Bridge Vibration Monitoring

State of the Art and Future Outlooks

By Andrea Zampieri, Ph.D.

Inspection and condition assessment of bridges requires detailed visual examinations that must be conducted at least biennially. This effort involves deploying crews on-site for an extended period of time, depending on structure-specific needs and bridge typology. At times, gaining access to specific structural elements can be a challenge. Such is the case for the main cables and hangers of suspension bridges and the girders of viaducts and arch structures, which sometimes require special rope access. Thus, it should come as no surprise that inspection expenses are one of the most relevant items in the life-cycle cost of bridges. As a limited budget is available to sustain these costs, and given the increasing inspection needs of the U.S. bridges, the bulk of which are nearing the end of their service life, the need for cost-effective condition assessment techniques has never been more critical. Visual inspections are also imperfect because they are subjective, given that they depend on the inspector's experience and judgment. When the very stability of the structure is in question, inspections may also pose safety hazards to the inspection crew on site.

In recent years, engineers and bridge managers have started to deploy structural health monitoring (SHM) systems to supplement visual examinations. SHM employs various sensors, such as accelerometers, strain gages, displacement transducers, acoustic sensors, and GPS systems, to name a few. These instruments remotely and automatically collect structural response data that can be processed to obtain information on the condition of the bridges. SHM can reduce inspection time and costs, provide objective data, and mitigate access difficulties and safety hazards. Vibration-based approaches to SHM aim to assess bridges' structural health by using vibration response data, usually collected by accelerometers installed on the structures. These sensors are widely employed because acceleration data are relatively easy and economical to obtain, are well-suited for many applications, and can be easily incorporated into various structural analysis and assessment strategies. As a result, vibration-based SHM plays a prominent role among the various types of SHM implementation as a support tool for structural evaluation and asset management. In the following, an overview of state-of-the-art techniques and an outline of emerging technologies are presented to ultimately offer a primer on the objectives, methodologies, and potential applications of bridge vibration monitoring.

Objectives and General Framework

Although different approaches to bridge vibration monitoring exist, a general framework for the practical implementation of the method could be outlined following the flowchart in *Figure 1*.

A sensor network is installed on the bridge. When new data are available, the digital records are processed to identify the modal parameters of the structure, namely the natural frequencies of vibration, mode shapes, and, in some applications, the damping ratios. It is important to observe that acceleration records target the global behavior of the structure, so the first few lower-frequency global modes of vibration

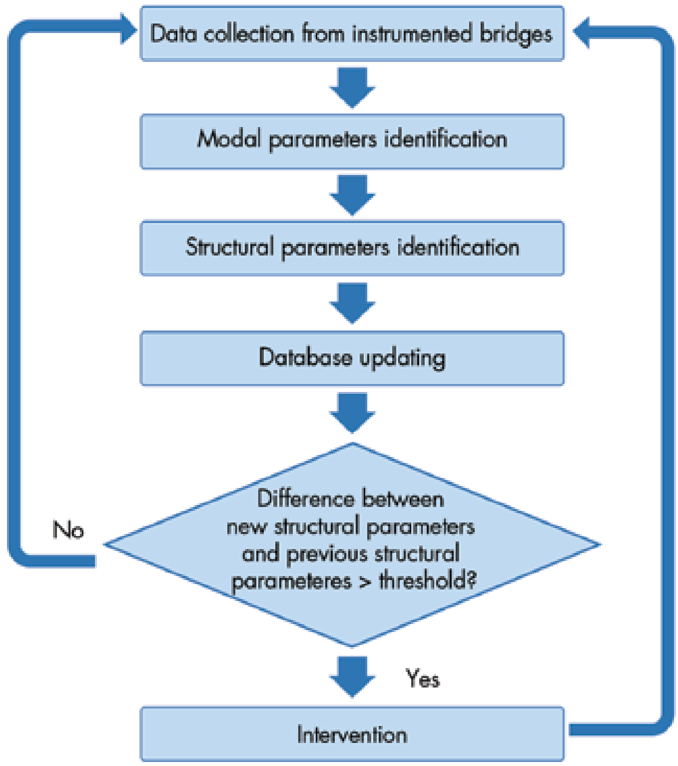

Figure 1. General framework for vibration-based SHM, based on Feng et al. 2013.

may be identified. Because these vibration characteristics depend on the mechanical properties of the structural system, the modal parameters identified from the vibration records may be employed to estimate the structural parameters – generally the stiffness – of selected structural elements within the bridge. Results are stored in a database, and values of stiffness that differ more than an established threshold compared to previously identified ones may signal an abnormal structural behavior, damage, or other conditions, depending on the specific application for which the monitoring activity is used. If deemed necessary, corrective interventions are made, and then the monitoring activity resumes.

