Dynamic monitoring plant integrated with a Weight in Motion apparatus aimed at having a more complete SHM system.

Giorgio Sforza[1[0009-0000-6729-0012]], Matjaž Skobir[2],
Francesco Ginesi[1[0009-0007-1101-1660]], Martin Hauptman[2]
[1] ESSEBI Srl – Rome - Italy
[2] CESTELd.o.o. – Trzin - Slovenia
sforza@essebiweb.it

Abstract. To evaluate the maintenance of the structural conditions of a viaduct or bridge, the temporal control of frequency variability is usually adopted. Considering that the frequency is very influenced by the temperature, small variations are not easily intercepted, and significant variations are instead often forerunners of irreversible damage. Another solution consists in the direct control of kinematic quantities. One particularly suitable in this regard is the velocity, as the kinetic energy is related to the elastic deformation energy. The detection of the vibration velocities alone, however, is not very indicative, as the variability can occur due to a simple increase in vibrations. The ideal would be to classify typical traffic conditions and use them as a basic element for comparing similar and recurring situations. Dynamic weighing makes it possible to catalog a multitude of traffic models, to be taken as reference models, to make effective velocity control. A sort of dimensionless and universalization of the measure. If then the dynamic weighing is done from the intrados, together with the measurement of the accelerations and the determination of the velocities, there is also evidence of the deformations in various points that can add useful information about the health of the artifact, in a context of elaboration of a large amount of data (big data).

Keywords: SHM, WIM, Operational Modal Analysis, Momentum, Kinetic Energy, Influence line, Likelihood statistical criteria, Machine Learning, Big Data

Introduction

The aim of this work is to relate two different types of measurement, in order to arrive at the possibility of predicting evolutionary conditions which, although slowly variable over time, in the long run could have a degenerative behavior and seriously compromise the operational functionality of a span or an entire deck of a bridge, overpass or viaduct. The basic idea is to create an evolutionary system, which starts from an extremely simplified pattern until it becomes progressively more and more complex and sophisticated, able to increasingly satisfy the user's needs. It is the infrastructure manager, who intends to have a predictive pattern available, capable of allowing maintenance interventions to be scheduled and, above all, to guarantee its integrity and functionality over time.

As far as the structural health monitoring (SHM) of a bridge or viaduct is concerned, in the state of art the modal parameters are those of greatest interest and which are the most popular. The frequency has an important significance for the characterization of the typology of these type of artifacts [1]. The main frequency, together with the higher harmonics, is an invariant which, as such, must remain unchanged over time. So, the temporal tracking of at least the fundamental frequency, and verifying its maintenance around two pre-established extremes, lower and upper, can be considered a first check for verifying the state of health of the artifact. At present, it is the universally accepted and applied method, even if it provides significant results only when the variability is macroscopic. That is, only structural instability of a certain significance entails appreciable variations in frequencies that are not, for example, masked by the thermal effect. Therefore this type of approach is not particularly suitable for assessments that intend to place themselves well in advance of the occurrence of anomalous events.

At this point it is a must to think of something else and one way to do it is to combine the SHM with the dynamic weighing, better known by the acronym WIM (Weigh in Motion). As far as monitoring is concerned, we refer only to the accelerometric measurement. On the other hand, relatively to dynamic weighing, solutions that intervene on the road surface, with a quartz or ceramic band, are excluded. Only solutions with intervention exclusively on the intrados of a portion of carriageway are taken into consideration, aimed at determining the transiting mass and its velocity.

1 Topic framing

At a least in first phase, about the SHM system, an attempt is made to simplify the problem as much as possible. In other words, reference is made to a single triaxial accelerometer installed on the intrados, near which the weighing system is installed. The WIM, also positioned on the intrados, consists of at least two extensometers at a known distance, capable of determining mass and speed of each axle of each passing vehicle (Fig. 1), limited to the lane taken into consideration.

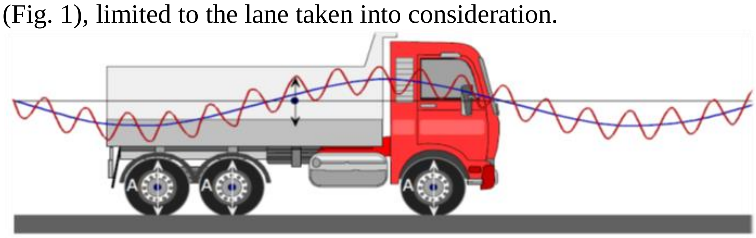

Fig. 1. Heavy vehicle that transits on a bridge and establishes a vibratory phenomenon

For the purpose of the present work, it is not important to know the physical characteristics of the passing vehicle, but we can limit ourselves to the axles only (without distinguishing them according to the vehicle to which they belong).

