Medicon Engineering Themes
Volume 6 Issue 5 May 2024
Article Type: Research Article
ISSN: 2834-7218

Optimal Conditions for Carrying out an OMA on Bridges and Viaducts, Both in Terms of Environmental Excitation and The Type of Transducers Used

Giorgio Sforza* and Vladyslav Samoylenko

ESSEBI Srl, Rome, Italy

***Corresponding Author:** Giorgio Sforza, ESSEBI Srl, Rome, Italy.

Received: April 29, 2024; **Published:** May 09, 2024

Abstract

In accordance with the latest national standard, the dynamic characterization of bridges and viaducts has become mandatory: a necessary action for newly constructed works in terms of dynamic testing and strongly recommended in the case of verification of existing structures. Based on the experience acquired for over fifteen years, we want to classify the construction types according to the actions to which they are subjected in relation to the possibility of carrying out an efficient operational analysis. In other words, to describe the optimal solutions according to the constructive characteristics; that is, if the excitation of the wind alone is better, or if it is preferable to have it combined with road or rail traffic that occurs nearby and how much it is preferable to stay on a motorway overpass, rather than on a road along-side, but not in continuity, with another in which traffic has not been interrupted. The work aims to evaluate the type of transducers most suitable for performing OMA on this type of structure. Having established that accelerometers, although less resolute than velocimeters, allow better phase stability, we will evaluate which of them that are the best in terms of performance-cost, especially in terms of spectral noise compared to the magnitude to be measured. The potential and limitations of wireless solutions are also analyzed and compared with traditional wired ones.

Keywords: EMA; OMA; SHM; ODS; MEMS; LORAWan; Dynamic Testing; Ethernet; EtherCAT; PoE; LAN Network; FRF; IEPE; Force Balance; WIM

Introduction

This paper is aimed at a comparative study concerning the definition of the best approach to implement for a dynamic study of bridges and viaducts: if newly built in terms of actual dynamic testing, if existing in terms of dynamic characterization. In fact, in the case of new buildings, not yet put into service, the experimental dynamic analysis is essential for verifying the correspondence of the theoretical modal parameters of the project with the experimental ones measured in the field; the same, faced with structures dating back to the past, the experimental modal tool serves to characterize them from a dynamic point of view to define, for example, fixed points, in order to be able to arrive at their numerical modelling, currently not available.

A good approach means defining the correct architecture to implement, the best excitation to use and the most suitable type of transducers to implement.

Citation: Giorgio Sforza., et al. “Optimal Conditions for Carrying out an OMA on Bridges and Viaducts, Both in Terms of Environmental Excitation and The Type of Transducers Used". Medicon Engineering Themes 6.5 (2024): 22-29.

Based on the repeated and multiple experiences of the writer, developed over more than twenty years, the most suitable architectural solution is the wired one. At least in the current state of the art, all possible wireless solutions are excluded as they are deficient from many points of view. Considering that experimental modal analyzes are often combined with long-lasting dynamic monitoring (SHM), the large amount of data to be processed (a significant minimum value for a good wave reconstruction is 200 samples/s) leads to high consumption which involve a power supply which must necessarily come from a fixed network. Faced with this constraint, which involves the need to create a real power supply network, the possibility of being able to have signal transmission without any physical support does not in fact lead to any practical advantage, on the contrary it often entails the possibility that come to create problems that can affect the reliability of the measurement itself. To overcome the problem associated with the large electrical absorption, there are solutions on the market that have consistent durations as they are based on timed or trigger systems that are activated for a few minutes a day. These solutions make it possible to work with buffer batteries that are recharged, one-off, with low-power photovoltaic systems, resulting in practically unlimited duration, without any other external energy support. Furthermore, always with the intention of having to achieve important autonomy, they are based on communication protocols that transmit an extremely limited data packet (LORAWan), which have nothing to do with medium-performance dynamic systems. And here what could appear as a great advantage turns into an insurmountable structural limitation which, in its essence, prevents the good execution of any modal analysis.

A fundamental characteristic of a modal analysis is the rigorous synchronization in phase in order to have solutions to the eigenvectors, for each eigenvalue, which are geometrically congruent and capable of providing modal shapes which make sense. Relying on a GPS solution could create big problems when there are short gaps in communication, which are far from infrequent, or when there are sources of disturbance which, although not preventing transmission, can lead to distortion. And it is no coincidence that in certain environments considered strategic or sensitive, this type of communication is still strongly discouraged.

