1st Latin-American Workshop on Structural Health Monitoring
LATAM-SHM 2023
December, 5-8 2023

DESIGN AND STUDY OF AN INSTRUMENTATION AND SOFTWARE FOR PERMANENT MONITORING OF A CABLE-STAYED BRIDGE

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Key words: Vibration monitoring, Digital Twins, Instrumentation, Environmental variability

Abstract. Permanent monitoring of the structural behavior of civil infrastructures require robust and reliable data acquisition systems. In this study, we present the dynamic monitoring of the Éric Tarbarly bridge in Nantes, France and its related acquisition system. This system enables to follow the temporal evolution of the modal parameters of the structure by storing accelerometers data, external environmental data and the associated metadata thanks to the HDF5 file format.

1 Introduction

In recent years, there has been a growing interest in continuously monitoring the structural behavior of civil infrastructures, with a focus on bridges. This study examines the dynamic monitoring of the Éric Tarbarly bridge in Nantes, France, a 210m long cable-stayed road bridge over the Loire River inaugurated in 2011. Dynamic monitoring, whether periodic or continuous, is crucial for understanding how the structure responds to factors like traffic, wind, and earthquakes, as well as tracking changes in its modal parameters. Differentiating between variations in modal parameters caused by damage and those due to environmental factors is a major challenge.

To address this challenge, the study introduces a real-time monitoring system called "Pegase" a versatile acquisition platform designed for structural health monitoring. The latest version of Pegase can collect data on multiple channels at up to 30kHz, with precise time-stamping for merging multi-sensor data. In this project, Pegase is implemented with eight mono-axial accelerometers operating at a 100Hz sampling rate. Data from these sensors are processed using a framework developed by the laboratory and stored in a standardized Hierarchical Data Format (HDF5).

Additionally, incorporating weather stations to account for environmental influences can complicate maintenance due to sensor placement requirements. To mitigate this issue, the study suggests and compares the use of various meteorological data sources for corrections in modal analysis. This includes local weather data, online data from network weather stations like METAR, and meteorological data from the Copernicus European program.

A generic presentation of the Eric Tabarly bridge is firstly done. Then, the developed tools and acquisition card are introduced. Finally, a comparative study of environmental parameters acquired by different means is proposed.

2 Éric Tarbarly bridge

The structure under examination is the Éric Tabarly bridge, located in Nantes, Western France, spanning the Loire river. Inaugurated in 2011, this cable-stayed road bridge stretches across 210 m. Its 27 m-wide steel deck comprises interconnected welded modules, symmetrical along its longitudinal axis, connected by spacers. Divided into two spans by a 57 m high steel pylon, the main span extends over 143 m. The bridge's construction incorporates nine parallel multi-strand cables on either side of the pylon, each varying in tension (ranging from 3000 kN to 10 000 kN), cross-sectional area (ranging from 0.005 m^2 to 0.0147 m^2), and length (ranging from 43 m to 133 m). Notably, the last five cables on the southern part are embedded in the abutment, a distinct feature of this design.

Support for the bridge occurs at three points: the southern part is embedded in the abutment, the northern part is upheld by an I-beam, and the deck is sustained by a concrete pile, while the pylon is anchored within the same concrete pile.

The bridge accommodates three lanes on each side of the deck: a bus lane, a regular roadway, and a dedicated bicycle path, alongside a pedestrian walkway.

