Structural health monitoring of bridge infrastructures using single-pass SAR data

Javier Maldonado[1, *], Julia I. Real[2], Alejandro Rodríguez[3] and Ernesto Serrano[4]

(1) IDVIA 2020 HORIZONTE 2020 S.L., Plaza de Bandas de Musica 5, Local 11, 46013, Valencia (Spain)
(2) Institute of Multidisciplinary Mathematics, Universitat Politècnica de València, 46022, València (Spain)
(3) INECO, Avda. Partenón, 4-6 Planta Baja Puerta 2, 28042, Madrid (Spain)
(4) IMESAPI, Avenida de Ramón y Cajal, 107, 28043 Madrid (Spain)

1 Introduction

A structural health monitoring (SHM) system provides an efficient way to diagnose the condition of critical and large-scale structures such as bridges. SHM usually focuses on the assessment of deformations and displacements with the use of external or embedded sensors. At a global level, SHM focuses on the assessment of the dynamic properties of the structure which includes the vibration characteristics using special sensors (e.g., accelerometers) [1], which are then validated by mechanical models, numerical simulations, or small-scale laboratory models with artificial damage [2].

The most common practice to perform SHM is to perform several types of sensors nodes such as accelerometers or strain gauges, among others. However, these nodes are expensive to install and maintain as they are often stolen from bridges. In recent years, EU-27 countries have allocated around 30% of total infrastructure investment to maintenance costs (over €16.000 Million/year from public funds) [3].

As a result, SHM techniques based on remote sensing have been developed in recent years. These techniques are based on Synthetic Apertura Radar (SAR), which can be used to quantify surface deformation but require many historical images with high coherence between them to perform the analysis. In addition, it is necessary to distinguish between the main causes of SAR phase changes (due to thermal expansion in bridges) to evaluate other bridge movements with high sensitivity.

In this context, this work proposes the development of a new SHM tool that continuously diagnoses bridge structures without the need for historical data and with lower implementation and

* javier.maldonado@idvia.es

maintenance costs. Consequently, the objective is to investigate a tool that allows the inspection of bridge infrastructures using remote sensing systems (satellites) with two capabilities:

- Prioritising which bridges to maintain based on the detected structural deficiencies (i.e. deflections at the centre of the span, inclinations in abutments and other deck elements, and differential settlements in abutments and piers).
- Performing the complete bridge diagnosis by using a calibrated numerical model capable of obtaining the natural frequencies of the deck, its damping coefficients and the scour depth.

2 Methods

SHM techniques based on remote sensing have been developed in recent years. Remote sensing is the process of detecting and monitoring the physical characteristics of an area by measuring its emitted and reflected radiation, whether from equipment located on drones, aircrafts, or satellites. These techniques are based on Synthetic Apertura Radar (SAR), which is an Earth observation tool that can be used to quantify surface deformation. Although it has been applied to various types of structures such as dams [4], [5] and bridges [6], [7] to determine their displacements (their deformations), it requires a large number of historical images with high coherence between them to perform the analysis. In addition, it is necessary to distinguish between the main causes of SAR phase changes (due to thermal expansion in bridges) in order to evaluate other bridge movements with high sensitivity [8], [9].

With the development of a new software tool based on the use of single-pass spatial SAR data, the complete vibration profile of the analysed infrastructure will be extracted from a single spatial SAR observation, highlighting the presence of any damage. This is done after an appropriate signal processing procedure. In particular, the vibrations of moving targets are detected by the radar and their positions in a SAR image are shifted in azimuth and range-azimuth and a blur may occur. This defocus component can be estimated through a single-pass SAR observation and represents valuable information that can be used in a modal analysis.

Once the vibration profile is obtained, said data can be used to determine the dynamic properties of the structure. In this way, it makes it possible to obtain a mathematical model that is a faithful representation of the real structure, on which different types of verifications can be carried out to find out the current state of the bridge, or even simulations of highly demanding scenarios for the structure and predict its behaviour. The differential equation governing the linear, time-invariant.

Once the vibration profile is obtained, said data can be used to determine the dynamic properties of the structure. In this way, it makes it possible to obtain a mathematical model that is a faithful representation of the real structure, on which different types of verifications can be carried out to find out the current state of the bridge, or even simulations of highly demanding scenarios

for the structure and predict its behaviour. The differential equation governing the linear, time-invariant multi-degree-of-freedom system, in which both the excitation and response of the structure are stationary, random processes, is shown below:

$$[M]\{\ddot{X}\}+[C]\{\dot{X}\}+[K]\{X\}=\{F(t)\}$$

where [M], [C] and [K] are the mass, damping and stiffness matrices, respectively; {X} is the vector of displacements in each degree of freedom of the system and F(t) is the external excitation.

