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DAMAGE DETECTION INTO ROAD PAVEMENTS THROUGH ACOUSTIC SIGNATURE ANALYSIS: FIRST RESULTS

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Efficient civil infrastructure management strictly depends on Structural Health Monitoring (SHM). Several studies have been conducted on the SHM of civil engineering constructions through the application of a large number of methods, which widely differ based on theory applied and technology used.
The aim of this work is to describe the preliminary results of a new acoustic method for road pavement SHM. The proposed method is based on the idea of monitoring the time behaviour of the spectral content of acoustic signals recorded from road pavements under vehicular traffic. The spectral content of the recorded signals is considered as the acoustic signature of the road pavement under investigation. It provides information about the structural health condition of the pavement.
Preliminary results were obtained considering asphalt concrete slabs. They show a correlation between the health conditions of the slabs (which were expressly damaged in different ways) and their acoustic signatures (recorded acoustic signals). Based on these preliminary results, further in situ measurements and analyses on road pavements will be carried out and different structural health conditions will be considered. Results can benefit both practitioners and researchers.
Keywords: structural health monitoring, road pavement.

1. Introduction

The vibro-acoustic response or signature of a road pavement under controlled or uncontrolled (traffic) conditions are growing in importance as emerging methods, which can provide useful hints about a pavement structural health and damage state of play.

The structural health monitoring or assessment (SHM or SHA) is performed on all the civil infrastructures, which must provide high safety and comfort levels to their users. Civil infrastructures are subjected to natural aging, which impacts their performances over time due to different environmental conditions (such as loads, thermal changes, seismic events, etc.). SHM may have different purposes ([1], and [2]) characterized by growing difficulty level, i.e.: i) damage detection; ii) damage localization; iii) damage type identification; iv) damage quantification. Regardless of the chosen purposes, methods need an appropriate statistical classification of the data gathered by sensors, followed by both signal processing and result analysis. This aims at leading to the identification of the health condition of the monitored structures. This work is focused on the detection of damage of road pavements and its quantification.

Literature shows numerous SHM methods, which focus on both concrete and masonry structures ([3], [4], and [5]), and also on bridges ([6], [7], and [8]).

Hola e Schabowicz [3] provided a classification of the methods used for the SHM of building. In particular, they state that there are three different types of SHM testing, i.e. destructive, semi-destructive (called below SDT), and non-destructive (usually called NDT). In addition, they state that the acoustic methods can be used for both the determination of material strength and its variation over time, and other characteristic of the structure (e.g. defects or cracks). Furthermore, they classify as acoustic methods the following: Ultrasonic method, Resonance method, Echo method, Impact-echo method, Spectral analysis of surface waves, Impulse-response method, Acoustic emission method.

Rehman et al. [7] carried out a literature review about the NDT methods used for the SHM of concrete bridges. They include among the stress-wave methods some of the methods cited above, i.e. Acoustic emission method, Impact echo testing, Sonic and Ultrasonic method, Impulse response method. These methods often use as source of noise or vibrations a striking hammer or devices that are capable to generate ultrasound wave (e.g. piezoelectric devices), and as a receiver a sensor capable of picking up the seismic waves (P, S, and surface waves) generated by the source, after they travel through the medium and its eventual defects or discontinuities.

Regarding the application of the acoustic method on road pavements and asphalt concrete, it is noteworthy the work of Mounier et al. [9]. They study the propagation of ultrasound waves through different asphalt concrete mixes in order to find both their complex modulus and their complex Poisson’s ratio at different temperatures, and using different approaches. As a result, they show the considerable linear viscous behaviour of this bituminous material as a function of the temperature for a wide range of frequencies. This behaviour affects the propagation velocity of the ultrasonic waves and the complex moduli, which decrease when the temperature increases because of the softening effect (the material become softer). Pahlavan et al. [10] studied the guided wave propagation on an aluminium plate covered with bitumen to simulate bridge deck structures. They state that the properties of the asphalt materials, like the dependence of the temperature, influence the fatigue crack inspection and monitoring systems. Alavi et al. [11] proposed a continuous health monitoring system for asphalt concrete pavements based on piezoelectric self-powered sensing technology. This kind of system uses the traffic loading for both empowering the sensors and damage diagnosis. The responses of a three-layers (asphalt, base and subgrade) pavement, with cracks in the bottom layers, under moving tire loading was simulated through a three-dimensional finite element model (ABAQUS). Moreover, laboratory tests were carried out on asphalt concrete slabs by a three-point bending machine in which three spherical packaging systems containing the piezoelectric sensors were embedded. Results of the simulations and the laboratory tests show that the damage progression can be expressed as a function of the probability density function (PDF) of time distribution of pavement strains. Indeed, the PDF and the corresponding cumulative distribution function (CDF) of strains provide information about the damage state of the pavement and how loads vary over time in terms of their frequency and magnitude. In more detail, the PDFs shift seems to allow localizing and quantifying the damage. Saboonchi et al. [12] focused on real time detection of the beginning of fatigue crack growth based on combined MEMS acoustic emission and strain sensors.