Figure 1: Éric Tabarly Bridge

3 System of instrumentation

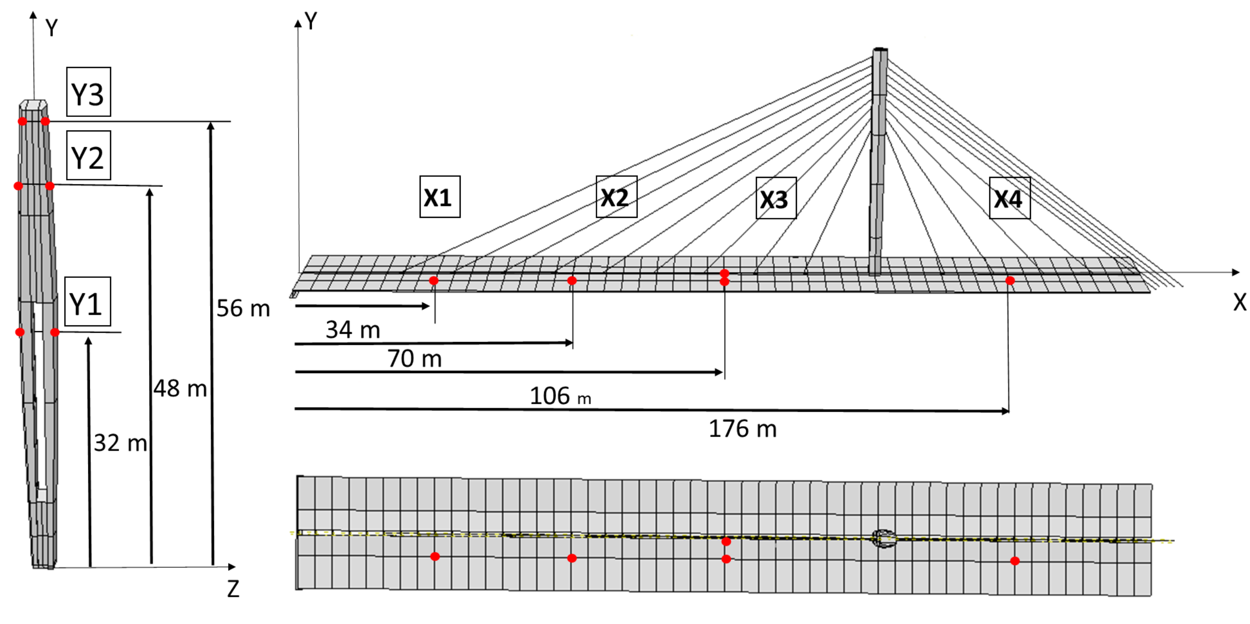
3.1 Instrumentation presentation

During 2016, a system of instrumentation was implemented to monitor the structural vibration patterns. This setup incorporates 16 single-axis accelerometers with a sensitivity of 2000 mV/G, evenly distributed with 8 accelerometers installed in both the deck and the pylon. The acceleration measurements are conducted hourly for a duration of 10 min at a frequency of 100 Hz.

The collected data is initially relayed to distinct acquisition cards—one for the deck accelerometers and another for those in the pylon—prior to transmission to a centralized server. This setup enables remote access to the measured data. However, due to a synchronization issue between the acquisition cards, the data obtained from the deck and the pylon will be managed separately.

The accelerometers utilized, known as *Silicon Designs 2210*, possess a range to capture acceleration from −10 G to 10 G and can effectively handle sampling frequencies up to 700 Hz.

Within each zone, the accelerometers are linked to a *PEGASE* generation 2 acquisition card developed by the company *A3IP* under an Université Gustave Eiffel license. Each acquisition card facilitates the exportation of voltage measurements from the accelerometers at a sampling frequency of 100 Hz, adequately suited to observe the resonance frequencies within a civil engineering structure.



(a) Pylon (b) Deck

Figure 2: Schematic of the pylon and deck instrumentation. Red dots represent the position of the accelerometers.

Within the deck, each slot is equipped with two single-axis accelerometers—one oriented along $\vec{Y}$ and the other along $\vec{Z}$. Notably, in $X2$ (as depicted in figure 2b), two accelerometers oriented along $\vec{Y}$ are positioned, enabling the distinction of torsion modes. Regarding the pylon, among the eight accelerometers, three are aligned with $\vec{Z}$, each situated at different heights, while the remaining accelerometers are aligned with $\vec{X}$. For heights $Y2$ and $Y3$, the Z-slots accommodate two single-axis accelerometers, one for each direction.

This setup generates continuously an important amount of data that needs to be carefully handled to be easily exploited.