Wired solution

One of the most interesting wired solutions is the granular one, with accelerometer modules arranged in series starting from an industrial PC, on which the management software platform resides and on whose mass memory an initial memorization takes place (data which, in packets, will be transferred to the cloud), which acts as a central unit. The accelerometer modules consist of a MEMS triaxial transducer and are equipped with all the electronics necessary for the conditioning and transformation of the analog to digital signal and for communication and network synchronization. They are usually connected by an ethernet cable to form a classic LAN network (Cat6), easy and simple to install with internal RJ45 connectors in water proof housing and cable glands. The cable has the important characteristic of carrying both the signal and the power supply and the latter is guaranteed at regular intervals, every certain number of modules and not beyond a certain absolute global distance, by a series of injectors or switches network type PoE. Such an architecture has limits only in the length of the cable between one module and the next (cautiously set no more than 50 m) and, in theory, is able to support a large number of modules (depending only on the performance characteristics of the PC). When this architecture is used in particularly large systems with many components, it is preferable to optimize with more than one slave PC, which are in turn connected to the network and headed by a master, which is the one that can be managed remotely, in the optics of a remote control.

A representative diagram of the most suitable wired architecture on a multi-span railway overpass is reported in Fig. 1. The circled markers indicate the triaxial accelerometers: the chain starts with accelerometer 1 and ends with accelerometer 18. Between accelerometer 4 and 5 there is a roadway crossing which, to avoid hindrances to traffic or to usual operating activities, extends along a joint, or directly on the intrados.

In the following functional diagram, Fig. 2. Connection type detail, it can instead be noted how the connection and signal transmission takes place in detail, starting from the industrial PC, through a PoE and, in cascade, with an in-out configuration serial chain involving all the transducers located along the artifact.

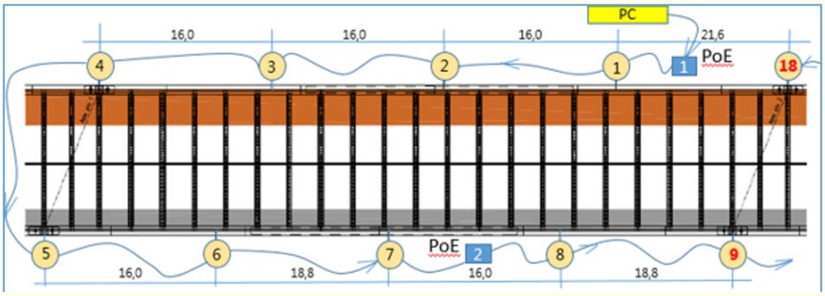

Figure 1: Typical multi-span layout.

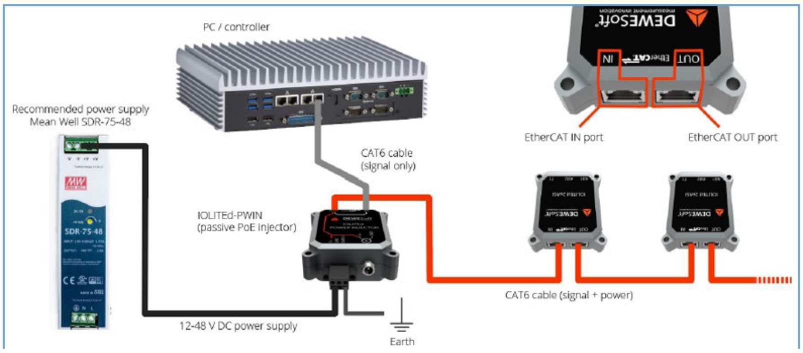

Figure 2: Connection type detail.

In such a scheme, the longed-for synchrony (for the frequencies involved, which are not particularly prohibitive, synchrony can occur within a millisecond, ensuring a phase error of less than 5%) can be guaranteed with the EtherCAT protocol.

Excitation of artifacts

As far as the excitation is concerned, the forced one is absolutely excluded, as it is expensive and often difficult to implement for applications in the infrastructural field, and the use of the natural, operational one, i.e. made available free of charge by the environment in which the artefact is contextualized, is turned out to be the elective choice. Bridges and viaducts, whatever their construction typology is, are very flexible structures and therefore easily excitable, even in presence of a very light breeze, never missing in any climatic condition.

Thus the wind, understood as a stochastic action, perfectly reproduces the conditions of an input comparable to a white noise spatially distributed in a random way around the object of interest, without any periodicity and with an intensity that remains more or less constant in the interval of frequencies of interest. As happened in the aeronautical and naval fields, the classical experimental modal analysis (EMA) has given way to the operational modal analysis (OMA), i.e. performed under normal operating conditions of the artifact, without worrying about how to excite it. The analytic construct remained the same and frequency response functions (FRF) gave way to cross-power functions.