It is important to understand that determinations on the condition of a bridge are based on detecting changes in its vibration characteristics. Hence, a fundamental principle of vibration-based SHM is that it requires a baseline set of modal parameters and their associated structural stiffness values to detect and quantify those changes. This baseline must represent the bridge in pristine condition or, more generally, the condition prior to the event under investigation has occurred. For instance, if the goal of the analysis is to determine whether a seismic event caused structural damage, which in turn means to detect whether structural stiffness decreased as a result of the event, a baseline set of modal and structural parameters, identified before the shaking, is required. This will enable a comparison with the modal and structural identification results obtained after the seismic event occurs. Also, it is important to note that records from multiple datasets collected over a long period yield more reliable baselines than those obtained from short-term monitoring campaigns with only a few records. This is because the parameters identified through each set of measurements are affected by the specific operational conditions – primarily temperature – when the vibration data are collected. By using multiple datasets, one can take statistics of the parameters identified from each set and build a statistical baseline model of the bridge to account for the effect of specific operational conditions.

Even more importantly, the benefits of vibration-based SHM are maximized through long-term monitoring deployments. This offers an opportunity to study the full history of the bridge, which is key to identifying potential structural concerns promptly, making educated decisions on maintenance interventions, and enabling other asset management provisions. Some examples of such applications and benefits are:

- By comparing the structural parameters identified before and after a potentially damaging event, such as an earthquake or a ship collision, a long-term vibration monitoring deployment enables the engineer to determine whether damage occurred, locate the structural elements affected, and quantify the extent of the damage.
- Tracking changes of a bridge's modal and structural parameters throughout its service life makes structural aging visible and quantifiable. Aging may be expected to produce small progressive shifts in bridge vibration characteristics associated with gradual decrements of structural stiffness over the structure's life.
- Detecting abrupt changes of bridge modal parameters compared to the baseline may unveil structural deterioration that could be unobservable utilizing mere visual inspection, enabling timely adoption of corrective measures before deterioration expands further. This leads to increased structural safety and potential savings over more extensive repairs required at a later stage. By doing so, vibration-based SHM may ultimately help transition from a reactive maintenance regimen to a preventative one, which is crucial to improving the condition of our country's aging bridges (ASCE, 2021).
- Vibration data collected during the service life of a bridge facilitate the estimation of the residual capacity of the structure. This allows asset managers to make better-informed decisions on matters such as determining whether structural rehabilitation is required, estimating the remaining service life of the bridge, verifying if load posting should be imposed, and deciding whether an aging bridge should be decommissioned. In addition, from the perspective of a monitored network of bridges, this may enable rational prioritization of interventions and more effective budgeting.

While long-term vibration monitoring could be helpful on a wide array of issues, short-term SHM campaigns may still be employed to address specific project needs. For example:

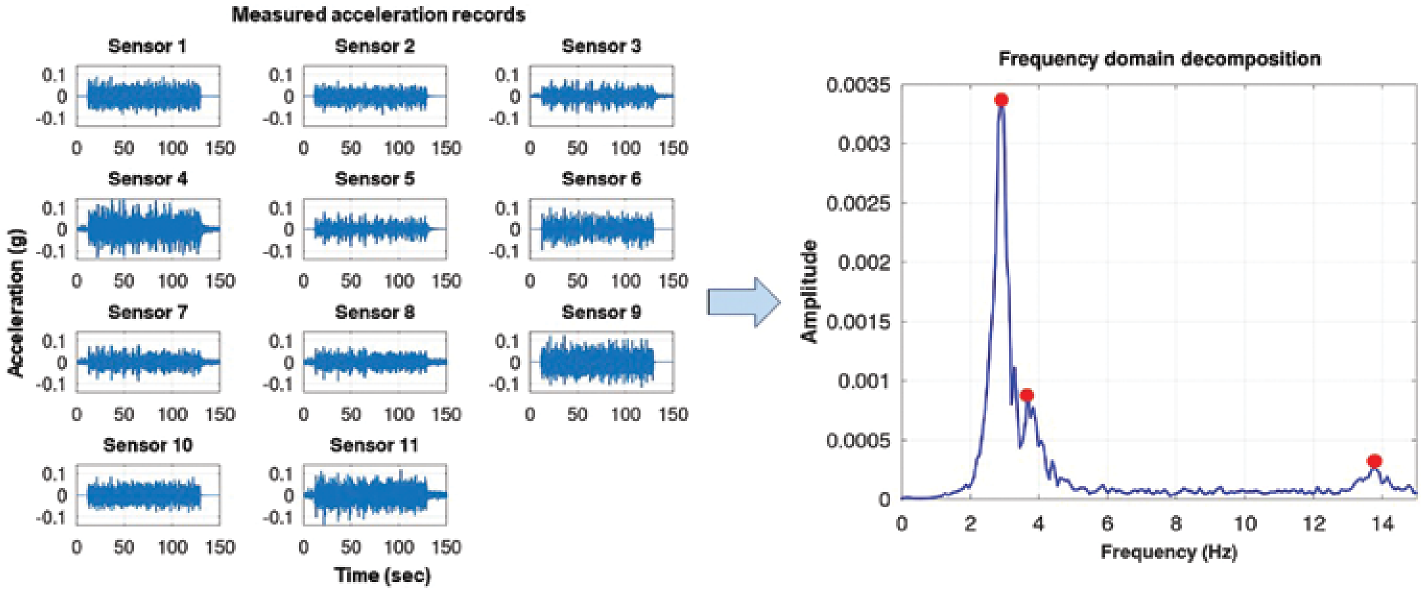

Figure 2. Ambient vibration records collected by eleven sensors installed on a bridge are used to identify the natural modes of vibration of the structure. The frequency domain decomposition plot shows three natural frequencies at approximately 2.9 Hz, 3.8 Hz, and 13.8 Hz. The acceleration records are available in Saiidi, n.d.

- Upon commissioning, bridges may be instrumented with temporary accelerometers to identify modal and structural parameters that can be compared against the design values to conclude whether the actual behavior of the bridge in service complies with the design expectations.
- Temporary accelerometer networks may be employed when bridge repair or strengthening is performed to measure the difference between the modal and structural parameters identified before and after the intervention. This information provides a measure of the effects of the repair or strengthening and allows verification of the design objectives.

Modal and Structural Parameters Identification

Much literature has been produced on modal parameter identification using vibration measurements, and different techniques are available for various types of vibration data. In most practical applications, ambient vibrations (e.g., vibrations induced by traffic across the bridge and nearby traffic, or in other words, the vibrations a bridge is subjected to in ordinary operational conditions) are used for modal identification purposes. The process of identifying the modal parameters of bridges from ambient vibration data is called *operational modal analysis*.

While several operational modal analysis techniques are available, they are all characterized by being output-only analysis methods. This means that bridge vibration response measurements collected by the accelerometers installed on the bridge – i.e., the output data – are sufficient to carry out the analysis, with no need to obtain explicit measurements of the input excitations. The most straightforward operational modal analysis approach is the *peak-picking method*. This method first transforms the measured digital vibration signals into the frequency domain employing well-known mathematical functions such as the discrete Fourier transform or the power spectral density function. The natural modes of vibration of the bridge are then identified simply by "picking" the peaks of these frequency representations of the vibration data.

However, the most common operational modal analysis technique used in practical applications is perhaps the *frequency domain decomposition*. It also relies on a frequency-domain transformation of the data. In fact, it can be interpreted as a refinement of the peak-picking method through more sophisticated mathematical tools. An example of the frequency domain decomposition method is shown in *Figure 2*. More details on operational modal analysis can be found in Brincker and Ventura, 2015.

Once the modal parameters are available, the structural parameters of the bridge can be estimated. A variety of techniques have been proposed in the literature to do so. The finite element model updating method discussed in depth by Friswell and Mottershead (1995) may be one of the greatest interest to practicing engineers. The fundamental principle of this technique is relatively simple. A parametric finite element model of the bridge is constructed, in which the stiffness of selected elements is treated as a variable parameter (i.e., the unknowns). The finite element model updating problem is solved by searching for stiffness values that minimize the difference between the modal parameters identified from the vibration data and the analytical modal parameters obtained from finite element analysis. Thus, structural parameters identification may be very much intended as an optimization problem that can be solved through various optimization algorithms.

Despite its conceptual simplicity, finite element model updating must be applied carefully. Because only a limited number of global modal parameters can be identified from the vibration data, attention must be placed on selecting the structural parameters to be used as unknowns of the finite element model updating problem. Selecting too many variables would make the optimization algorithm ill-conditioned, resulting in multiple possible solutions to the problem rather than a unique solution. This issue may be mitigated by performing a sensitivity analysis to explore the influence of each candidate variable on the bridge's modal parameters to help select the proper unknowns of the finite element model updating problem.