3.2 Data management

In order to record and access the data, the standard Hierarchical Data Format (HDF5) file format is used. Established by the Open Geospatial Consortium (OGC), it offers a robust and flexible solution for storing and managing complex data. Thanks to its platform independency and its support for metadata, it is a versatile format for managing diverse datasets. Its efficient input/output (I/O) operations, scalability, cross-language support, and features like data compression and parallel I/O contribute to its popularity in scientific and engineering applications. For this project, HDF5 provides a way to store different data types with various sampling rates and their associated metadata in a single structure. Data processing is done in `Python` thanks to the standard HDF5 library `h5py`. Many standard libraries for handling large data support natively HDF5 or conversion to other formats (such as `zarr`) can be easily done. For instance, the use of the `xarray` or `pandas` libraries enable fast and convenient processing of long-term data.

Figure 3 shows an example of accelerometers data, on 30 seconds data samples only. Additionally, the meteorological data presented in the next section and used in this paper are appended to the HDF5 file during a post-processing stage, for reproducibility of the algorithms.

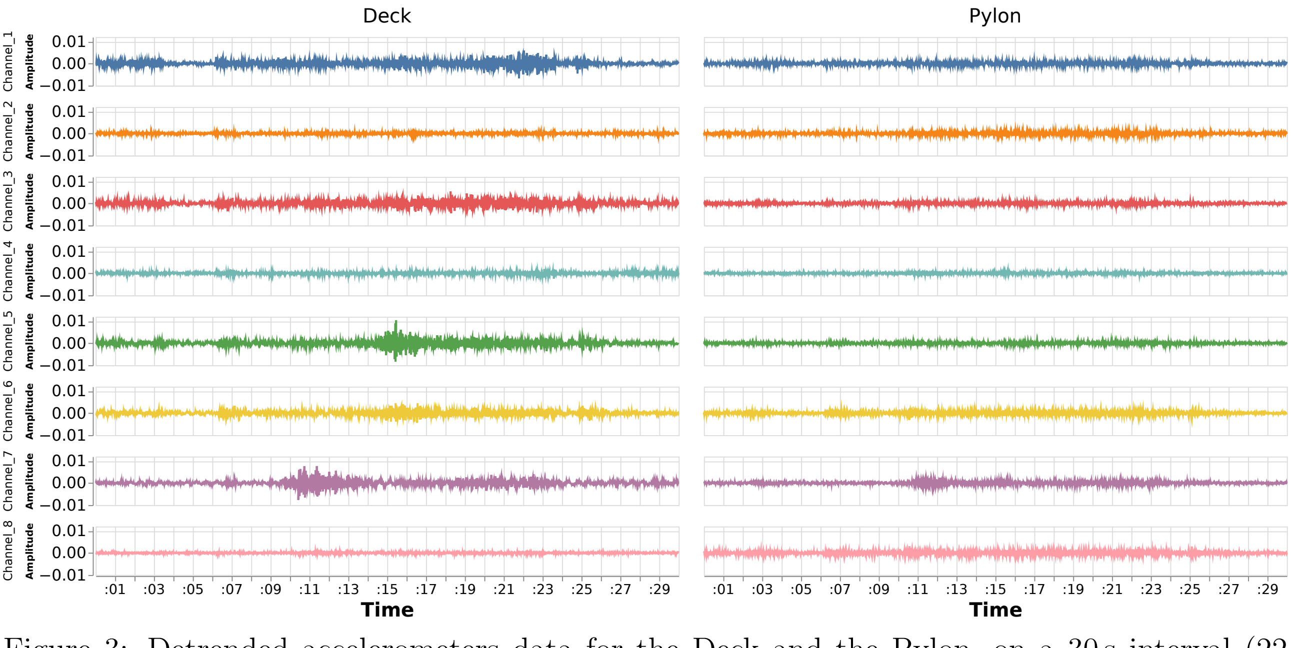


Figure 3: Detrended accelerometers data for the Deck and the Pylon, on a 30 s interval (22 april of 2018)

4 Meteorological data sources

One of the main challenge of performing the monitoring of modal analysis is to be able to distinguish between a variation caused by damage and a variation due to environmental factors and, in particular, the temperature on which the present paper will focus on. Such temperature value can be measured by adding a local weather station to the instrumentation. However, such data convenient solution is not always suitable for security purposes and it adds more complexity in the global instrumentation maintenance [7]. Instead, we propose the use of meteorological data acquired online and present the correlation that can exists between the different temperatures values from different data sources and the estimated modal frequencies of the bridge.