By referring to the acoustic response of a pavement as perceived by a bystander who is close to the road, note that in order to reflect more accurately the frequency response of the human ear, the "A-weighting" scale is commonly used (dBA), in which the sound pressure levels (SPL, dBA) for the lower frequency bands and higher frequency bands are reduced by certain amounts before they are being combined together to give one single sound pressure level value [13]. Generally, the traffic noise level is measured through sound level meters, which consist on a microphone, a data analyser and a display. Traffic noise depends on traffic, vehicles, drivers, and pavement characteristics [14]. The main sources of traffic noise refer to the power unit of the vehicle and the tyre-road contact (rolling noise, see [15], [16], [17]). Both depend on the speed of the vehicle. In particular, rolling noise is the main factor at high speeds (higher than 40-80 km/h, see [14], and [15]). Traffic noise level (SPL) is about 70-80 dBA at 10 m from traffic ([18], [19], [20], [21], [22], and

[23]). In more detail, it is very important to consider not only overall amplitude characteristics (SLP) but also noise composition with regard to frequency (spectral content). To this end, note that typical traffic noise spectra have a maximum value at about 1000-2000 Hz [12]. Microphone-based systems are also used for tests on road pavements in order to measure the sound absorption coefficient (e.g. standards ISO 13472-1, ISO 13472-2, ISO 10354-2), and the rolling noise (e.g. standards ISO 11819-1, ISO 11819-2).

The concept of the vibration and acoustic signature is widely used by process and fabrication industries in order to estimate the availability, the reliability and the efficiency of the key components of machineries through real time and not invasive monitoring techniques and advanced signal processing (see for example [24], [25], and [26]). These industries use this method to monitor their productivity, to control their products in terms of quality and safety, and also to optimise the management process. But, it is easy to understand that this concept can be extended to other fields. For example Aggelis et al. [27] studied different fracture modes in marble and cementitious materials under flexural load in terms of acoustic signature of their acoustic emission. Another example is the work of Leonard et al. [28], which used vibro-acoustic signature to study the power transformer tap-changers.

From the analysis of the literature, it is possible to state that the acoustic methods are gradually proving their effectiveness for the SHM of civil infrastructures (see [29], and [30]). This is due to the following facts: a) these methods are less intrusive (non-destructive or semi-destructive methods, or NDT and SDT respectively) than the commonly used methods; b) they are able to take advantage from the new technologies (both software and hardware); c) they are capable to provide detailed information about the structural health conditions of the monitored infrastructures, from measurements more and more simple and cheap. In this work, the concept of acoustic signature will be applied in an uncommon way, by merging different fields of interest, i.e., road infrastructures, traffic loads, noise generation, and structural health conditions.

2. Method

The aim of this work is to lay the groundwork for a new, non-destructive acoustic method for the SHM of road pavements. In this work, the health condition refers to the structural integrity ranging from that of a new pavement (as-built, hence without external od internal cracks) to the one of a damaged pavement (where it is ease to identify deep cracks, potholes, or classes of surface distress). The new method should be able to detect, at an early stage, the internal cracks of an apparently intact pavement, starting from acoustic signals analysis. Hence, it should identify the cracks that were generated in the subbase-base layers interface, when they are not already propagated through all the pavement layers up to the wearing course layer.

The core idea of the method is to consider the road pavement under test as a medium in which there is a transmission of acoustic signals (see Fig. 1). The method assumes the vehicles as the sound source because of the tyre-road interaction. This interaction produces vibrations and sounds that propagate inside the medium. It is possible to pick-up the sounds using a microphone placed into a little hole (1-2 cm of diameter) drilled in the pavement. For this reason, more precisely, this method can be classified as a semi-destructive method (or SDT). Acoustic signals can be recorded by the soundcard of a laptop through a proper Matlab® code. The same code is also used for signal analysis.

