Development of a remote and low-cost bridge monitoring system

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Abstract. Structures made from concrete, metal or any other material, are designed to have a long service life. However, to ensure a durable structure, it must have constant and efficient maintenance. Structural Health Monitoring (SHM) can be described as the method of monitoring and evaluating the structural health through the collection and analysis of data extracted from sensors, which are connected or not to the structure in matter. In this way, the difficulties are in how to collect that data, analyze it and have information about it to give a final response about the structure status. This research focus at the development of a low-cost bridge management system, which will allow remote monitoring of special structures and shows its real time status. Subjects as Finite Element (FE) modelling, dynamic test and Internet of Things (IoT) are studied to create a viable system. The first step is modelling a case-study bridge on SAP2000 to analyze the theoretical behavior of the bridge. The second step is using low-cost devices to extract data with low noise, process it and send a response about the structure status, involving Wireless Sensor Networks. Then, experimental results are analyzed.

Keywords: SHM, Finite Element Analysis, IoT, Dynamic Test.

1 Introduction

To ensure a durable structure, it must have constant and efficient maintenance. However, due to the high cost of local inspection that involves sophisticated equipment and qualified professionals, there is a lack of maintenance of special structures, as bridges and viaducts, in Brazil.

Bolina and Pacheco [1] presents that the problems caused by vibration have become more perceptive in the last few years, which is a consequence of slimmer and more flexible structures under dynamic load. Therefore, it is necessary to carry out a dynamic analysis, considering the structure's natural frequency, which can be a good indicator of its status. When a structural system is loaded with an extreme force, disturbing its static balance, and then unloaded, it is noticeable that the system vibrates around its natural balance condition. This kind of vibration is known as natural vibration, and every structure has one, which means, it has vibration modes and their corresponding frequencies that depend on the system parameters, as mass distribution, stiffness and support constraints [2].

As bridges are concerned, the vibration comes from the live loads that can be the wind or the car traffic on them. The live load on a special structure can cause resonance phenomenon which is very significant and might lead to a very high level of vibration, if the introduced frequency matches with the structure's natural frequency, causing serious problems or even dangerous accidents [3].

Certainly, the monitoring of bridges would have avoided the waste of time and money from governments or private companies that must fix damages in the structures due to the lack of inspection. Furthermore, it would have saved lives lost in accidents caused by decrepit structures.

For these reasons, the necessity of monitoring special structures has been increasing throughout the years. This research aims at the development of a low-cost bridge management system, which will allow a remote monitoring of the structure's real time status. Subjects as Finite Element (FE) modelling, dynamic test for modelling calibration and Internet of Things (IoT) have been studied to develop the system proposed.

2 Methodology

2.1 Object of study

In order to create the structure monitoring system, a case-study bridge was selected to be used as a reference for analysis, tests and validations of what is proposed. Therefore, it is necessary to understand its main characteristics. The bridge is located on the 13th quilometer of the Anchieta highway, São Paulo, Brazil. With the project provided by responsible dealership of the bridge, it was possible to identify its elements, such as girders, cross girders, crossbeams, foundation and elastomeric support devices. Figure 1 shows the cross-section of the studied bridge.

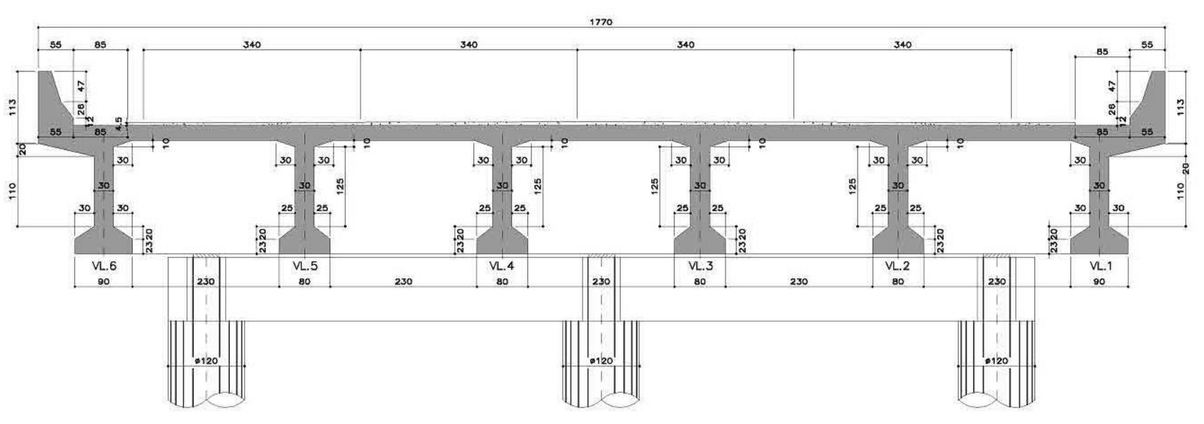

Figure 1. Cross-section of the analysed bridge (dimensions in centimeters)