As a guideline, in one section, the one of interest, the accelerations are measured along three axes of reference with which the deck vibrates. Not so much for the weighing as for the determination of the transit velocity, one must necessarily refer to a certain limited but defined development in the longitudinal direction. The transiting mass and the transiting speed are measured too.

The scientific literature is teeming with applications in which the energy of elastic deformation is related to the kinetic energy of the vibratory phenomenon [2], [3].

In a simple vibration system, the maximum kinetic energy E_K is reached at the instant of maximum velocity when the system is passing through zero displacement.

$$\text{Kinetic Energy} = K_1 \frac{1}{2} \rho V v^2 \tag{1}$$

in which K_1 is a constant depending on the shape of deflection curve and point position, V is the volume, ρ is the density, $m=\rho V$ is the mass and v the system vibration velocity.

The maximum strain energy occurs when the velocity is zero and the deflection curve is at a maximum, and

$$\text{Strain Energy} = K_2 \frac{1}{2} V \frac{\sigma^2}{E} \tag{2}$$

In which K_2 is a constant depending on the shape of deflection curve and point position, E is the longitudinal modulus of elasticity, σ the stress.

According to the conservation energy principle

$$K_1 \frac{1}{2} \rho V v^2 = K_2 \frac{1}{2} V \frac{\sigma^2}{E} \tag{3}$$

So that

$$\sigma = \sqrt{\frac{K_1}{K_2}} \sqrt{\rho E}\, v \tag{4}$$

For this reason, it is undoubtedly better to refer to the velocity of the vibratory phenomenon, rather than to the acceleration, calculated by means of a numerical integration of the primary quantity measured. This is like saying that instead of adopting a differential method, based on the integration of the equation that represents the second law of dynamics, F = ma, the energy method, based on potential methods, is preferred.

Let we consider the WIM system as a black box. At least for the moment it is not of interest to act at the level of the actual quantities measured, but only to know the events due to normal transit in the relevant roadway, i.e., the mass corresponding to an axle, or to the entire vehicle, and the corresponding transit velocity. With these two quantities it is possible to define the momentum and the kinetic energy of the so-called transit. Two quantities that are equally effective for framing the problem: the first in which mass and velocity have the same dignity, the second in which speed assumes a dominant role (quadratic dependence). Assuming kinetic energy, instead of momentum as a reference, means considering more relevant, and therefore more harmful, fast transits even if with reduced mass, compared to slower transits with greater mass.

2 Basic approach

A first impact approach, which will necessarily be subject to subsequent refinements, is to refer to a defined observation period T (for example 3 months), then dividing it by N (number of slots into which to divide the observation period) such that you have

$$\vartheta = \frac{T}{N} \tag{5}$$

with θ duration of the slot. If, for example, we take N=2.160 we get the duration of the slot equal to 3.600 s.

Referring to the output of the WIM system, for each single slot, it will be possible to measure the transits in terms of mass and velocity of the elements involved. Nothing prevents us from moving directly in terms of one of these magnitudes or both taken separately; however, it is thought that the best solution, as mentioned above, is to combine these two quantities in terms of momentum Q or kinetic energy E_K (or both taken into consideration). Referring to Q, the product of mass and velocity determined provides us with the momentum that crosses the section of the lane of the deck, in the period of time considered. If this is releted to the duration of the slot, then we have the total momentum of the slot. We would therefore have N global momentum, each one pertaining to each slot, for the entire observation period T. The output of the SHM system, in the simplest of cases, is the recording in terms of time histories of a triaxial accelerometer, the one closest to the WIM station (generally there should be many more like in the test bench in Fig. 6). As mentioned, the signals must be processed, in terms of numerical integration, to obtain the vibration velocity along the three axes. To further simplify the processing, reference is made to a single time history, vector sum of the three measured axes (it is normal to expect that the component of the dominant acceleration due to the transit of vehicles is along the gravity direction).

If f_c is the sampling rate (never lower than 200 Hz), we can calculate the RMS value (Fig. 2) of the resulting velocity vector every interval τ, such as to have an adequate number of samples as a function of the frequency (for example 10 s) and average the values over the duration of the slot (in the example above, the duration of the slot being one hour, there will be 360 RMS values).

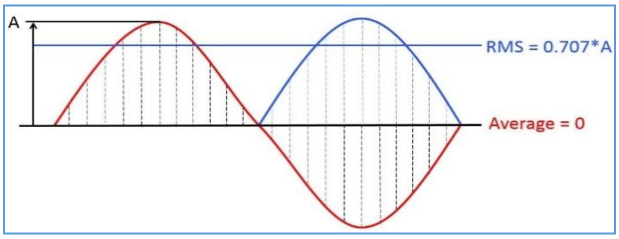

Fig. 2. Explanation why it is advisable to refer to the RMS value and not to the average.