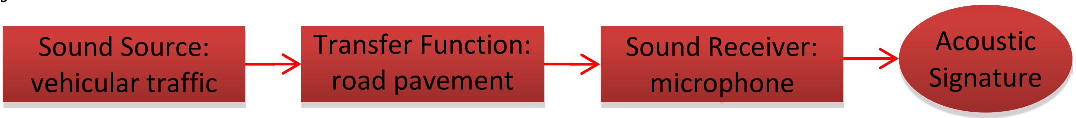


Figure 1. Overview of the proposed semi-destructive acoustic method for road pavements SHM.

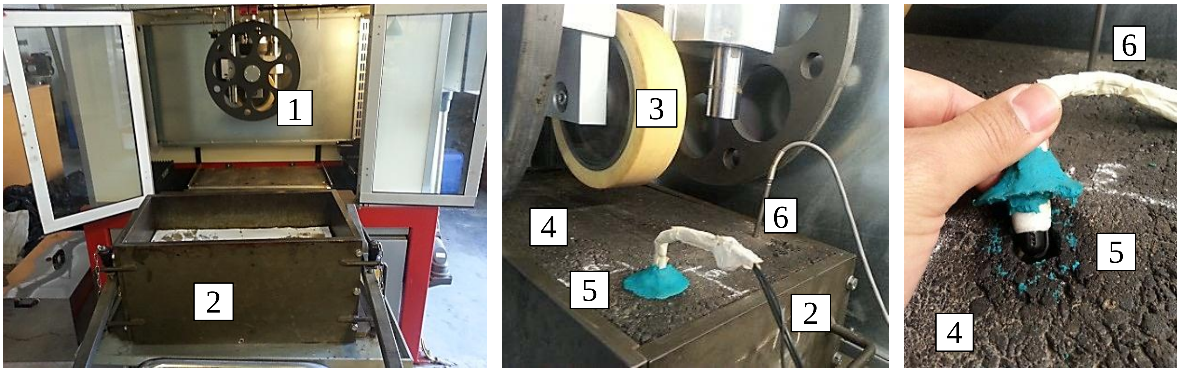
It is expected that many characteristics of the recorded signals are related to the level of deterioration of the road pavement. The actual relationship between the level and type of deterioration and the spectral content of the recorded signals is currently under investigation.

The main assumption on which this work is based is that the spectral content of an acoustic signal that passed through an undamaged pavement is different from that of a signal that travelled through a damaged pavement (either if this latter presents surface distress or not). A further assumption is that each and every level of deterioration can be associated to a specific acoustic signature. As starting approximation, different acoustic signatures can be distinguished from the Periodograms [31] of the recorded acoustic signals using as an indicator the spectral centroid (see Eq. 1).

3. Experimental set up

In order to investigate the effects of the passage of the wheel of a vehicle on a road pavement, laboratory tests using a Wheel Tracking Machine (or WTM, see Fig. 2) were carried out on dense graded friction course (DGFC) slabs. This machine is designed to produce/compact slabs and to carry out the rutting test. During the rutting test a rubber wheel rolls back and forth on a slab held in place by a metallic housing, under controlled conditions (it is possible to set: the temperature of the test chamber, the speed of the wheel, the load applied by the wheel, and the number of passages of the wheel). In this work the WTM was chosen: i) To produce and compact, under controlled conditions, three DGFC slabs, which were considered as samples of a road surface (Colorado Procedure – Laboratory 5116-10); ii) To generate realistic conditions in terms of both the load applied by a vehicle's wheel and the noise generated by a rolling wheel on a road surface, in order to record acoustic signals from the produced slabs (EN 12697-22).

Figure 2 shows: 1. The test chamber of the WTM used during the in-lab tests in which the temperature was set at 30 °C; 2. The metallic housing where the slabs were placed in order to impede it any movements during the passage of the rubber wheel (3); 4. One out of the three slabs under investigation (dimensions: 500×260×50 mm^3); 5. The microphone used to detect the acoustic signals during the tests, placed in the hole drilled in the slabs and held in place by modelling clay; 6. One out of the two thermocouples set into a hole drilled in the slabs, and used to measure the temperature of the slabs during the tests.



Legend: 1:Test chamber of the Wheel Tracking Machine (WTM); 2: Metallic housing of the slab; 3: Rubber wheel of the WTM; 4: Hot mix asphalt slab; 5: Microphone placed in the hole drilled in the slab, held in place by modeling clay; 6: Thermocouple into the drilled hole.

Figure 2. Experimental set up, comprised of Wheel Tracking Machine, microphone, and DGFC slab.