2.2 Finite Element model

The first step was modelling the bridge on SAP2000, which is a software used to perform the structural and dynamic analysis of the bridge. Also, it is a Finite Element program, and the structure was introduced through its 3D interface, where the bridge elements are represented by bars and shell elements. These bars and shells receive the physical and geometric properties of the structural element they correspond to in the model, such as area and inertia. The bridge is made from C30 concrete (ultimate strength of 30 MPa), apart for the support device, an elastomer that behaves similarly to rubber. Material properties were also considered in the model. Permanent loads, pavement, and wheel guards are placed on the shell element that represents the slab. The self-weight load is inserted per element to avoid interference. When the model is completed, it must be processed to analyze the results and thus proceed to the next steps of the work.

2.3 BIM model

The bridge was also modeled in BIM, using Revit at first, an Autodesk® software. For the time being, the main elements of the structure were modeled, such as foundation, girders, cross girders, support devices, deck and the wheel guard. As the angles do not form exactly 90 degrees, it was necessary to create specific families for the bridge beams and for the wheel guard. With the bridge already modeled, InfraWorks software was used to implement the model in its surroundings, importing the area from Google Earth, selecting the desired area and inserting the bridge in its corresponding geographical position. Figure 2 represents the BIM model of the bridge from both Autodesk® softwares.

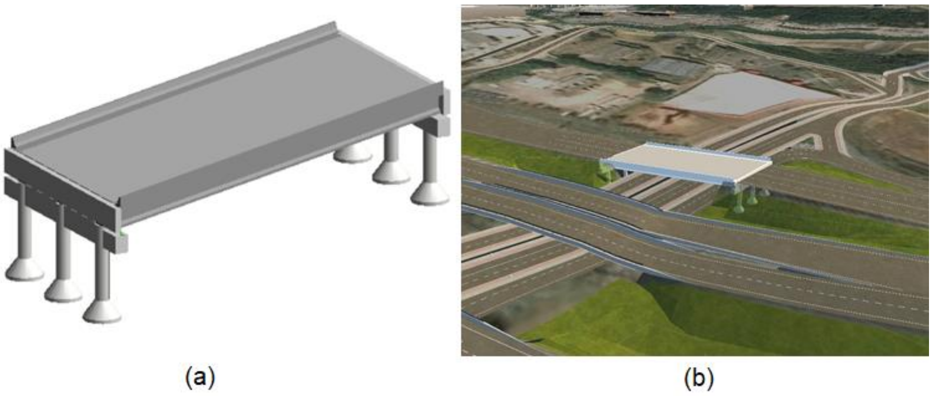

Figure 2. BIM models of the bridge using Autodesk® softwares
(a) Revit (b) Infraworks

2.4 Proposed monitoring system

Briefly, the challenge of this analysis was the development of a structure monitoring system that allows the company responsible for it to identify possible damage to the structure in real time, allowing actions to be taken to prevent further damage, seeking the lowest cost possible. In this way, the idealized system works by verifying if there has been a significant change in the dynamic behavior of the structure under analysis and issuing an alert if positive.

The use of a structure monitoring system is important to manage the bridge. With the correct parameters inserted in the virtual BIM model, it is possible to extract fundamental specifications that, when linked to the information obtained by the monitoring system, allow to identify the structure's behavior in certain situations. In addition, forecasting and scheduling dates for visual inspection and possible maintenance becomes more assertive.

Regarding the identification of the dynamic behavior of the structure, accelerometers were used to capture vibrations at critical points previously stipulated according to the geometric characteristics of the bridge. In this case, since it is a bi-supported bridge, it is understood that the largest deflections occur in the middle of the span, which makes this region more susceptible to vibrations. For the identification of the vibration modes, if desired, three devices capable of obtaining acceleration data in the middle of the longitudinal span are installed at three different points of the cross section: one device more to the left, one central and one more to the right.