In this approach, let's call it primordial, we are exempt from making even the slightest statistical consideration and each slot is associated with a single value of the momentum Q and a single value of the vibration velocity. If we have N slots, to cover the entire observation period T, we will have a matrix with N rows and 2 columns, precisely the momentum and the vibration velocity. If N is high enough, there will be all the elements to be able to associate the two quantities in a one-to-one correspondence. Valid elements, based on more than twenty years of experience, suggest that there may be a valid correlation such that, within certain tolerance limits, which provide the range of variability, a value of momentum Q can correspond to a reference velocity vibration value v, calculated as described above [4]. If this does not happen, either because with Q being equal there would be a higher vibration level, measured by *v*, or because v remains unchanged at lower Q values, the artifact deserves more attention and must be placed under observation. If this situation persists over time, even tending to progress, first a series of alerts and then alarms are triggered, precursors of punctual and in-depth investigations.

The above is based on the control over time of the vibration speed, as an average value on the duration of the slot of the RMS values calculated on an elementary interval. That interval is related to the excitation conditions of the artifact, referred to the time slot, in terms of mass and velocity, synthesized in derived quantities (Q and E_K). It could happen that the number of slots N taken into consideration, to define the observation period T, are not sufficient to establish an incontrovertible one-to-one correlation. Or that the extreme simplification adopted, without the introduction of sophisticated statistical elements, leads to dispersed situations, not at all attributable to a reproducible relationship of cause and effect. Excessively lengthening the observation time, with a high number of slots, is counterproductive due to the fact of having a high number of one-to-one correspondences which would make management much more difficult. The solution to undertake, certainly more meaningful, to be considered as an improvement step in a process of continuous refinement, is to resort to statistical distributions, both in terms of burdening stresses and vibratory responses, and compare them, by means indicators of likelihood, in order to find matches aimed at reducing and partializing the number of samplings. In fact, the method consists in identifying a finite, and possibly extremely limited, number of traffic distributions, identified by the momentum Q, or by the kinetic energy E_K, of the traffic circulating in the section under examination. An equal number of vibration speed distributions correspond biuniquely to them, to be considered effects of the causes that originated them. Here too, in a simplistic way, which in any case must give the impetus to future developments, reference is made to what happens in a section and the lines of influence of the physical quantities of interest are not taken into account.

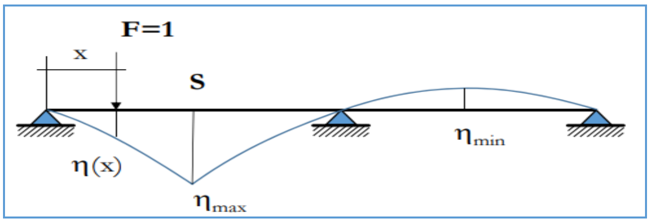

Fig. 3. Influence line of the generic quantity G in section S

As can be seen from the graph in Fig. 3, supposing that S is the section under examination, the value of its ordinate is the effect caused by the transiting load when it is on the section itself. At that same instant there will be other vehicles on the bridge, which will give, in terms of corresponding influence line, their effect in S [6]. Finally, in section S, within the limits of the linearity of the problem, in which the principle of superposition of effects holds, it is necessary to take into consideration the sum of all actions, in terms of corresponding influence lines, relating to all the vehicles transiting on the relevant lane of the bridge at that moment. At this point it is not important to know the acting loads, as the intrados measurement with a strain gauge or optical fiber would automatically allow to determine the overall effect, in terms of stress characteristic, due to the transit of vehicles on the bridge. This could make it possible to exclude the use of a WIM station were it not for the fact that, at least in the current state of the art, it is fundamental for determining the transit velocity of loads.

Ultimately, referring to a deformation gauge in its own right and as such, belonging to the SHM system which, by means of appropriate calculations, would give the overall momentum in that section, and therefore the overall effect due to the globality of the stresses acting in that instant on the bridge deck (mainly due to direct transit on the section in question). In this condition, the WIM system would only serve to provide the transit velocity in the section which, although associated with the transit of the vehicle in the section of interest, can be referred to the resulting overall momentum (i.e. due to the simultaneous transit of all the other vehicles on the bridge) with an excellent level of approximation.