Three slabs were produced (Fig. 3). The first one was called UC (Un-Cracked slab), the second one LC (Lightly-Cracked slab), and the last one HC (Highly-Cracked slab). In the LC and HC slabs, two different macro cracks were made in the lower surface (the one opposite to the upper where the wheel rolls), across the wheel path (see Fig. 3). The cracks dimensions are 260×3×10 mm^3 for the LC and 260×3×20 mm^3 for the HC. Consequently they differ only for their depth, i.e. 10 mm and 20 mm, respectively. The hardware system for the detection, recording and analysis of the acoustic signals from the slabs under investigation consists in a broadband microphone and a laptop. An appropriate Matlab® code records the signals at the sampling frequency of 192 kilo samples per second (kS/s) and successively processes the signal.

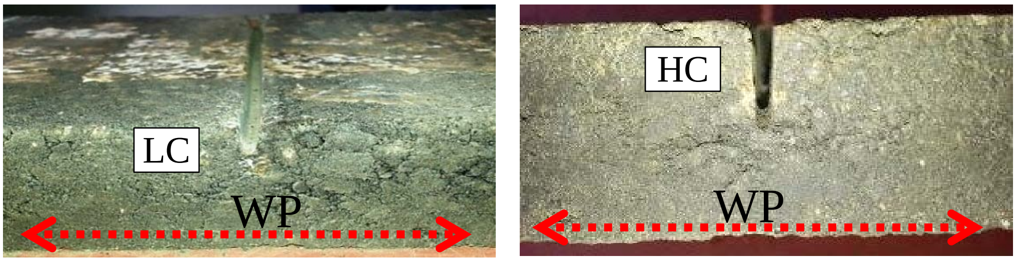


Figure 3. Details of the two macro cracks set up in the two DGFC slabs (LC, HC: Lightly-Cracked, Highly-Cracked; WP: wheel path direction in the upper surface).

The laboratory tests were carried out using the WTM on the three slabs, according to the following steps: i. The slab was put in the metallic housing to prevent any undesired displacement; ii. The two thermocouples were placed into the two holes located on two opposite corners of the upper slab face; iii. The microphone was placed in a suitable hole and held in place by a sufficient amount of modeling clay; iv. The test chamber was sealed by closing its two doors; v. Using the control panel of the WTM, the test parameters have been set, i.e. the temperature of 30 °C, the load of the wheel (0.7 kN corresponding to about 0.3 MPa), and the number of passages of the wheel on the slab (200); vi. The WTM and the signal recording were started at the same time. It is important to notice that the value of the load of the wheel is the same of the load used during the rutting test. Computations were carried out in order to estimate the load of a wheel of a heavy vehicle (about 500 kPa) and of a wheel of a light vehicle (about 200 kPa). Analyses included the derivation of spectra and centroids. In more detail, the power spectra of the recorded signals of the three slabs under test were derived and plotted as well as their spectral centroids. Note that the spectral centroid is the “center of mass” of the spectrum [32] and it can be derived based on the following formula:

$$f_c = \frac{\sum_{n=0}^{N-1} p_n \cdot f_n}{\sum_{n=0}^{N-1} p_n}, \tag{1}$$

where f_c is the spectral centroid; N is the sample length for the acoustic signal; p_n represent the weights, i.e. the values on the y-axis of the power spectrum; f_n are the frequencies (x-axis of the power spectrum).

4. Results

The figures below show the Periodogram or Power Spectral Density (PSD, [31]) of the vibro-acoustic signals transmitted through the slabs and their spectral centroids (see Figures 4-6, frequency range: 20-1500 Hz). About the spectral centroids (derived in the range 200-1000 Hz), please note that they are 592 Hz for UC, 444 Hz for LC, and 377 Hz for HC. From a preliminary analysis of the acoustic signatures of the three slabs under investigation, it may be observed that they are similar in the range 20-200 Hz, but they are really different in the range 200-1000 Hz. The common parts of the three signatures may be related to the vibro-acoustic response of the material, which is not affected by the abovementioned cracks. The differences may be attributed instead to the presence of different depth cracks of the slabs, i.e. UC (no cracks), LC and HC. In order to quantify these differences, the shifts of the spectral centroids are computed in the range 200-1000 Hz. As it can be seen in the figures 4, 5, and 6, there has been a migration of the spectral centroids toward the low frequencies, based on crack depth. In particular, the frequency value of the centroid is 592 Hz for the Un-Cracked slab, while it approaches a value of 444 Hz for the Lightly-Cracked slab (10-mm crack), and finally is 377 Hz for the Highly-Cracked slab (20-mm crack). The presence of the two cracks in the slabs seems to cause an absorption of the power (almost 20 dBW/Hz around 700 Hz) of the acoustic signals that pass through the slabs. This absorption appears evident especially for 600-900 Hz. On the other hand, there is an increase of the power density level (almost 20 dBW/Hz around 350 Hz) in the range 200-600 Hz, while the power density level is almost the same in the range 400-600 Hz.