Those meteorological data include meteorological records from the nearest airport weather station, acquired online from the METeorological Aerodrome Report (METAR) [1] and satellite data from the European Copernicus program [4].

4.1 Meteorological Aerodrome Report (METAR)

METAR is a normalized format to create weather reports, based on permanent weather observation stations or airports and generated periodically (usually once an half an hour or once an hour).

4.2 Copernicus Climate Data Store (CDS)

The Climate Data Store (CDS) is part of the European program Copernicus aiming at collecting and providing edge-cutting and updated continuous data on Earth state. The CDS provides a single point access to many european datasets including observations, reanalysis and forecasts. For post-processing temperature computation, we propose to use the reanalysis dataset and particularly ERA5-land dataset [4].

4.3 Meteorological Data Comparison

Figure 4 shows a comparison between the METAR data and Copernicus data used. Previous studies have shown that the air temperature and relative humidity obtained with METAR data can be quite accurate, depending on the distance of the instrumentation site to the closest airport. At the opposite, Copernicus CDS provides fair results regarding the fact that those results are more reproducible and the data are easier to access and to process [7].

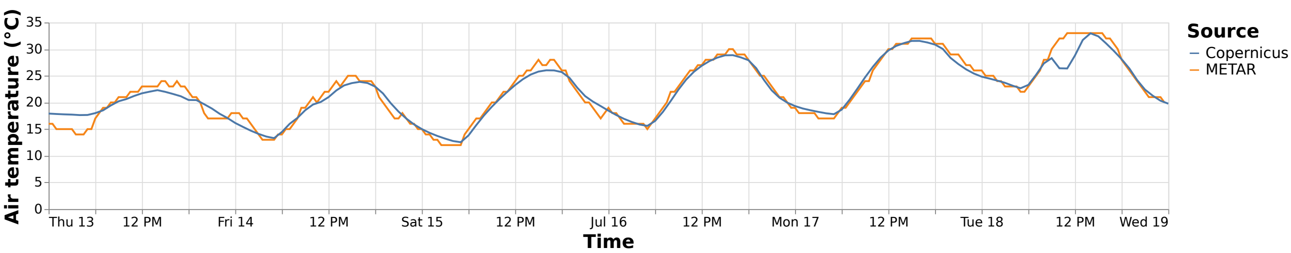


Figure 4: Air temperature obtained with Copernicus CDS (blue) and METAR (orange) (13-19 july 2017).

5 Long-term analysis application

The developed instrumentation and acquisition system enables the processing of A week of July, 2017 have been processed to perform a monitoring of the structure towards its modal frequencies evolution through time and temperature variations.

In order to determine the eigenmodes of the structure, we will employ the covariance-driven stochastic subspace identification (SSI) method as outlined in the reference [5]. This method utilizes measurements from the accelerometers to extract the eigenfrequency, damping coefficient, and amplitude of displacements associated with each mode. The eigenmode values are calculated with a system order of 80 for both the deck and pylon data, as described in the algorithm presented in [2]. Figure 5 shows the SSI diagram representing the model order versus the frequency for both the Deck and the Pylon. Such diagram shows which modes are stable towards the model order. Please note that further identification of the eigenmodes could have been possible by comparing the SSI results with a finite element model. However, in this study, the focus is made on the possible correlation between the frequencies and the weather reports to take into account the climatic effects that influence the value of the identified eigenfrequencies.