3 Application case

An example of an application to develop the aforementioned observations and considerations is the combined SHM and WIM plant specifically installed on a bridge over the Sava river (Fig. 4 e Fig. 5) in Tomacevo, in the peripheral area of Ljubljana (Slovenia).

Fig. 4. Side view of the bridge in its portion that affects the riverbed towards Ljubljana (SI)

Fig. 5. Underside of the bridge at the crossing of the Sava river

The Fig. 6 shows the layout of the accelerometric transducers, belonging to the portion of the SHM system. Corresponding to the accelerometers 8 and 12, still on the intrados, there are traps (consisting of strain gauges extensometers) for dynamic weighing (WIM).

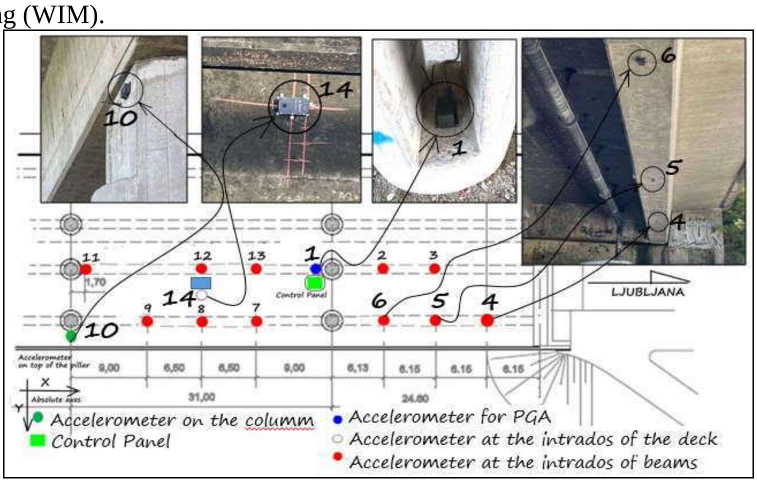

Fig. 6. Layout of the SHM plant at the introdos of the bridge

With a preprocessing on the dynamic weighting data, starting from the masses and velocities, for each vehicle transiting on the lane of the carriageway of interest, the kinetic energy and the momentum were calculated, to be used for the subsequent traffic models [7]. The procedural method applied is shown below. The data relating to each day are divided according to the time of entry into the bridge, from 00:00 to 24:00, thus having 24 vectors of data available each day, which have different lengths, in relation to the number of vehicles transited on the bridge in every hour. For each of the vectors a distribution of kinetic energies is then constructed. For each day 24 energy distributions are built, which provide a quantification of the amount of traffic passing through. In Fig.7 two typical distributions relating to two different hours of a normal day, the first with low traffic intensity and the second with intense traffic, are represented.

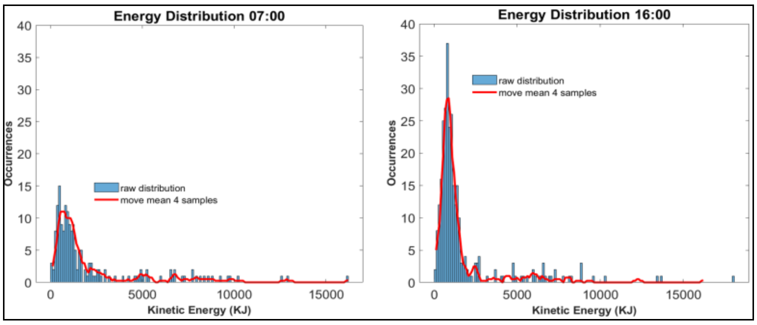

Fig. 7. Distributions of kinetic energies in two characteristic hours of a typical day

The masses distributions have a trend superimposable to that of the kinetic energies and the trend of the kinetic energies depends on the latter, since very heavy vehicles are infrequent. Vehicle velocities, on the other hand, have a trend centered around a value which, in this case, is equal to 25 m/s.

4 Future improvements and extensions

At this point, using one or more statistical parameters [4], these distribution trends can be correlated with each other, in order to understand whether they are representative of the same traffic pattern, or whether they relate to two different ones. A calculation of the area under the curve of the moving average of the distribution of kinetic energies could quantify the amount of traffic at a certain time. The modal value of the masses or kinetic energies distribution allows to trace the type of most recurring vehicles that transit on bridge. The kurtosis allows to understand how recurrent this typology is and finally skewness could allow to quantify the tail of the distribution and therefore the less probable events, but of greater stress for the bridge (very heavy or very fast vehicles). This procedure is repeated iteratively for all the other distributions of the day, labeling each of them.