Future Outlooks

In recent years, advances in computer technology have paved the way for data science and artificial intelligence to take on a central role in nearly every scientific research field. And, as sensors become cheaper and more widely available, novel archetypes of the built environment have come forth through concepts such as smart city and ubiquitous sensing. Bridge vibration monitoring is affected in many ways by these novel scientific and technological perspectives, as they are opening new frontiers in collecting and processing vibration data.

One paradigmatic example is the recent proposal of crowdsensing platforms for bridge vibration monitoring. This technology stems from the observation that today's sensors are ubiquitous. In fact, it is safe to say that each of us carries an accelerometer in our pocket every day – on smartphones. Thus, the main idea of crowdsensing is to perform operational modal analysis of the structures by taking advantage of aggregate acceleration data collected by the smartphones from users traveling across bridges. Compared to traditional vibration monitoring applications, the clear advantage is that crowdsensing frees bridge owners from the burden of installing and maintaining a sensor network. And this may encourage more extensive adoption of bridge vibration monitoring technologies in the industry, which is still relatively limited compared to the research effort produced in this field. In addition, a crowdsensing platform provides a wealth of data, highly granular both in space and time, that traditional sensor networks are incapable of producing.

Yet, these schemes also present technical difficulties. First and foremost, this is because smartphones are mobile sensors rather than fixed ones, making modal identification of bridges challenging. Additional complexity is added by the fact that the bridge vibration data collected are affected by the dynamics of the car and the disturbance of the user interaction with the smartphone. While crowdsensing platforms cannot be viewed as market-ready technologies yet, their application to real-life problems may be closer than one would expect.

To appreciate the pace at which research is moving forward, it suffices to note that the first laboratory experiment to test the potential of smartphone sensors for vibration-based SHM was conducted in 2015 (Feng et al. 2015). In 2018, the natural frequencies of a real-life bridge were identified using the data collected by a smartphone mounted on the dashboard of a car over 42 trips across the bridge (Matarazzo et al. 2018).

The crowdsensing paradigm effectively highlights how novel technologies increase the amount of readily available data at an affordable cost and suggests that bridge vibration monitoring may play a more prominent role in bridge condition assessment and management in the future. From a broader perspective, these technological advances showcase the fast-changing professional landscape that we face today. Such a scenario challenges structural engineers to develop new skills in fields ranging from sensing and computer algorithms to data management and user behavior. Yet, these skills must be integrated with traditional structural engineering knowledge, for it is essential to better understand how to effectively use the wealth of data that will be readily obtainable in the future for the benefit of asset management. ▪

Full references are included in the online PDF version of the article at **STRUCTUREmag.org**.

Andrea Zampieri is a Bridge Engineer at Parsons Corporation in New York City. (andrea.zampieri@parsons.com)

References

Feng M.Q., H.C. Gomez, and A. Zampieri, "Health Diagnostics of Highway Bridges Using Vibration Response Data," in Health Assessment of Engineered Structures: Bridges, Building and Other Infrastructures, Edited by A. Haldar, *World Scientific*, 2013.

The American Society of Civil Engineers (ASCE), 2021 *Report Card for America's Infrastructure*, available at: **https://infrastructurereportcard.org/wp-content/uploads/2020/12/National_IRC_2021-report.pdf**

Brincker R., and C. Ventura, *Introduction to Operational Modal Analysis*, Wiley, 2015.

Saiidi, M. (n.d). NEES-2005-0032: *Using NEES as a Testbed for Studying Soil-Foundation-Structure Interaction: Shaking Table Tests*. DesignSafe-CI. Retrieved April 26, 2021, from **www.designsafe-ci.org/data/browser/public/nees.public/NEES-2005-0032.groups**

Friswell M.I., and J.E. Mottershead, *Finite Element Model Updating in Structural Dynamics*, Kluver Academic Publishers, 1995.

Feng M.Q., Y. Fukuda, M. Mizuta, and E. Ozer, 2015, "Citizen Sensors for SHM: Use of Accelerometer Data from Smartphones," *Sensors*, Vol. 15, No. 2, pp. 2980-2998.

Matarazzo T.J., P. Santi, S.N. Pakzad, K. Carter, C. Ratti, B. Moaveni, C. Osgood, and N. Jacob, 2018, "Crowdsensing Framework for Monitoring Bridge Vibrations Using Moving Smartphones," *Proceedings of the IEEE*, Vol. 106, No. 4, pp. 577-593.