Once the numerical model has been set up, it can be calibrated by matching the natural frequencies preciously obtained with the SAR data. This is done by modifying the properties of the materials and the stiffness of the soil iteratively. The model validation is subsequently performed based on the vibration spectrum measured at the centre of the bridge span.

3 Results

The result of this work is the creation of a tool that provides the possibility of monitoring the structural health (SHM) of bridges and predicting their evolution over time from spatial data. The proposed software tool allows to monitor slab, girder and slab, box girder and concrete arch bridges and to elaborate predictive models on the evolution of their structural parameters, being able to implement a predictive maintenance philosophy.

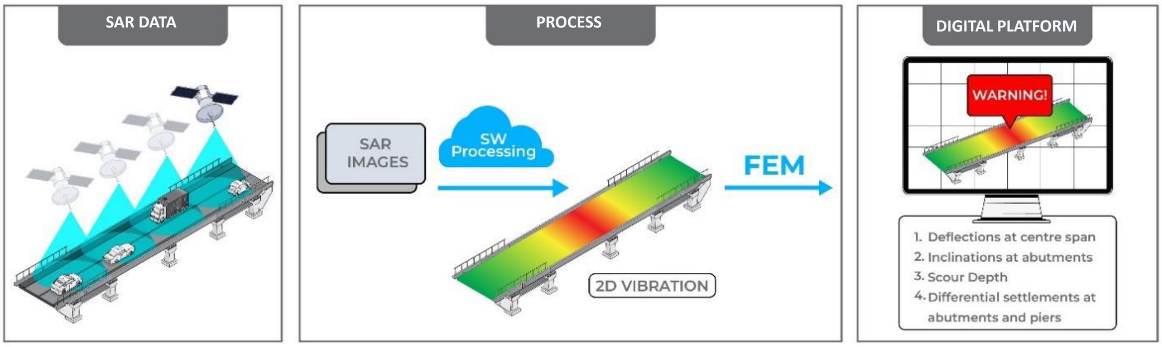

Figure 1. SHM using single-pass SAR data solution schematic.

4 Conclusions

Once this work has been developed, different challenges have been overcome arising from the need to: i) demonstrate the performance of the single-pass SAR data interferometry algorithm with a constellation of satellites; ii) reduce artifacts in the SAR images; and iii) transform the SAR observations into the natural frequencies needed for the calibration of the numerical model.

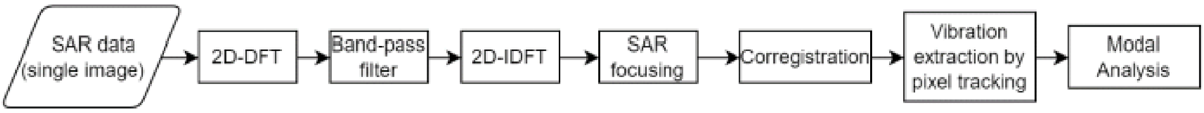

Figure 2. Single-pass interferometry algorithm framework.

Successful development of the system will require overcoming challenges. Some of the challenges overcome to develop the new tool are listed below:

- to demonstrate the performance of the single-pass SAR data interferometry algorithm with a constellation of satellites (e.g., Sentinel-1, Radarsat constellation and COSMO-SkyMed).
- reducing and/or eliminating radio-frequency interference and speckle.
- to transform the SAR observations into the natural frequencies required for the numerical model calibration.

References

[1] Gkoumas, K. et al., Research and innovation in bridge maintenance, inspection and monitoring. *Publications Office of the European Union*, 2019.

[2] Li, S. et al., SMC structural health monitoring benchmark problem using monitored data from an actual cable-stayed bridge. *Structural Control and Health Monitoring*, 21(2): 156--172, 2014.

[3] European Union Road Federation, Road Statistics Yearbook. 2021.

[4] Ullo, S. L. et al., Application of DInSAR technique to high coherence Sentinel-1 images for dam monitoring and result validation through in situ measurements. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing,* 12(3): 875--890, 2019.

[5] Sousa, J. J. et al., Potential of C-band SAR interferometry for dam monitoring. *Procedia Computer Science*, 100: 1103--1114, 2016.

[6] Lazecky, M. et al., Potential of satellite InSAR techniques for monitoring of bridge deformations. *2015 Joint Urban Remote Sensing Event (JURSE)*, 1--4, 2015.

[7] De Corso, T. et al., Application of DInSAR technique to high coherence satellite images for strategic infrastructure monitoring. *IGARSS 2020-2020 IEEE International Geoscience and Remote Sensing Symposium*, 4235--4238, 2020.

[8] Huang, Q. et al., Displacement monitoring and health evaluation of two bridges using Sentinel-1 SAR images. *Remote Sensing*, 10(11), 2018.

[9] Fornaro, G., Reale, D., Verde, S., Bridge thermal dilation monitoring with millimeter sensitivity via multidimensional SAR imaging. *IEEE Geoscience and Remote Sensing Letters*, 10(4): 677--681, 2012.