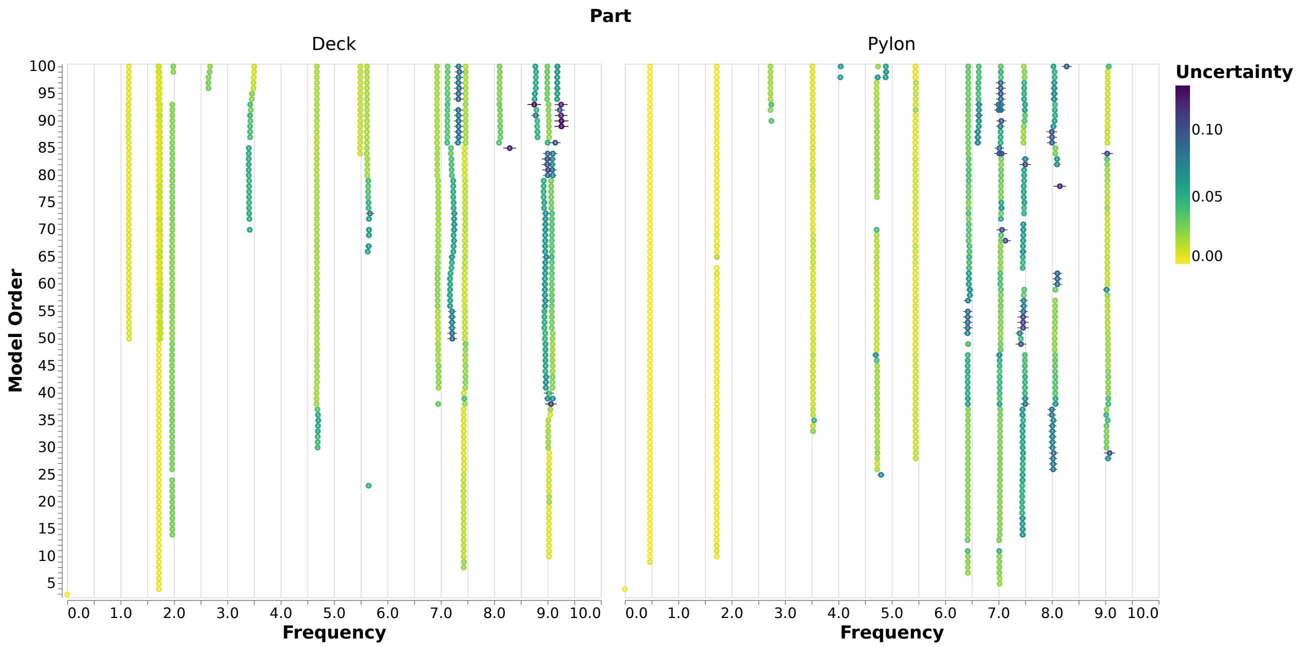


Figure 5: SSI results for the Deck and the Pylon at a given time (2017-07-13 16h).

Figure 6 represents the evolution of eigenfrequencies over time, with a focus of an identified mode around 3.5 Hz on the Pylon. In particular, there is a variation in frequency and this variation has a time period similar to that of temperature.

By plotting the temperature against the frequency, as in Figure 7, a correlation between temperature and frequency can be noticed. However, further investigations on a longer period and different modes needs to be perform to actually deduct a strong relation between the two quantities[6, 3]. Furthermore, it seems that the different meteorological providers give similar results and thus, can be used for future temperature correction.