As the proposal is to install three different devices to capture acceleration data, it is necessary to have a fourth device capable of receiving information from the other three, processing it and then sending it to the monitoring center. To send the information from the acceleration devices to the central device, it was decided to add a radio frequency module to the devices, allowing the sending of signals between them.

There will be a monitoring center and for it to receive data from the central device, it was determined that communication would be via 4G mobile network, since it allows a high rate of data transmission over long distances, which provides real-time monitoring getting all the desired information about the state of the devices.

Therefore, there is a final dashboard in the monitoring center, which allows those responsible for the bridge to analyze the data and results obtained, defining actions to be taken in case of alerts. Figure 3 represents the position of the installed devices on the brige and the system's communication flow, from the accelerometers to the final dashboard.

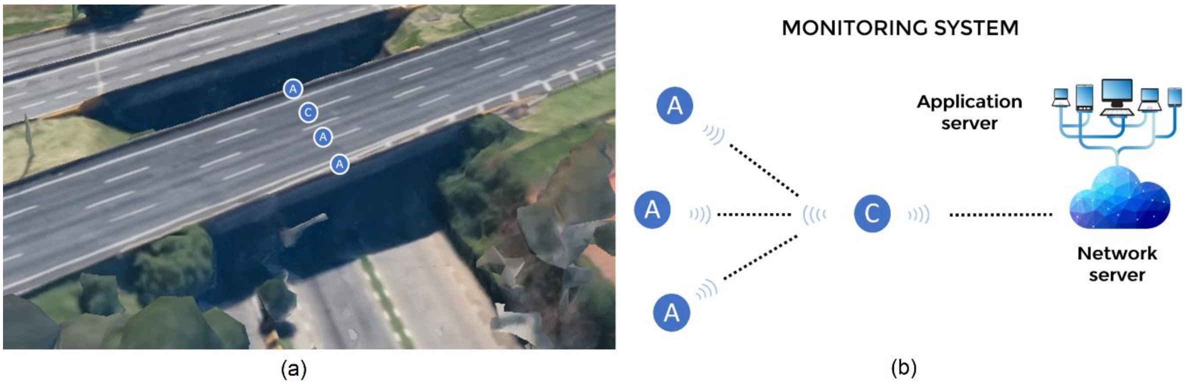

Figure 3. Scheme of the Monitoring System
(a) position of devices on the bridge (b) system's communication flow

3 Results and Discussion

Up to the present time, it has been possible to advance in parts in the development of the proposed monitoring system, as well as in the computational modeling of the object of study, both in BIM modeling and Finite Element modeling. BIM model used softwares such as Revit and Infraworks, as presented at the methodology section. Figure 4 shows the Finite Element model developed through SAP2000. In addition, part of the algorithms that will be used in the final monitoring system has also been developed, as well as field experiments for collecting and analyzing bridge data, in order to obtain results that could demonstrate relationships with the numerical model and generate insights for other approaches to the problem.

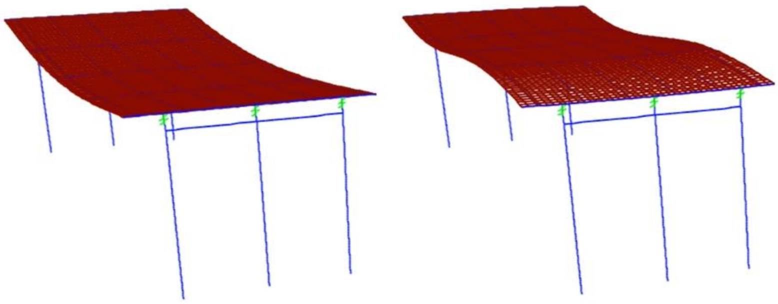

Figure 4. Example of bridge's modes of vibration through SAP2000.

Two initial prototypes were developed, one being the acceleration measuring device (A) and the other the central device (C). Device A contains a microcontroller Arduino NANO and device C contains both an Arduino UNO and a microcomputer Raspberry Pi 4B. At the beginning of the prototype's development, the basic idea was to start developing the programs of the devices for capturing accelerations, analyzing the data and sending data to the cloud.