In the same way it is necessary to create distributions of the vibration velocities, obtainable by numerical integration from those of the measured accelerations, each always relating to an hour of the day, so that the aforementioned vibration distribution can be associated with the corresponding kinetic energy distribution of the passing vehicols. The graph in Fig. 8 refers to the RMS values, calculated over a time of 10 s.

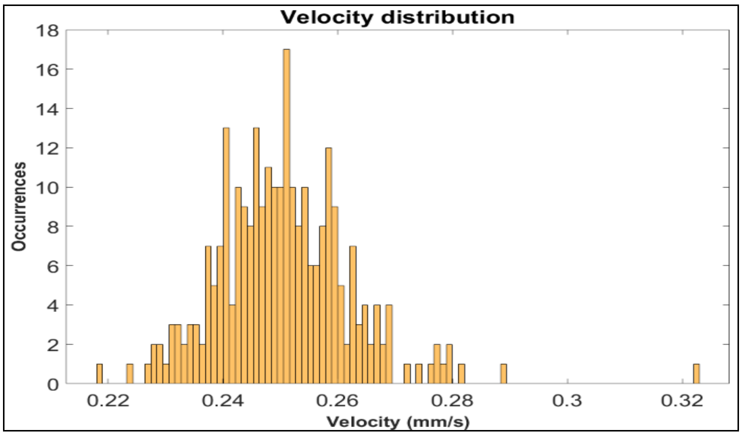

Fig. 8. Vibration RMS velocities distribution of the bridge deck

This procedure is currently underway and is expected to last for a period of at least 6 months until a set of data will be available that will bring together all the possible types of traffic, in a one-to-one correspondence between the energy parameters of circulating vehicles and the vibration speed of the bridge deck.

At the end of this self-learning period, the correlation can be defined as sufficiently reliable. When fully operational, continously all data of a day will be processed. The single hours of acquisition will be analyzed and each of them labeled with a type of traffic and therefore a precise velocity distribution must correspond to it. If the velocity distribution found in the training period does not correspond to the type of traffic because, for example, the modal value of the aforementioned distribution tends progressively, albeit slowly, to increase, one proceeds with increasingly more observation and attention towards that type of traffic, up to the generation of alerts which, translating into alarms, herald preventive maintenance actions.

5 Afterword

By adopting the aforementioned likelihood criteria, the comparison between all the slots will allow to obtain a subset of probability distributions, of momentum or kinetic energy, considered significant and to identify the typical traffic related to the artifact under observation, to which the corresponding RMS velocity distributions, that characterize the vibratory phenomenon, are associated. In this sense, one of the objectives of this work is also to define how long the observation period must last and, above all, how long the slot must be, i.e. what should be the limits of the reference window from which to move the comparison evaluation. The typical modus operandi of this approach is to start with tentative considerations and then, thanks to successive refinements, proceed towards a progressive definition of the optimum condition.

Within the subset of the time windows thus defined, if, for subsequent comparisons, a lack of correspondence is found, which obviously tends to persist or even worsen, this means that there is a variation in the response of the bridge, i.e. that it is changing its structural characteristics.

A definitive step, albeit ambitious, is to apply the basic concepts of machine learning [8] and define a synthesis function of the vibration velocities, associated with each stress distribution, and to be considered as expected values, to be compared to those from time to time once measured.

References

1. Heylen, W., Lammens, S., Sas, P.: Modal Analysis Theory and Testing Katholieke Univeriteit Leuven – Belgium (1997).
2. Irvine, T.: Shock and vibration stress as a function of velocity. Vibrationdata.com
3. Gaberson, H, A: Conditions under which displacement, velocity or acceleration should be used for diagnostics monitoring. Shock and Vibrations Bulletin 40, Dec 1969
4. Ang, A.H., Tang, W.H.: Probability Concepts in Engineering, Planning and Design. Wiley and Sons (1975).
5. Moses, F.: Weigh-in-Motion System Using Instrumented Bridges. In: Transportation Engineering Journal of ASCE, Proceedings of the ASCE, Vol.105, No.TE3, 233-249 (1979).
6. Karoumi, R., OBrien, E. J., Quilligan, M.: Calculating an influence line from direct measurements. Bridge Engineering, 159(1-2), p. 31–34 (2006).
7. Skokandić, D., Žnidarič A., Mandić-Ivanković A., Kreslin, M.: Application of Bridge Weigh-in-Motion measurements in assessment of existing road bridges. The Value of Structural Health Monitoring for the reliable Bridge Management Zagreb 2-3 March 2017.
8. Žnidarič, A., Kulauzović B.: Innovative use of bridge-wim as an efficient tool for optimized safety assessment of bridges. 28th ARRB International Conference – Next Generation Connectivity, Brisbane, Queensland 2018.