reported values are the maximum of the parameter recorded between two messages. Maximum velocity and acceleration history shows that the bridge is heavily loaded during normal service. Also note the very low values on 2023/01/19–20 related to the strike that disrupted public transport.

Fig. 7. Main page for the PROBE-2 sensor installed on Trignac PRA. Showing detailed SOH over the period 2022/12/30 – 2023/01/30.

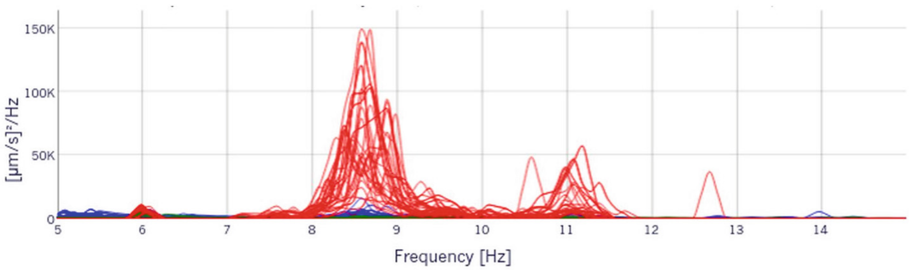

Fig. 8. PSDs transmitted by the sensor from 2022/12/31 to 2023/01/28 for the three directions (blue is the rail direction, green is the road direction and red is vertical).

Figure 9 shows the PSDs received each day during 1 month. These PSDs are injected in the OMA algorithm and the output, each day, is a set of EF candidates that are plotted in a single column corresponding to a single time slot of 1 day in Fig. 9. Note that there is no smoothing, no filtering, no a posteriori data selection in Fig. 9. The output is built with the raw EF based on 30 s PSD selected on each component over a 24h cycle. We then apply an auto-adaptative algorithm to detect changes in the distribution of EF over time and eventually raise an alert.

The stability of EF over time reflects the stability of the health state of the Trignac PRA.

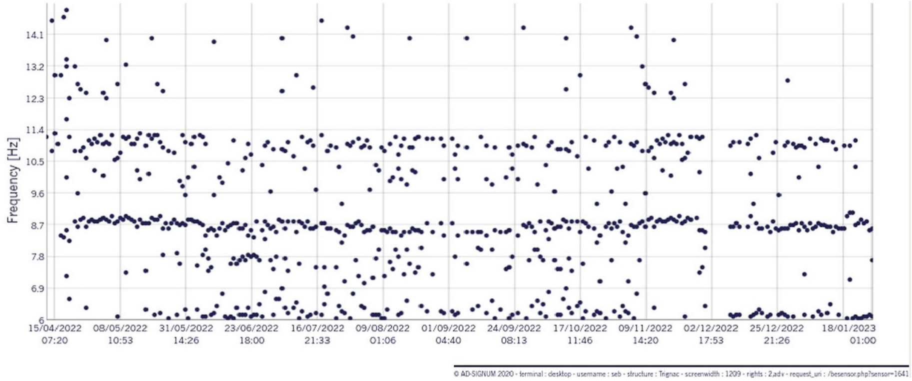

Fig. 9. Distribution of probable eigenfrequencies over time on the Trignac PRA. Each point represents an eigenfrequency candidate.

4 Next Steps and Concluding Remarks

The results obtained as of we write this note are encouraging as we are able do establish a base state-of-health of the structure contributing to its long-term continuous monitoring. In addition, shock detection provides information on singular events that may affect the short and long term stability of the structure.

The installation of all sensors will be completed on the 4 PRAs. In the meanwhile, works on detected events will continue at LEMTA, based on machine-learning approaches. The final step will be to implement the automatic algorithms developed by LEMTA in the PROBE-2 sensor. At that point, based on spectral analysis, the sensor will be able to decipher the nature and size of the cause of a shock in real time. The aim is to give the accurate information to the managing authority in charge of the decision regarding the safety of public transport.

Our approach combines global monitoring for the long term stability of the structure and real time detection and qualification of shocks. The edge-computing strategy considerably reduces the volume of data to be transmitted. Most of the processing is performed on-site, reducing not only the costs for assets and operations, but also the carbon foot-print as very few data has to be transmitted, stored, and processed in the cloud.

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