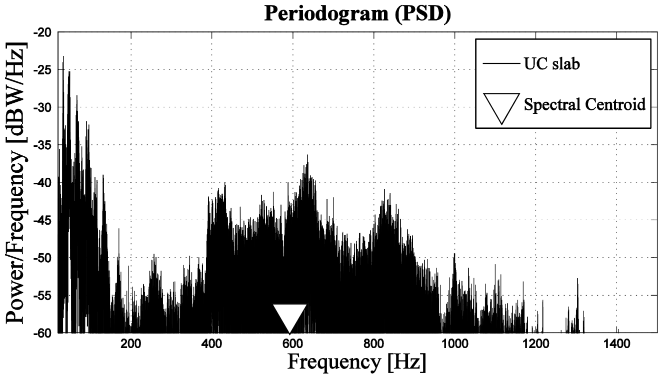


Figure 4. Acoustic signature of the UC DGFC (Un-Cracked slab of the type “dense grade friction course”).

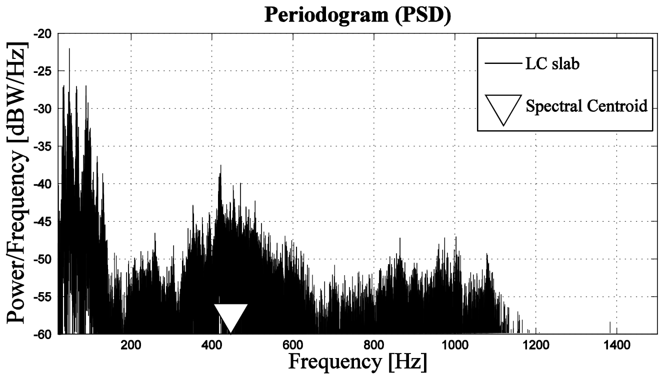


Figure 5. Acoustic signature of the DGFC slabs called LC (Lightly-Cracked slab).

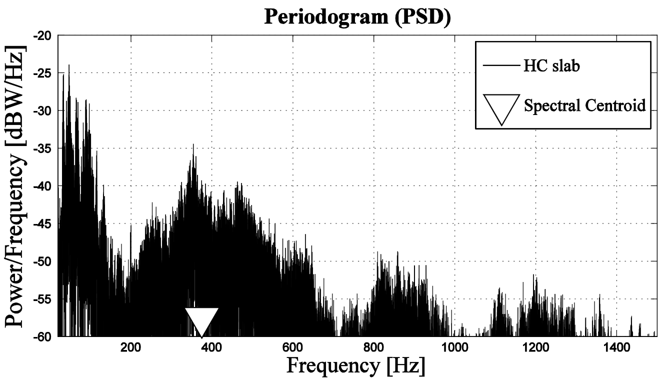


Figure 6. Acoustic signature of the DGFC slabs called HC (Highly-Cracked slab).

5. Conclusions

In this study the bases of a new acoustic semi-destructive method for the structural health monitoring of road pavements have been outlined. Traffic generates vibro-acoustic energy and the road pavement is considered as the medium in which part of this energy propagates. Signals propagate through the different layers of the pavement and they are recorded by means of a microphone placed in a hole drilled on the wearing course of the road. The spectral analysis of the acoustic signals recorded during laboratory tests on DGFC slabs shows that different levels of damage can be associated to different power spectra of recorded signals. In particular, when a macro crack is present on the slab, the spectral centroid of the power spectrum moves toward the low frequencies. The higher is the depth of the macro crack, the higher is the shift of the spectral centroid.

With the aim of confirming these experimental results, on-site tests will be carried out on both un-cracked and cracked road pavements. During these tests the acoustic signal related to the real vehicular traffic will be characterized. Moreover, the acoustic signatures of different kind of road pavements (e.g., pavements with different thicknesses, elastic moduli, specific gravities, etc.) will be collected to build a complete database. This database would be a useful instrument for the estimation of the health condition of a road. The association between the acoustic signature derived through the proposed method and the health condition (or the level of damage) of a road under investigation, could be accomplished automatically, for example, through the use of pattern recognition techniques [33] like the ones based on neural networks.

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