Citation: Giorgio Sforza., et al. "Optimal Conditions for Carrying out an OMA on Bridges and Viaducts, Both in Terms of Environmental Excitation and The Type of Transducers Used". Medicon Engineering Themes 6.5 (2024): 22-29.

Figure 3: Wind as effective propeller.

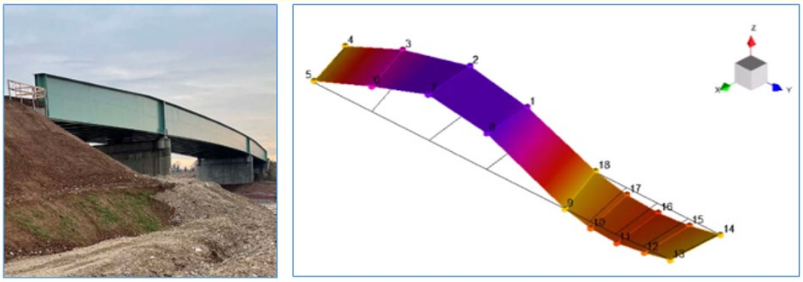

Figure 4: Overpass in Lonato del Garda (BS) and its first modal shape.

As an extreme case, Fig. 5, we report the example of ancient masonry arched bridges studied on more than one occasion with satisfactory results. Although extremely rigid, they often have the peculiarity of being in areas with an orographic conformation such as to generate, due to the Venturi effect, particularly intense windy flows, capable of shaking morphologically massive structures.

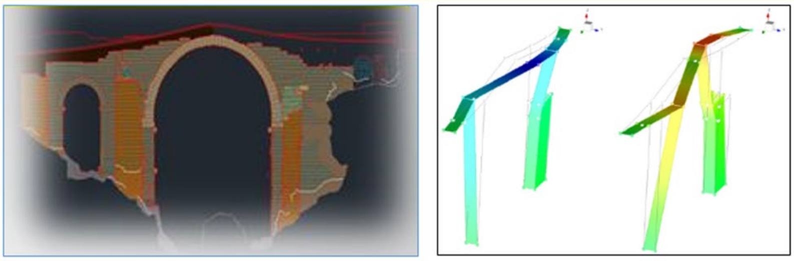

Figure 5: Laser scanner survey of the Etruscan Bridge in Vulci (VT) and its first modal shape.

Citation: Giorgio Sforza., et al. "Optimal Conditions for Carrying out an OMA on Bridges and Viaducts, Both in Terms of Environmental Excitation and The Type of Transducers Used". Medicon Engineering Themes 6.5 (2024): 22-29.

Not only the wind, but also normal human actions, of a random nature, can be useful for the generation of a random input. Often, in particular days of flat calm, in fact, the usual activities that take place inside a building for the most disparate uses, can replace the windy action. The same happens for a bridge or viaduct. The excitation could be the vehicular traffic on it if one decides not to interrupt it: a normal circulation has very little effect on the mass variation, if compared to the own weights of the artifact (structural and carried), and any disturbing action can be easily eliminated with algorithms of the harmonic removal type. Even better if the traffic acts on a roadway that is structurally separate from that of interest, which can be flanked (as happens on a two-way motorway on two viaducts intended as separate entities, one of which, the one to be tested, is closed to traffic, and the other normally transited) or to be in the most disparate configurations (overpass, underpass, oblique arrangement in a particularly complex node and so on).

Number of transducers

Another fact to take into consideration is the number of transducers used in the analysis: obviously the higher the number, the more effective the analysis is, not so much in determining the frequencies, but in the full definition of the modal shapes which are softer and more distinguishable from each other, especially where coupling phenomena occur. As an example, Fig. 6, the double modal analysis performed on the deck of the well-known Ponte del Risorgimento over the Tiber in Rome is cited: the first in 2014 and the second repeated in 2019.

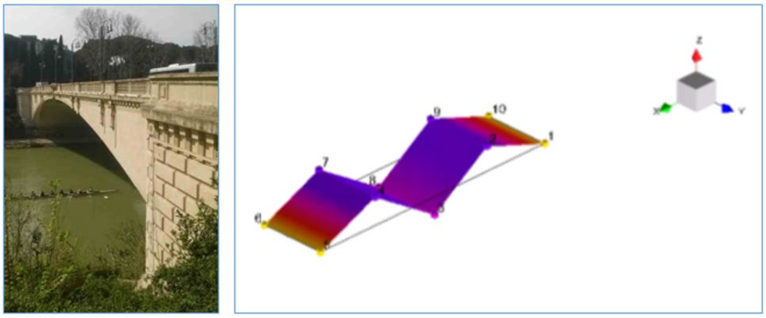

Figure 6: Ponte del Risorgimento (RM) with higher order shape.