To obtain data and understand the usual behavior of the studied bridge, an *in-loco* test was performed, using the device developed by Antonine [4]. Antonine's device works in a similar way to device A that is being developed in the present paper. There is an accelerometer (MMA8451) connected to a microcontroller (ESP32). A real-time clock (RTC), a SD card read/write module and a lithium battery are also connected to the microcontroller. Thus, it is a remote device that allows the collection of acceleration data and recording of that data on the SD card for later analysis with the aid of a computer, presenting extreme ease for its use. The test lasted one hour and three minutes and was carried out under normal traffic conditions on the bridge. Two devices were used to capture acceleration, which were positioned in the middle of the bridge span, close to the wheel guard.

While the sensors measured the accelerations on the bridge, the exact times of the moments when trucks produced perceptible vibrations were noted for later checking together with the data recorded by the accelerometers. During the test period, eighteen sections of truck passing were noted. A program was developed to calculate the Fast Fourier Transform (FFT) of the test analysis sections and save a general report with graphs and results obtained.

It is noted that the vibration was visibly identified by the devices. Thus, through the FFT, a peak frequency of 2.903 Hz was found, which represents the natural frequency of the bridge for the vibration mode at the respective moment when the truck passed it. In this way, it is intended to adjust the numerical model in order to find a natural frequency close to that obtained experimentally for the vibration mode in question.

Another point of analysis was the possibility of visualizing the bridge's damping in this same case of truck. Therefore, this case is still being analyzed individually in order to obtain other relevant information, such as the bridge's damping rate. Figure 5 shows (a) the measured acceleration data and, in an initial scope, (b) a linear regression model that was performed to adjust the damping curve.

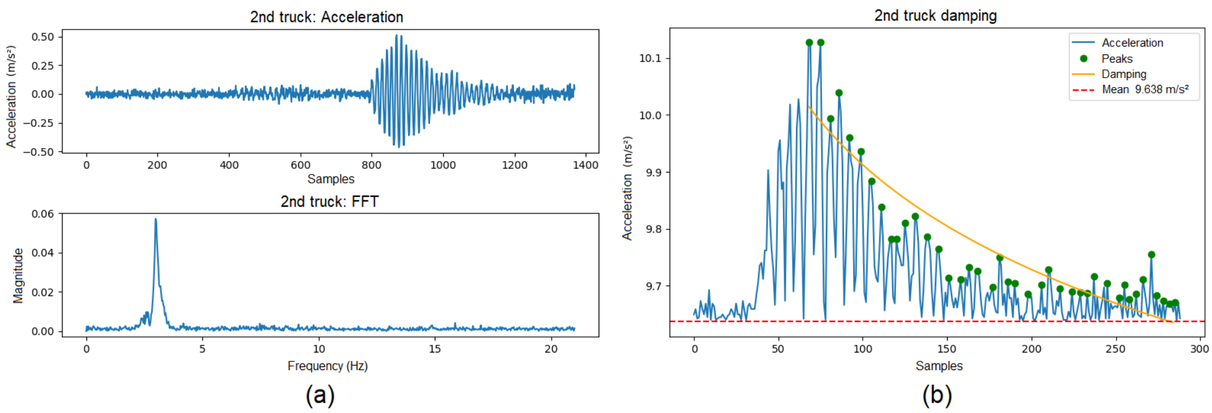

Figure 5. Results obtained for the second truck.
(a) accelerations and frequency (b) damping analysis

4 Conclusions

As the research has demonstrated, great part of the computational modelling and the monitoring system of bridges have been developed. Some of the algorithms that will be used in the final system have already been created, also, a partial test using a device to collect accelerations took place on the bridge in order to guide the further steps of the research. The FE model in SAP2000 needs to be adjusted to be as precise as possible comparing to the real bridge case. To do so, a dynamic test will take place on the bridge, thus, the necessary adjustments will be done in the model to achieve the experimental frequency.

The results so far, from the partial test, show visibly the vibration of the bridge, from which the structure's natural frequency was obtained through the Fast Fourier Transformation (FFT). Therefore, the device that will be used in the monitoring system is able to capture a clear signal of the vibration, allowing a good analysis of the frequencies. On top of that, the results also showed that the bridge damping can be detected by the devices, permitting the use of damping rates in the criteria that will be used to decide whether there were changes on the dynamic behavior of the bridge.

Finally, even though there are only partial tests and results yet, they are very promising in leading the research to its objective, the development of a low-cost bridge monitoring system that is precise and efficient.

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