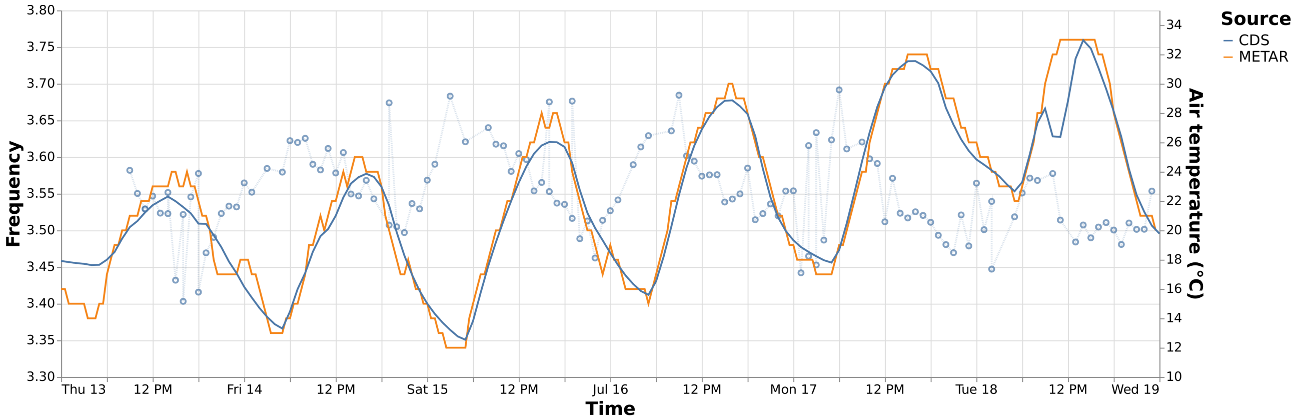


Figure 6: Comparison between temperature variation and eigenfrequency variation (light blue), for a given mode, on the Pylon.

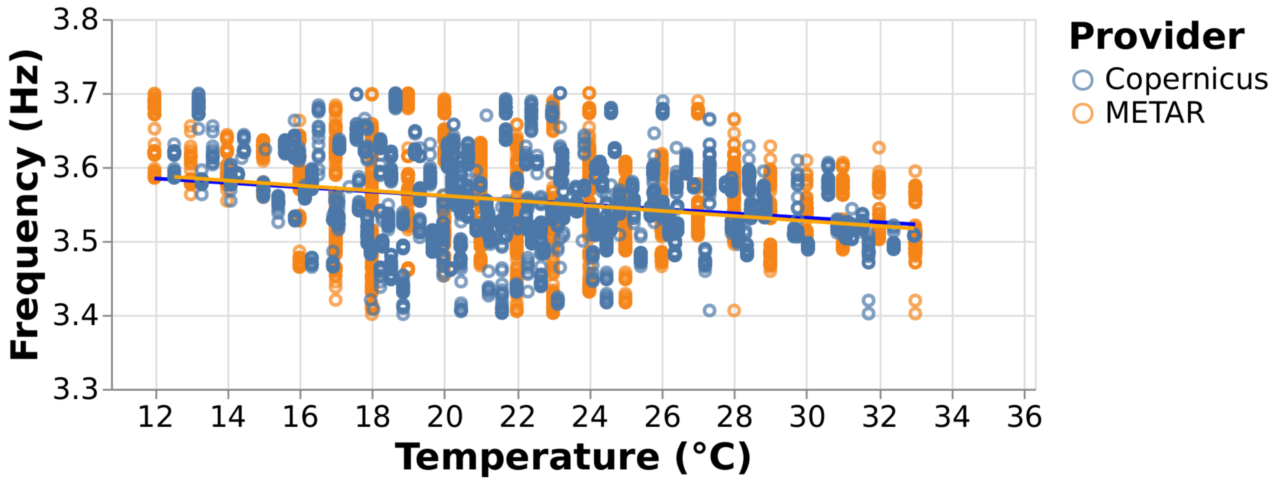


Figure 7: Temperature versus Frequency for Pylon data, around a mode at 3.5 Hz.

6 Conclusion & Perspectives

Real-time monitoring of civil engineering structures requires proper data acquisition systems to remotely assess their condition. A full acquisition system using a Pegase real-time monitoring platform for structural health monitoring has been presented. The management of such instrumentation, leading to an important amount of data has been introduced, with the use of the HDF5 file format for robust and efficient storage format solution. The use of external data providers such as METAR data or Copernicus Climate Data Store enables to overcome lack of local weather data. The monitoring system provided quality time-series of accelerations and weather data, enabling reproducibility of the applied algorithms.

Moreover, an example of long-term analysis application have shown the possibility of using those data for computing modal properties of the structure. It has been show that different meteorological sources could be used similarly to enrich the monitoring's informations. In particular, such enrichment could help for assessing more accurately potential damage situations, with the use, for instance, of the environment temperature. However, an extended with other external variables and over a longer period is needed to permit a better analysis and actually conclude on the correlation of the different variables.

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