The first analysis was performed with a limited number of low noise piezoelectric seismic transducers (PCB 393B12) in mono and biaxial configuration and the second with a large number of triaxial MEMS transducers (five on each side walkway). The frequencies after years have returned exactly the same. The modal shapes obtained with the latest analysis were softer and more distinct, demonstrating that, on this type of artefact, the quantity of measuring points is more important than having a more extreme quality on a limited number of them.

Transducers characteristics

Having ascertained that it is good practice to have many transducers with the aim to obtain a greater diffusivity and better geometric definition of the graphic representation of vibration shapes, even at the expense of the measurement resolution, it is now a matter of defining what are the performance limits that the transducers must possess. In the field of experimental modal analyses, precisely because of the simplicity of the measurement chains that can be implemented and listed above, achievable as if implementing a normal LAN network, the solutions with IEPE or Force Balance accelerometers have increasingly given way to those with accelerometers MEMS which, in recent years, have had a progressive introduction, with ever more performing solutions. In fact, increasingly innovative chips are being introduced with ever higher performance-price ratios. All this type of transducer has a precision identifiable in the

Citation: Giorgio Sforza., et al. “Optimal Conditions for Carrying out an OMA on Bridges and Viaducts, Both in Terms of Environmental Excitation and The Type of Transducers Used". Medicon Engineering Themes 6.5 (2024): 22-29.

maximum linearity error, of the order of 0,1% of the full scale, similar to that of their more famous cousins.

Where they lack compared to the latter is in the most important parameter, which characterizes the performance of an accelerometer, i.e. the resolution understood as the signal-to-noise ratio, often indicated as spectral noise, referred precisely to the frequency of interest, and expressed in μg/√Hz units. The current standard of use stands at a threshold value of 25 μg/√Hz, which, in essence, is that dictated by the ADXL 354 or ADXL 355 chips from Analog Devices, used by many instrumentation producers for the civil field, with particular reference to the SHM. Also the DEWESoft IOLITEi 3xMEMS accelerometers, normally used by ESSEBI to obtain the results previously described, with decidedly positive results, belong to this family. Here below, Fig. 7, are the results of the experimental determination of spectral noise performed by ESSEBI on a pneumatic test bench in the laboratories of the Department of Aerospace Engineering of the Roma Tre University, which involved a significant batch of transducers.

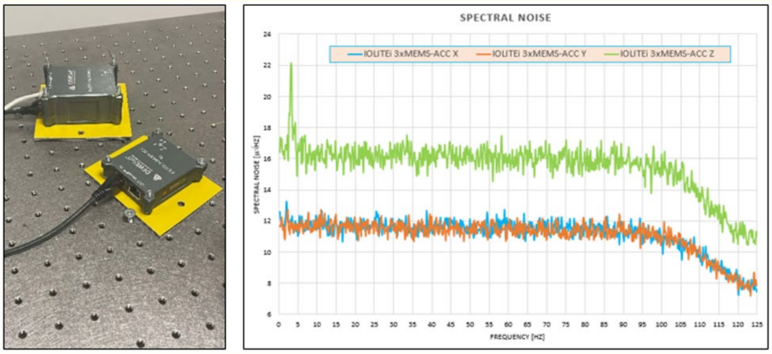

Figure 7: IOLITEi 3xMEMS-ACC spectral noise measured on pneumatic bench.

The z axis is the noisiest one with values which, over the whole band of use, settle around 16 μg/√Hz, with a spike around 3 Hz which, only for that frequency, brings it to reach 22 μg/√Hz. Instead, the surprising ones are the x and y axes, arranged in the horizontal plane of the instrument. The spectral noise for both axes is certified at values between 12 μg/√Hz and 13 μg/√Hz, perfectly in line with what is declared by the MEMS manufacturer on the instrument datasheet.

Although the accelerometers based on a maximum spectral noise standard declared not exceeding 25 μg/√Hz are more than fine for all applications concerning OMA, ODS and SHM analyses on bridges and viaducts, an updated and more performing version of the 'IOLITEi 3xMEMS, of "s" type, with a chip from another manufacturer has a declared spectral noise less than 0.7 μg/√Hz, about 40 times lower than that currently used with satisfactory performance. Below, Fig. 8, is the comparison graph on the z axis, the noisiest one, with a MEMS of normal use, carried out last August, in the early afternoon, inside a Roman park (Parco degli Acquedotti) with little attendance at that hour.

In the range between direct current and 10 Hz for the IOLITEi3xMEMS accelerometer, defined as "regular", the spectral noise is attested around 20 μg/√Hz (ordinate on the left), while for the IOLITEi3xMEMS accelerometer, defined as "s type" is massively lower (sorted on the right). Up to the frequency of 7 Hz (which covers the significant harmonic range for a generic infrastructural artifact) the maximum spectral noise is 0,4 μg/√Hz; in the following section, although it tends to rise, it is however contained below 1.6 μg/√Hz. This peak is however attributable to some environmental noise, and not to noise from the electronics, picked up by the instrument even if in a sufficiently silent area and at decidedly quiet times.

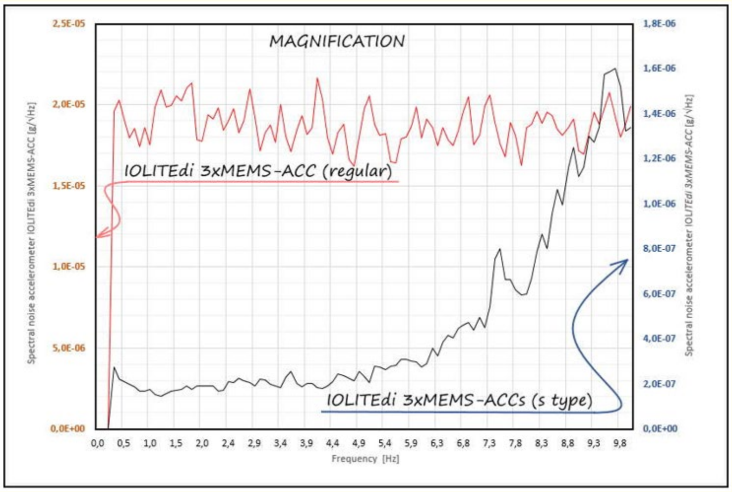

Figure 8: IOLITEi 3xMEMS-ACC spectral noise measured on pneumatic bench.

At the moment, the high cost, especially of the basic MEMS element, does not make the "s type" accelerometer competitive, and practically applicable in the field of road infrastructures. A future alignment of prices could allow an introduction which, although not massive, could help to make one-off measurements with high resolution. The aforesaid accelerometer will then find wide application to evaluate the very small variations in vibration velocity, in terms of evolutionary trend, which, in the context of WIM-SHM integrated systems, is indicative of variations in the deformation energy and therefore of progression of any damage.

In conclusion, if in the sector of road infrastructures the instruments currently available, less pretentious and of lower cost, can brilliantly be used with excellent results, the same cannot be said for the artefacts that concern the cultural heritage sector, in masonry, and therefore more rigid and able to move, with the same excitation, with decidedly lower amplitude intensities. Here, in this case, the more performing accelerometer finds a natural application, as an essential element for a complete and exhaustive resolution of the problem.

References

1. Brinker R and Ventura C. "Introduction to Operational Modal Analysis". Wiley (2015).
2. Peeters B., et al. "Efficient operational modal testing and analysis for design verification and restoration baseline assessment: Italian case studies". EVACES - Varenna (IT) Ott 3-5 (2011).
3. Sforza G. New Frontiers of Structural Monitoring. Wireless structural monitoring with remote reading. Rome University "La Sapienza" (2011).
4. Sforza G. Facade of the Municipal Theatre in L'Aquila (Italy) – Operational Modal Analy-sis – LMS internal – Leuven (BE) - (2010).
5. Dynamic characterization of the Basilica of S. Maria di Collemaggio after the earthquake of 2009 by means of operational modal analysis - 17th International Conference on Computational Methods and Experimental Measurements - Opatija, Croatia (2015).
6. Sforza G. "Understanding the dynamics of Vulci's Devil's Bridge". White Paper Issued by Siemens PLM Software (2016).
7. Marzullo F and Sforza G. Viaduct over the Polcevera. Premature end of a post-war engineering milestone. Quaderni di Legislazione Tecnica, n°4 (2018).
8. Sforza G. "Structural Health Monitoring with MEMS accelerometers". Dewesoft Meeting of Minds (2020).
9. Ewins DJ. Modal Testing: Theory, practice and application 2 Ed. Research Studies Press Ltd., Baldock England (2000).

Volume 6 Issue 5 May 2024

Citation: Giorgio Sforza., et al. “Optimal Conditions for Carrying out an OMA on Bridges and Viaducts, Both in Terms of Environmental Excitation and The Type of Transducers Used". Medicon Engineering Themes 6.5 (2024): 22-29.